Performance of MoS_2 Coated Gears Exposed to Humid Air During Storage (Study Number Two)

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Abstract

This work is a follow-on to a prior study on the effect of exposure to humid air on the durability of a molybdenum disulfide (MoS_2) dry film lubricant on spur gears operated in vacuum, motivated by the James Webb Space Telescope (JWST) mission. In this study, MoS_2 dry-lubricating films matching JWST specification were applied to test gears. The gear specimens were subjected to a brief run-in period in vacuum prior to their exposure to humid air, mimicking the sequence of mechanism checkout testing, exposure to air during integration, and then storage prior to launch. Test gear exposure times to humid air ranged from 1 hour to 326 days. After exposure, gear durability tests were conducted as an indication of film lifetime. MoS_2 dry film lubricants that were exposed to humid air (57% RH) exhibited reduced film durability relative to DFLs that were not exposed. On average, the exposed specimens demonstrated 75% shorter film life. The severity of the reduction in film durability did not correlate with the duration of exposure, i.e., long exposures to humid air were not more impactful to film durability than were short exposures.

Introduction

The purpose of this work was to study the effect and exposure to humid air on the durability of a MoS_2 dry film lubricant (DFL) on spur gears operated in vacuum. This study was motivated by the JWST Mission. It is one part of a NASA Engineering Safety Center effort to evaluate potential risks and performance effects to JWST instrument mechanisms and components lubricated with sputtered MoS_2 films. This effort employed both spiral orbit tribometer and gear experiments. Gear teeth experience a unique combination of rolling and sliding friction that differs from pin-on-disk (pure sliding), bearings (mostly rolling), and spiral orbit tribometer testing. The content presented here is limited to results from gear specimens, as a follow-on to a previous publication evaluating the performance of MoS_2 DFL lubricated gears exposed to humid air during storage [1]. The scope of these investigations is detailed in Table 1. Note that durability test results from [1] are included as part of this analysis, referred to as gear set #1. Reference [1] contains additional inspection data from gear set #1 that are not repeated in this publication (i.e., SEM and profilometer data).

The DFLs evaluated in this investigation were sputtered "pure" MoS_2 films matching JWST specifications. The term “pure” does not imply quantification of trace species; the term “pure” is used to differentiate from nanocomposite-type MoS_2 DFL compositions.

Exposure to humid air is known to impact the lubricating performance of MoS_2; changes to the performance and tribological life of a MoS_2 DFL are dependent on the conditions of exposure and the material composition of the film (e.g., co-sputtered or nanocomposite films). The oxidation process of MoS_2 produces molecules of poorly lubricating MoO_3, leading to decreased performance and durability of the DFL. [2,3] However, the practical effects of long-term exposure are not fully understood and experimental data in this area of research is limited. Prior experimental studies have been conducted for many popular space lubricants in a range of exposure conditions and operating environments. This body of knowledge

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has led to the development of best practices for the handling and storage of lubricated parts, but the overall impact of exposure to humid air is highly specific to lubricant type and formulation. [2,3,4]

Table 1. Gear Evaluation Scope and Summary

Test Group	Focus and Work Detail	Work Results Summary
Gear set #1	• Develop criteria to compare lifetimes of unexposed vs. exposed surfaces (condition indicator concept) • Evaluate dry film lifetimes using a set of induction-hardened gears (unexposed vs. exposed) • MoS_2 DFL was supplied by local firm.	• Data was reported at the 44th Aerospace Mechanisms Symposium, May 16-18, 2016 • Commentary from technical community influenced the focus and work detail for evaluation of Gear Set #2
Gear Set #2	• Evaluate dry film lifetimes using a set of case-carburized gears (unexposed vs. exposed) • Adopted a short “running-in” period prior to storage and exposure in constant-humidity chamber • MoS_2 DFL was per JWST flight hardware specification	• Data reported herein

MoS_2 DFLs provide lubrication by the breaking of weak van der Waals bonds between the basal planes of adjacent molecules of MoS_2, allowing layers to "flow" over one another when loaded in shear. This lubricating behavior relies on the layers of a DFL being oriented such that the plate-shaped molecules of MoS_2 are allowed to slide in the desired direction of motion, parallel to the hard substrate material. Luckily, the surface of an MoS_2 film with an undesirable or un-ordered orientation will be realigned during a mechanism's initial cycles of operation ("run-in"), due to the tendency of the molecules to shear together in layers, forming a preferentially ordered surface as the friction between the lubricated components approaches steady state. [3,5]

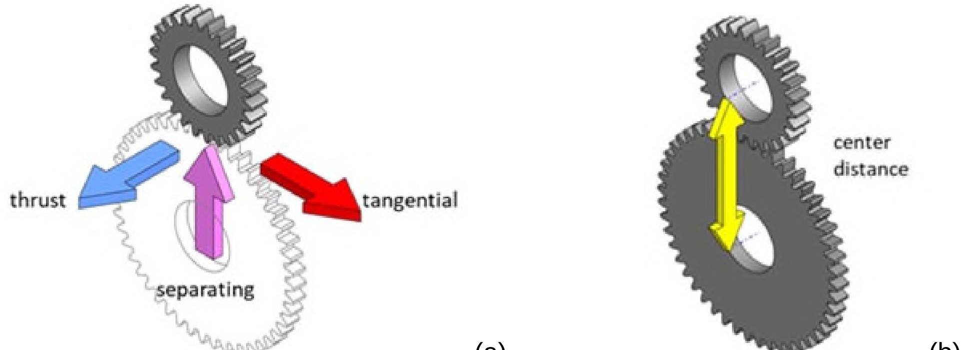
Preferential orientation of a MoS_2 DFL reduces the film's starting coefficient of friction and can provide additional resistance to oxidation. [6,7,8] The sputtering of MoS_2 produces columnar structures containing crystallites oriented perpendicularly to the substrate material, generally undesirable for lubrication performance and oxidation prevention. Run-in cycles on a MoS_2 DFL lubricated component re-orient the MoS_2 to the preferred basal orientation, but the impact of this effect on the lifetime of MoS_2 DFL subjected to humid air exposure is unquantified, particularly in the case of MoS_2 DFL lubricated gears.

