Development of an Actuator

FOR AMBIENT TO CRYO APPLICATION

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Management Summary

During the qualification campaign of the NIRSpec (near-infrared spectrometer) instrument mechanism, the actuator could not achieve the expected lifetime that had been extended during the development phase. The initial design could not be adapted to the requested number of revolutions during that phase.

Consequently the actuator needed to be modified so that the function of the mechanism would not be endangered or, by extension, the overall function of the NIRSpec instrument. The modification included a change of the overall actuator design—internal dimensions, tolerances, materials, lubrication and assembly process—while keeping the interface to the mechanism, mass and function.

The lessons learned from the inspection of the failed actuator have been implemented in order to ensure the development and qualification success. The initially available time for this activity was in the range of six months to meet the overall program schedule.

Introduction

The actuator consists of a three-stage gearbox flanged to a stepper motor. A lever connected to the actuator by an eccentric mechanism moves the upper sled of the refocusing mechanism assembly (RMA)—an optical NIRSpec sub-unit carrying highly sensitive mirrors (Fig. 1).

The high non-operational temperature range of 296K—as well as the low operational temperature of 30K—require a special design considering the great thermal expansions between 27K and 323K, as well as a proper material selection that deals with the change of mechanical properties at cryogenic temperatures. Both the new material concept and the molybdenum disulfide (MoS_2) lubrication coating confronted the engineers with unexpected effects.

In order to keep the development risk (both technically and regarding the schedule) low, two different breadboard models and one qualification model have been built and tested; two flight models and one flight spare will be delivered to the customer.

Key Equipment Design and Performance Requirements

The refocusing mechanism of the NIRSpec instrument provides the focusing function by means of two corner mirrors changing the optical path length by movement of the mirrors.

Three titanium blades guide the RMA upper sled, which is driven by an eccentric drive requiring a maximum torque of about 0.55 Nm. Considering ECSS (*Ed.'s note: a space environment standard; i.e., a standard for calculation of radiation effects and a policy for design margins*), margins, the actuator has to generate a worst-case torque of 1.21 Nm at ambient and 1.4 Nm at 30K, driven with a rated current of 120 mA. This is realized by a stepper motor attached to a planetary gear with a gear ratio of 184:1 distributed to three stages.

The most important requirement is the wide operational temperature range from 30K to 323K. The observations at the first actuator demonstrate the high importance of both the selection of a proper dry lubrication as well as a CTE (coefficient of thermal expansion)-consistent design, ensuring constant tolerances within the operational temperatures for both the bearings and gears.

According to the expected in-orbit cycles, as well as the flight model test campaign, the qualification model has to be loaded in different cycles from the mid-stroke position, resulting in a total of about 400,000 motor revolutions (including ECSS margins) without significant performance reduction. As learned from the first actuator, special attention has to be paid to the metal-to-metal contact due to coating wear between sliding parts. Therefore, a redundant lubrication design should be considered, especially taking into account the RMA being a single-failure object; that means a breakdown of the sub-unit results in the inability to re-focus the NIRSpec instrument.

The actuator's operation in an environment close to contamination-critical optical equipment rules out lubrication systems with particulate or molecular contamination, and yet requires solid lubrication.

Initial Design of First Actuator and Lessons Learned

The first RMA actuator consisted of a material mix of six different sorts of steel with an estimated COE (common operating environment) at 30K, varying between 7.5 x 10^{-6} 1/K (ball bearings) and 15 x 10^{-6} 1/K (gearbox housing). This design was based on experience in gearbox development for usual applications—every single material has its specific strength playing on the individual function. But this cryogenic application cannot be called usual, and different strategies must be pursued.

The shrinking at cryo is likely to have caused increased friction and therefore affected the lifetime significantly. The lubricant used—Dicronite—showed significant signs of abrasion after life testing (about 330,000 motor revolutions), resulting in metal-to-metal contact as well as a major increase in necessary current; according to ECSS, a clear failure of life test.

Motor current measurements during the life test demonstrated that the actuator lubrication would have survived the nominal lifetime but, due to lifetime extension, the results as described above have been obtained.

Similar actuators have been successfully used in ground-based cryo applications, but in areas where an exchange of a failed actuator can be performed at any time.

Design of the New Actuator

Figure 4 represents the new actuator in cross-section; the main design was kept, in general, but the rear motor bearing was substituted by larger duplex bearings. The rotor axial pre-load spring was moved from the front duplex to the rear bearing. Ideally the front duplex bearings of the motor should have been arranged in 0-orientation to allow a limited rotation of the rotor axis (isostatic support conditions). Due to assembly constraints, an X-arrangement had to be selected in combination with an increased play of the rotor axis rear bearing. The planetary gear with three stages still has a gear ratio of 184:1.

The material concept was changed significantly to a CTE-consistent design as increased friction and raised bearing loads are supposed to be at least part of the reason for the first actuator's failure.

As Figure 5 illustrates, all motor and gearbox parts—except the screws—are manufactured of either hardened Cronidur (X30) or titanium; the higher CTE of the screws only results in behavior comparable to extension bolts, and the machining of well known material for these critical functional components minimizes risks.

Coating for Solid Lubrication

After the failure of the Dicronite coating during life test, a solid lubricant concept had to be selected that is well known

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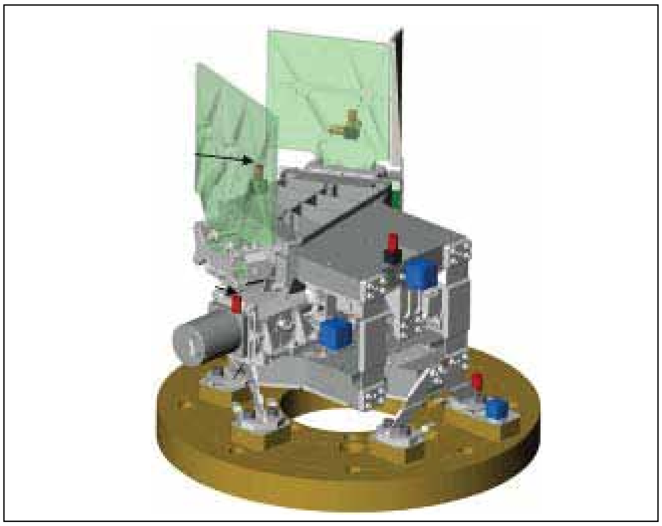
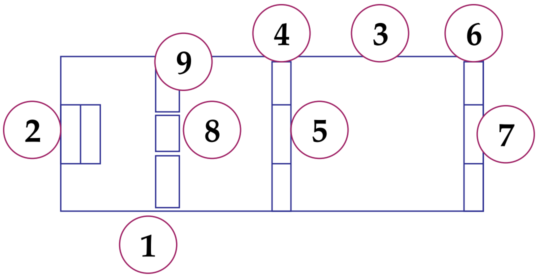


Figure 1—Refocusing mechanism assembly.



No	Nomination	DIN	Common Name	CTE (20°C)	Est. CTE (30K)
1	Gearbox housing	1.4305	X10	17	15
2	Gearbox bearings	1.4108	X30	9.9	7.5
3	Motor housing	1.4301	X5	17	15
4	Front motor flange	1.4305	X10	17	15
5	Front motor bearing	1.4108	X30	9.9	7.5
6	Rear motor flange	1.4305	X10	17	15
7	Rear motor bearing	1.4037	X65	10.8	8.5
8	Sun wheel	1.4112	X90	10.4	8.3
9	Planetary wheel	1.4034	X46	10.5	8.3

Figure 2—Material concept of first actuator.