Gear Testing Equipment

Test Rig

The vacuum gear rig will be described with the aid of Figures 1 and 2. The force created by the meshing gear teeth can be described as three orthogonal forces: the tangential force, the separating force, and the thrust force (Figure 1). Each of these forces is measured by a dedicated sensor affixed to the vacuum gear rig’s drive system, as depicted in Figure 2.

The pinion rotation is provided by a variable speed electric motor. A magnetic-particle brake attached to the output shaft imposes torque on the gear. A pressurized air cylinder controls the pinion position (Figure 2a). The air cylinder acts through a pivot axis to rotate the drive motor plate that mounts the driving shaft and drive motor. The rotation of the drive motor plate moves the pinion toward the gear in an arc motion to bring the teeth into mesh. The pressure to the cylinder, and thereby shaft center distance, is adjusted by a hand-operated valve. A linear variable displacement transducer (LVDT) measures the position of the drive motor plate, and this sensor output was used to establish the proper gear center distance (not shown in Figure 2).



(a) (b)

Figure 1. Depiction of measured gear characteristics. (a) Gear forces: tangential (red), separating (purple) and thrust (blue). (b) Gear operating center distance

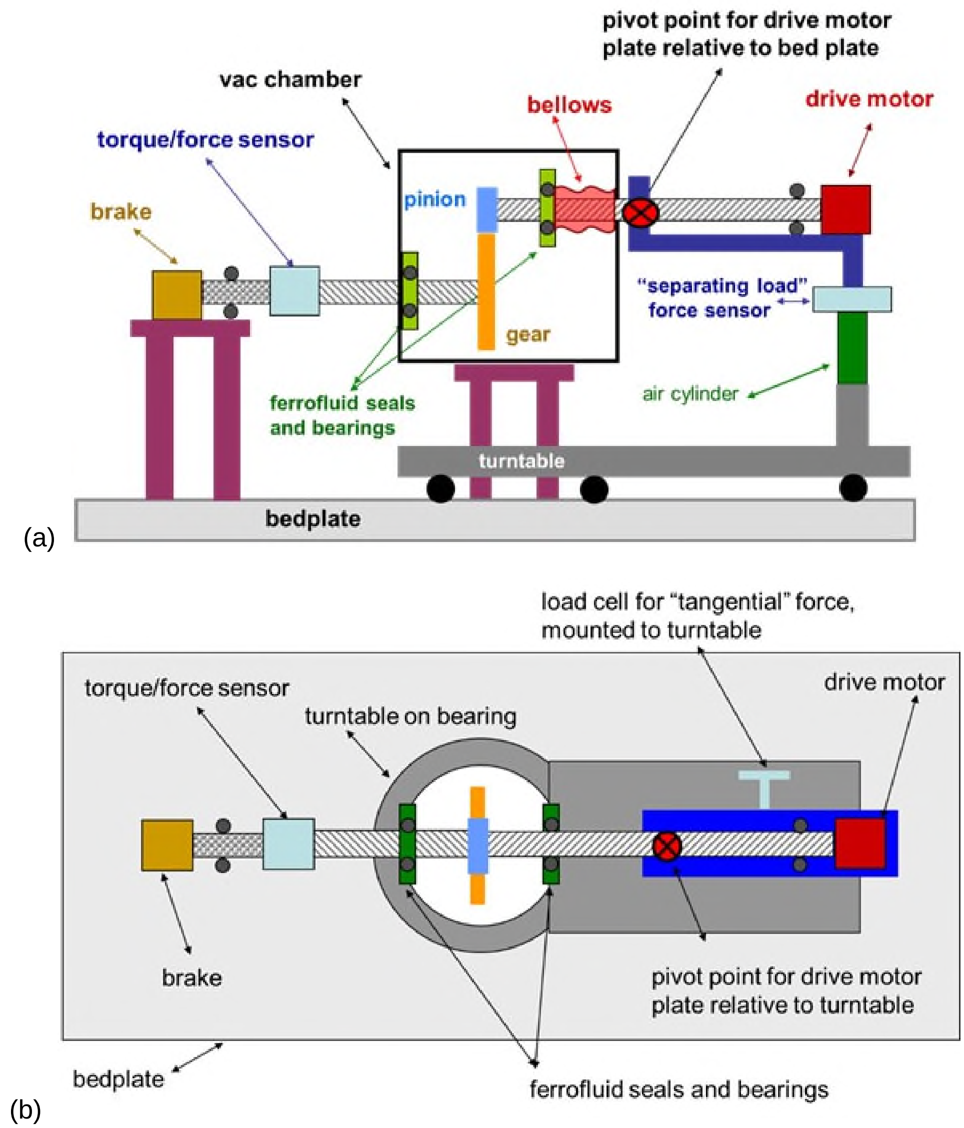


Figure 2. Schematic representation of vacuum gear rig. (a) Side view. (b) Overhead view.

The rig features a turntable that can be used to impose controlled misalignment of shafts for roller experiments. For gear testing, the turntable was adjusted to align the shaft.

A turbomolecular pump assisted by a scroll pump provides vacuum in the test chamber. Ferrofluid seals maintain the vacuum at the shaft-chamber interfaces. The typical condition in the test chamber is a pressure of 3x10-7 Torr. The most prevalent remaining constituent in the chamber during testing is water vapor as was determined using a residual gas analyzer [9]. Shaft speeds and total number of shaft revolutions were measured using 6000-pulse encoders on each shaft, and the torque on the output shaft was measured by a torquemeter with 22 N-m (200 in-lb) capacity.

The gearing center distance was measured indirectly by an LVDT affixed to a mounting bracket at the base of the drive motor. The LVDT output was related to the operating center distance using calibration results. For each tooth mesh cycle, the friction force reverses direction at the pitch point thereby imparting center distance change that is detected by the LVDT. The friction magnitude influences the magnitudes of the center distance motions, lower friction producing smaller center distance motions.

The gear teeth surface conditions were photographed at regular testing intervals through a viewport using a single-lens reflex camera with a 150 mm micro lens and a 12 million effective pixel image sensor. Lighting conditions and camera settings were consistent between tests.

<u>Humidity Exposure Chamber</u>

Test gear specimens were exposed to humid air in an enclosure (Figure 3) containing a saturated salt solution of water and sodium bromide below the specimens. The sodium bromide solution nominally maintains a relative humidity (RH) of 57% in a closed system. Excursions of relative humidity ranged from 55-60% during transients of the laboratory temperature. This range was deemed acceptable for approximating the 60% RH storage environment matching the maximum level of exposure experienced by the JWST components considered in this investigation.

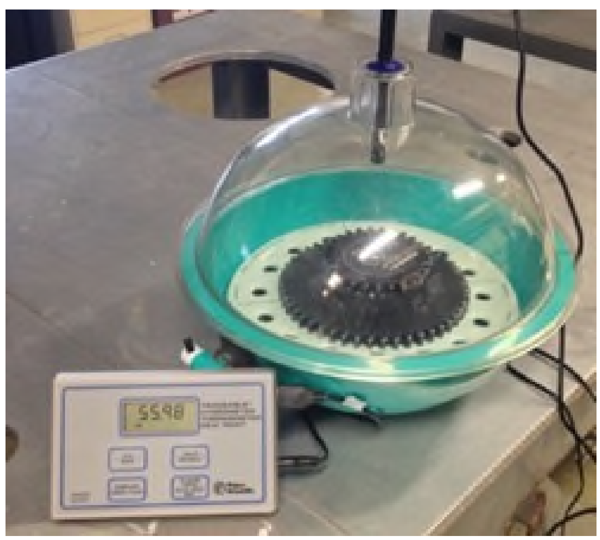


Figure 3. Humidity-exposure chamber for test gears.

<u>Test gears</u>

Readily available stock gears with appropriate center distance were selected and customized for use in this study. The customizations of the stock gear design were the bore diameters, sized for a COTS keyless shaft-locking device, and custom face widths. Design information for the test gears is provided in Table 2.

For gear set #1, there were six pairs of pinions and gears. The material was steel per Japanese material standard S45C (considered equivalent to AISI 1045). The teeth were induction hardened to surface hardness of HRc 50-60 and ground.

Table 2. Gear Design Summary

Parameter	Gear	Pinion
Number of Teeth	48	26
Face Width	10 mm	13 mm
Module	3 mm	3 mm
Pitch Diameter	144 mm	78 mm
Outside Diameter	150 mm	84 mm
Pressure Angle	20°	20°
Surface Hardness	50 to 60 HRc	52 to 60 HRc
Core Hardness	30 to 35 HRc	30 to 35 HRc
Carburization Depth	0.4 to 0.8 mm	0.4 to 0.8 mm

For gear set #2, there were six pairs of pinions and gears of the same geometry as gear set #1, but a different steel was selected. Stainless steel gears (which would have best matched the JWST mechanism gear materials) were not available in a timely manner, resulting in the selection of a case-carburized steel, Japanese material standard SCM415. This steel is considered approximately equivalent to U.S. standard AISI 4115, a low carbon steel (C = 0.15%) commonly used for power transmission gears and having higher strength than AISI 1045. The stock gear specification for surface hardness was 52-60 HRc. The case-carburized condition of gear set #2 was more representative of the subsurface hardness profile of JWST mechanism gears, compared to the relatively shallow case depth of the induction hardened specimens of gear set #1.

<u>DFL for Test Gears</u>
The test gears were coated with a pure MoS_2 DFL by sputtering. While some JWST mechanisms use nanocomposite MoS_2 coatings [i.e., ref. 5], the mechanisms of interest for this work use a pure MoS_2 DFL. Herein the term "pure" does not imply quantification of trace species, but the term "pure" is used to differentiate from nanocomposite-type MoS_2 DFL compositions.

Following the testing and reporting of results for gear set #1, which had a requested coating thickness of 3 to 4 μm, the requested nominal coating thickness for gear set #2 was modified to 2-3 µm to match the JWST specification. The vendor for the coating for gear set #1 was a well-experienced domestic (U.S.-based) vendor. The vendor for gear set #2 was an overseas-based vendor that is the proprietary owner of the specification used for JSWT flight hardware for the mechanisms of interest.

Each gearset required two runs in the sputtering chamber to accommodate the required number of parts. Witness coupons were used to approximate the thickness of the film on the gears and were verified by the vendor to be within the JWST specification. Stylus profilometer measurements taken with gear set #1 indicated that the sputtering process did not change the roughness of the gears' working flanks [1]. After sputtering, the gears were sealed in bags using a dry inert cover gas. Gears to be tested as unexposed remained in the sealed bags until the start of the installation procedure. The time from the opening of the bag until the gears were in a vacuum condition in the test rig was minimized to all practical extent, typically on the order of 1 hour.

Experimental Method

<u>Test Methods - Common Methodology used for both Gear Set #1 and Gear Set #2</u>
The first step of the testing protocol was to document the specimens for the test (serial numbers and installation orientations) and to note the visual condition of each gear, sometimes including digital photographs. Next, the gear pair was mounted onto the test shafts, the vacuum chamber closed, and then the chamber pressure was stabilized over several hours, and typically overnight, prior to applying torque and motion. The chamber pressure was $7x10^{-7}$ Torr or less at the beginning of each test. Figure 4 shows a pair of the MoS_2 coated test gears out of sealed bags just prior to test and shows the gears in the test chamber just prior to closing the vacuum chamber door.

(a)

(b)

Figure 4. Test gears. (a) Just prior to testing. (b) Installed in rig just prior to closing of test chamber.

Testing was done at a constant demanded brake torque and motor speed. The demanded torque was 6.8 Nm for the gear, at a test speed of 80 rpm for the pinion (and consequently 43.3 rpm for the gear). The power transmitted was 31 watts. The torque was selected to provide a tooth load intensity (force per unit face width) similar to the tooth load intensity for the mechanisms of interest. The speed was selected to minimize rig dynamic loading and vibration, as determined by previous testing efforts. Testing for endurance of the coatings typically required durations longer than a working day, and unattended testing was not attempted. The testing was paused overnight, as needed, with the test chamber vacuum maintained by continuous operation of the turbopump, and then testing was resumed the following day.

The test progression was monitored by visual inspection of the tooth surfaces through a viewport, aided at times by a strobe light to “freeze” the motion. The visual condition was also recorded by digital photographs illuminated by a short duration flash through a second viewport that provided a view of the gear teeth (but not of pinion teeth). The test progression was monitored by displays of the sensor data plotted as functions of pinion revolutions. Some previous development tests revealed that as wear severity and friction increase, sensor outputs became more erratic even though their mean value remain constant. For example, when friction on the gear teeth increases, the range of the separation force increases even though the mean may still be constant. This phenomenon is the result of the tooth friction force reversing direction as the tooth contact passes through the pitch point. Thereby, the friction force first adds to, and then subtracts from, the magnitude of the separating force during the tooth mesh cycle. With higher tooth friction the excursions from the mean become larger.

Based on prior experiences with health monitoring of geared machines, these observations led to the generation of “condition indicators” to monitor the overall effectiveness of the MoS_2 films. Data for each sensor (output torque, thrust force, tangent force, separating force, gear center distance) was sampled at 1 kHz for a period of 1 second, and the standard deviation of each signal over that period was calculated and catalogued as a “condition indicator”. For each 1 second interval throughout a test, the condition indicators for each sensor were plotted as a function of accumulated pinion revolutions. Such condition indicators were reliable indicators of changes in the lubricating performance of the MoS_2 DFL.

Figure 5 provides an example plot of a condition indicator monitored over the duration of a life test (5a), and an example set of data collected in a 1 second period that was used to calculate a single condition indicator (5b). Three regions are marked in Figure 5a: “Region I” is the smooth-running regime, “Region II” the start of MoS_2 compromise, and “Region III” is the significant friction regime. The beginning of Region II is marked, indicating approximately where the performance of the MoS_2 DFL was first compromised. The example data shown in Figure 5b was collected from the thrust force sensor at an illustrative point of operation in Region III, where relatively high tooth friction generates a varying signal, evident in the last 400 samples.

Film durability was determined using the condition indicator trend plots. The film durability was defined as the number of pinion revolutions until the film compromise started, such as indicated in Figure 5b. The film compromise was defined as the very beginning of a steady degradation of the film's performance regarding friction. A mechanism may continue to perform its intended function for some time after such film degradation begins. The intent was to assess a relative measure of the film durability, with and without exposure to humid air.

For gear set #1, film durability in each test was determined as follows. Lifetimes were determined based on each condition indicator, one at a time, by forming a consensus among four team members. The condition indicators for thrust force, tangent force, and gear center distance were found to be the most sensitive to changes in the lubricating performance of the MoS_2 DFL. Three independent estimates of the film durability were generated for each test, one estimate for each of these condition indicators. These three estimates were then averaged to determine an overall film durability value for each test.

For gear set #2, film durability was determined by a revised procedure. Each of three team members reviewed condition indicator trend plots independently, and each member provided one film durability value for each test, taking all three condition indicators into account for the evaluation. A single overall film durability value was determined for each test by averaging the values provided by each of three team members. This approach tended to reduce sensitivity to outliers in the condition indicator responses and allowed for unbiased estimates from each team member.

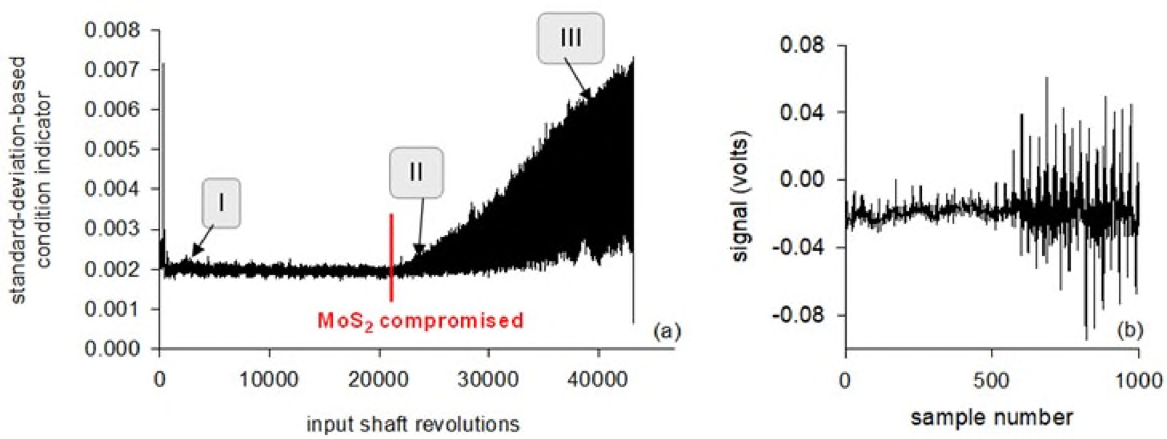


Figure 5. Typical trend and features of a condition indicator of MoS_2 film function. (a) Trend of condition indicator for the center distance (LVDT sensor), for test 1B. (b) Typical data record for calculation of standard-deviation-based condition indicator

<u>Test Methods – Test Set #1</u>

The test matrix used for gear set #1 was per Table 3. A balanced set (equal number of tests for exposed and unexposed surfaces) was planned and executed. For gear set #1, the unexposed surfaces had no run-in cycles prior to exposure to humid air in the constant-humidity chamber.

Table 3. Test Matrix for Gear Set #1

Test Name	Test Article Pairing	Pinion Serial Number	Gear Serial Number	Tooth Side Loaded	Exposed	Total Exposure Duration	Testing Order Sequence
MOS2 1-A	1	P4	G1	A	No	-	1
MOS2 1-B				B	Yes	10 days	3
MOS2 2-A	2	P6	G6	A	No	-	2
MOS2 2-B				B	Yes	28 days	6
MOS2 3-A	3	P2	G2	A	No	-	4
MOS2 3-B				B	Yes	17 days	9
MOS2 4-A	4	P1	G3	A	No	-	5
MOS2 4-B				B	Yes	17 days	10
MOS2 5-A	5	P3	G5	A	No	-	7
MOS2 5-B				B	No	-	8
MOS2 6-A	6	P5	G4	A	Yes	77 days	11
MOS2 6-B				B	Yes	77 days	12

Test Methods – Test Set #2

The test matrix used for gear set #2 was per Table 4. A balanced set (equal number of tests for exposed and unexposed surfaces) was planned. Not all planned tests could be completed because of test rig failures. At one point in time, a shaft seal that allows for the rig's vacuum condition needed to be removed and replaced. The replacement part was a long-lead time item. Therefore, this situation created some constraints on the possible exposure times, and this resulted in the exposure times noted in the table. For gear set #2, the unexposed surfaces have a short running-in period of approximately 100 revolutions of the pinion member prior to exposure to humid air in the constant-humidity chamber.

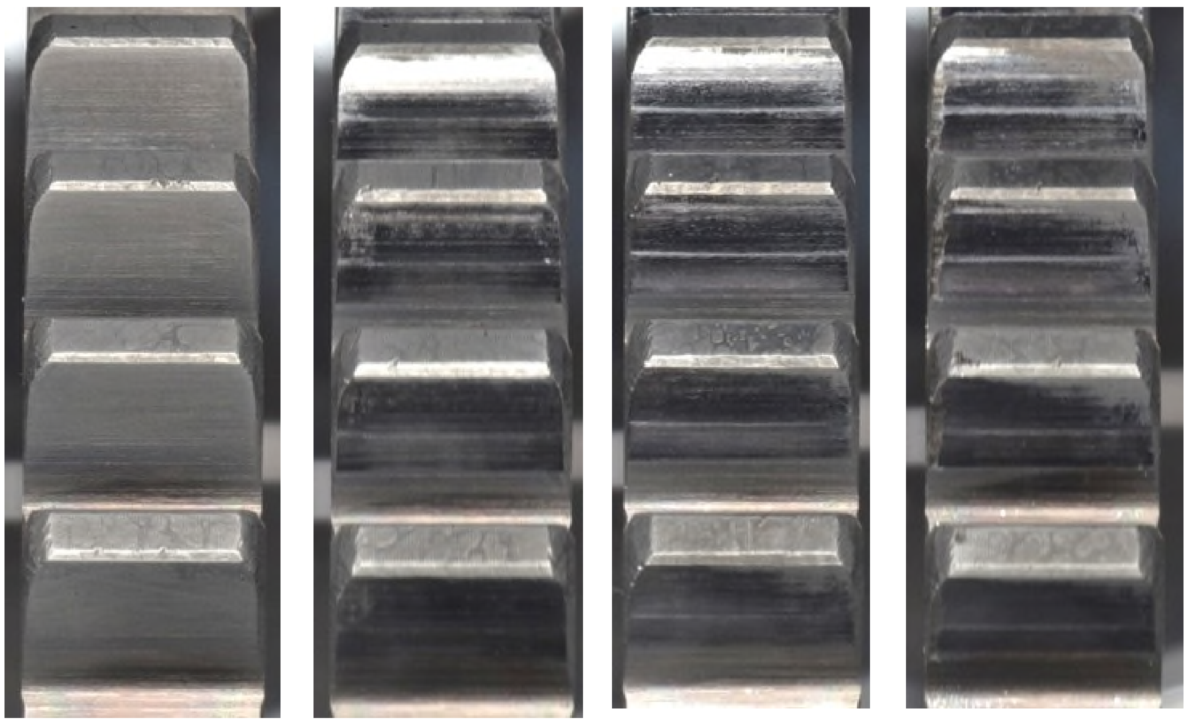
Table 4. Test Matrix for Gear Set #2

Test Name	Test Article Pairing	Pinion Serial Number	Gear Serial Number	Tooth Side Loaded	Exposed	Total Exposure Duration	Testing Order Sequence
2019-1A	1	19-P1	19-G1	A	Yes	326 days	9
2019-1B				B	No	-	1
2019-2A	2	19-P2	19-G2	A	Yes	296 days	8
2019-2B				B	No	-	2
2019-3A	3	19-P3	19-G3	A	Yes	280 days	7
2019-3B				B	No	-	3
2019-4A	4	19-P4	19-G4	A	Yes	253 days	6
2019-4B				B	No	-	4
2019-5A	5	19-P5	19-G5	A	Yes	213 days	5
2019-5B				B	No	-	*
2019-6A	6	19-P6	19-G6	A	*	*	*
2019-6B				B	*	*	*
* Test equipment problems; test could not be completed.							

Results and Discussion

Observations from Photo Documentation – Tested Gears

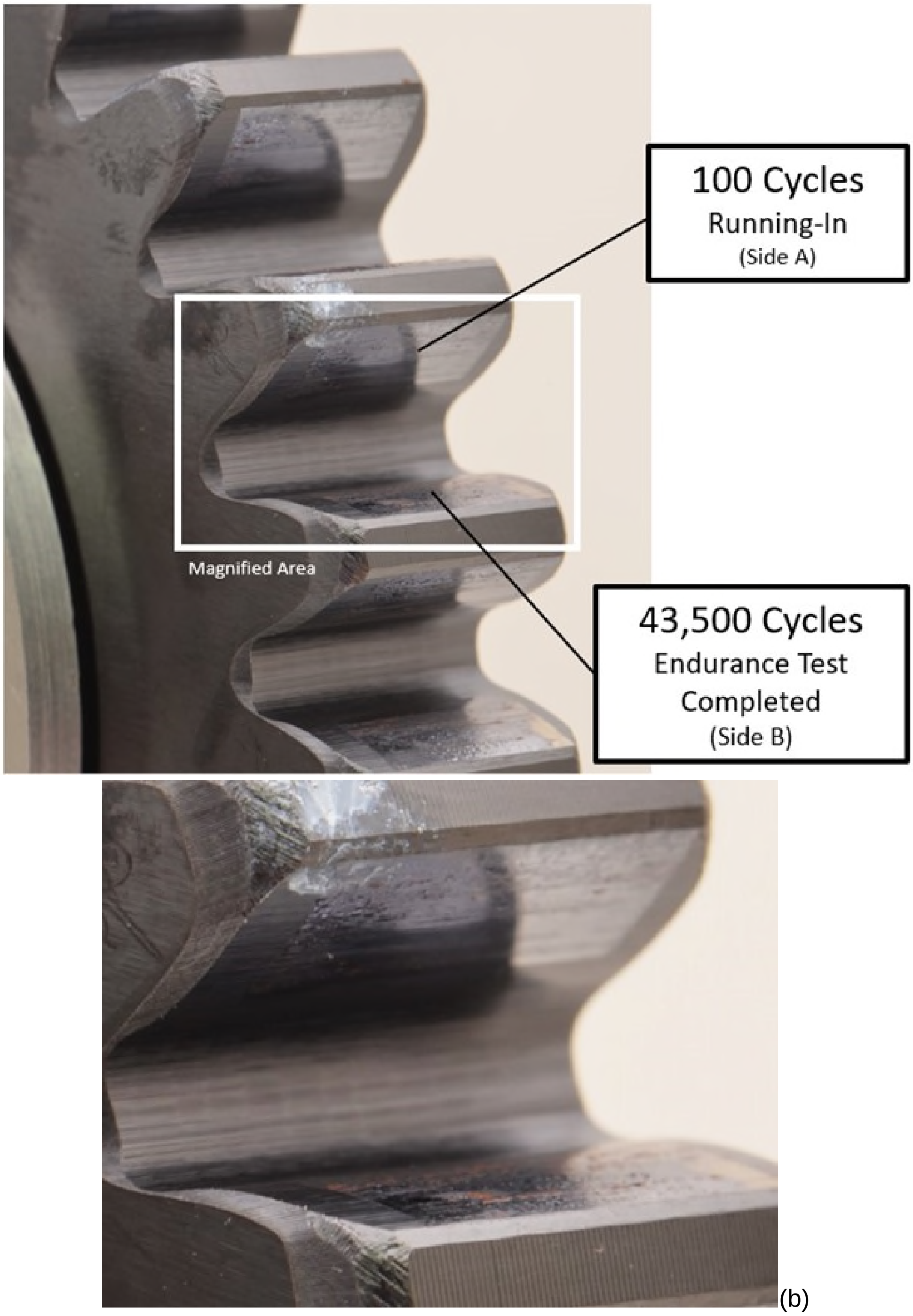
The behaviors of the films were also evaluated by studying photographs, profilometry, and SEM inspections. During initial running of each gear pair, it was noted that the tooth surface running-in required very few tooth contact cycles. In other words, the tooth surface appearance changed dramatically, becoming glossier and reflective in appearance after only a few revolutions, and subsequent further visual changes to the tooth surfaces occurred at a very slow and steady rate. Figure 6 illustrates typical results of how the surface visual appearance changed for the gear teeth during a test using gears from gearset #1. The first two images from left to right show the teeth prior to any running and then again after only 1% of the total running time. The other two images in Figure 6 show the teeth after 50% and 99% of the test duration. The last two images show that with further running the visual condition changes less dramatically over the final 98% of running as compared to the first 1% of running durations.



Prior to start | ~1% of test duration | ~50% of test duration | ~99% of test duration

Figure 6. Gear teeth surface appearance for different durations of testing.

For the case of gear set #2, a brief running-in of the gears was performed in vacuum condition, comprising approximately 100 rotations of the input member (pinion) prior to exposing the gear pairs to humid air. Figure 7 shows the appearance of pinion 19-used for test 19-1B (per Table 4), after a 326-day exposure to humid air and just prior to installation for film durability tests. The photos depict the significant change of visual appearance of the gear teeth after only 100 operating cycles (Figure 7a). From a macro-perspective, surfaces with only 100 contact cycles appear like surfaces with more than 40,000 cycles. Gears having had exposure to humidity could show visual signs of iron oxidation, per observed red-brown colorations (Figure 7b) [1]. In general, surfaces from gear set #2 that had a 100-cycle run-in prior to humid air exposure developed more significant regions of red-brown colorations as compared to gears from set #1 that had no run-in prior to exposure. The brief running-in appears to expose the steel substrate at asperity peak features, and/or diminish the MoS_2 film thickness at localized areas (i.e., oxidation is observed visually without the aid of magnification).



(a)

(b)

Figure 7. Photo of the surface condition of the 26-tooth pinion 19-P1, following completion of endurance test of unexposed surfaces (one side of teeth), 100 cycle run-in (second side of the tooth), and exposure to humidity for 326 days. (a) Overall view. (b) Closeup to capture red-colored oxidation locations.

Note that the test gears were made from a plain carbon steel. The preferred experimental approach would have been to use a stainless steel such as hardened 440C, but such gears could not be obtained within the constraints of this assessment. The best and accepted practice for space mechanisms is to use an appropriate stainless steel for gears and other parts that experience rolling and sliding. The oxidation seen on the plain carbon steel test gears during this assessment may have been enhanced by the presence of MoS_2 while in the humidity of the storage environment.

Dry Film Effective Lifetimes – Gears

During all in-vacuum operation of the test gear specimens, a set of "condition indicators" were calculated from real-time sensor data averaged over a period of one second. Film durability for each test was derived from the condition indicators calculated for three of the measured parameters; the gear center distance, thrust force, and tangent force. For each test, an average film durability was calculated per procedures described in the 'Experimental Method' section above. The results are collected in Tables 5 (for gear set #1, published previously) and 6 (for gear set #2, new data).

The film durability for unexposed gear specimens from set #2 were similar to the results from set #1. The average unexposed film durability from set #1 was 100,200 revolutions, with a median of 83,500 revolutions; set #2 averaged 91,200 revolutions, with a median of 96,800 revolutions for unexposed gears. These values closely replicate the unexposed film durability of set #1, despite differing substrate materials, hardening processes, and applied film thicknesses.

The average film durability of gears exposed to humid air was less than the average durability of unexposed gears, as observed for both gear sets. The average film durability of exposed gears from set #1 was 64,900 revolutions (a 35% reduction relative to the unexposed tests for this set), with a median of 68,800 revolutions (an 18% reduction). The loss in film durability from set #2 was more severe, with an average durability of 24,300 revolutions (a 73% reduction relative to the unexposed tests), and a median value of 24,700 revolutions (a 75% reduction).

Table 5. Test Results of Film Durability, Gear Set # 1

		Film Durability (pinion revolutions)			
Test Name	**Exposure Duration**	**Center Distance**	**Thrust Force**	**Tangent Force**	**Average Value**
MOS2 1-A	0 days	52,000	52,000	56,000	53,333
MOS2 2-A	0 days	59,000	61,000	65,000	61,667
MOS2 3-A	0 days	207,000	184,000	180,000	190,333
MOS2 4-A	0 days	86,000	69,000	94,000	83,000
MOS2 5-A	0 days	125,000	125,000	136,000	128,667
MOS2 5-B	0 days	83,000	80,000	89,000	84,000
MOS2 1-B	10 days	21,000	20,000	22,000	21,000
MOS2 2-B	28 days	69,000	55,000	74,000	66,000
MOS2 3-B	17 days	59,000	65,000	66,000	63,333
MOS2 4-B	17 days	81,000	78,000	95,000	84,667
MOS2 6-A	77 days	84,000	76,000	88,000	82,667
MOS2 6-B	77 days	70,000	71,000	74,000	71,667

* "Average Value" is the average of the 3 durability estimates to the left; Center Distance, Thrust Force, and Tangent Force.

Unexposed Group	Average = 100,200	Median = 83,500
Exposed Group	Average = 64,900	Median = 68,800
Percent Reduction:	**35%**	**18%**

Table 6. Test Results of Film Durability, Gear Set # 2

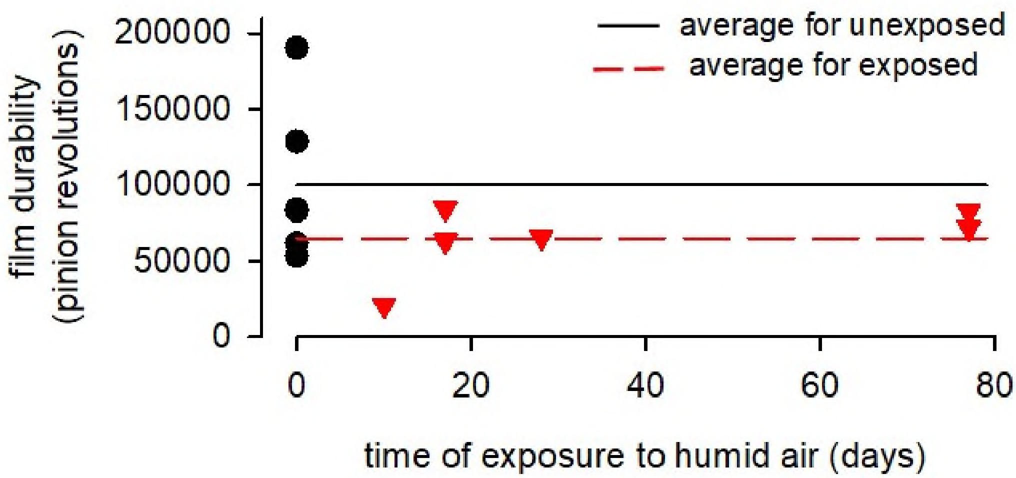
		Film Durability (pinion revolutions)			
Test Name	**Exposure Duration**	**Center Distance**	**Thrust Force**	**Tangent Force**	**Average Value**
MOS2 1-A	0 days	52,000	52,000	56,000	53,333
MOS2 2-A	0 days	59,000	61,000	65,000	61,667
MOS2 3-A	0 days	207,000	184,000	180,000	190,333
MOS2 4-A	0 days	86,000	69,000	94,000	83,000
MOS2 1-B	326 days	21,000	20,000	22,000	21,000
MOS2 2-B	296 days	69,000	55,000	74,000	66,000
MOS2 3-B	280 days	59,000	65,000	66,000	63,333
MOS2 4-B	253 days	81,000	78,000	95,000	84,667
MOS2 6-A	213 days	84,000	76,000	88,000	82,667
* "Average Value" is the average of the 3 durability estimates to the left; Center Distance, Thrust Force, and Tangent Force.					
	Unexposed Group	Average = 91,167		Median = 96,833	
	Exposed Group	Average = 24,267		Median = 24,667	
	Percent Reduction:	**73%**		**75%**	

These reductions in film durability attributed to humid air exposure are of similar order of magnitude as compared to the 55 to 20% range of reductions reported by Lince, Loewenthal, and Clark [2] from pin-on-disk evaluations.

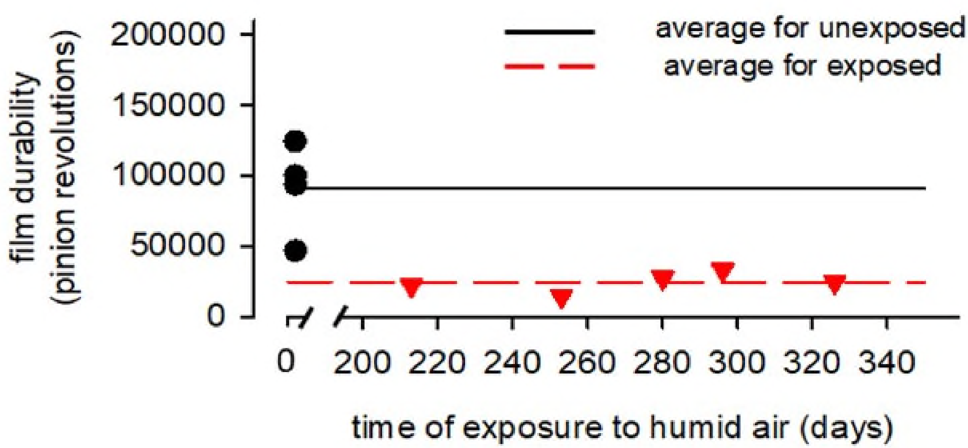
The average film durability values are plotted as a function of the duration of exposure to humid air in Figure 8, using data from Tables 5 and 6. While the film durability for exposed surfaces was lower on average than for unexposed surfaces, there is no clear correlation between film durability and the duration of exposure to humid air.

While the range of scatter in film durability is significant, it should be noted that this order of scatter is common for gear wear data. Gear wear experiments for liquid lubrication conditions exhibits similar scatter [10]. Gear wear behavior is influenced by many attributes that can be difficult to control for, such as differing surface textures between specimens, or tooth-to-tooth and gear-to-gear geometric tolerances. Even small variations in the manufacturing process will influence the performance of each individual gear; minute changes in the condition of cutting tools used to form the gear, the exact position of a gear in the heat treatment furnace, etc. Large scatter in performance data can make it difficult to determine quantitative trends, except when very large datasets can be produced.

In spite of the relatively modest number of specimens evaluated in this investigation, the main influencing variables are clear. The most significant of these factors is exposure to humid air; gears that were not exposed to humidity prior to testing exhibited greater film durability than gears that were exposed. The most dramatic reductions occurred in gear specimens that were subjected to a small number of revolutions in vacuum prior to their exposure to humid air. This reduction in film durability does not appear to depend on the duration of a specimens' exposure to humid air; specimens subjected to the shortest exposures and specimens subjected to the longest exposures exhibited comparable reductions in film durability.



(a)



(b)

Figure 8. Film durability as function of time of exposure to humid air. (a) Results for gear set #1. (b) Results for gear set #2.

Summary and Concluding Remarks

This investigation was conducted to study the relative durability of a MoS_2 DFL applied to gear teeth before and after exposure to humid air. The DFLs evaluated in this assessment were applied by a particular overseas vendor as required by a JWST specification for the mechanisms of interest. A previous investigation was conducted using a similar MoS_2 DFL supplied by a domestic vendor [1], referred to as gear set #1. Test specimen gears used in this investigation, gear set #2, were prepared by applying a pure (not nanocomposite-type) MoS_2 DFL to case-carburized steel gears via sputtering. Specimens were then subjected to a brief run-in procedure (100 cycles) in vacuum followed by controlled exposure to a humid air environment at 60% RH for durations ranging from 10 to 326 days.

MoS_2 DFL gear specimens subjected to long-term humid air exposure exhibited lower film durability relative to the baseline unexposed specimens. While the average film durability of unexposed specimens was similar between both studies, the reduction in film durability observed in gear set #2 (75% less life) was more severe than in gear set #1 (35% less life). By visual inspection, the run-in procedure introduced in this investigation appears to have exposed the steel substrate at worn asperity peaks or at localized areas of high MoS_2 wear. Signs of iron oxidation were visible as red-brown colorations on the tooth surfaces of gear specimens after exposure to humid air. More coloration was observed in gear set #2 which had been run-in prior to RH exposure as compared to gear set #1, which had no run-in prior to RH exposure.

The severity of the reduction in film durability after exposure to humid air did not correlate with the duration of exposure. Long exposures to humid air did not reduce film durability more severely than shorter exposures.

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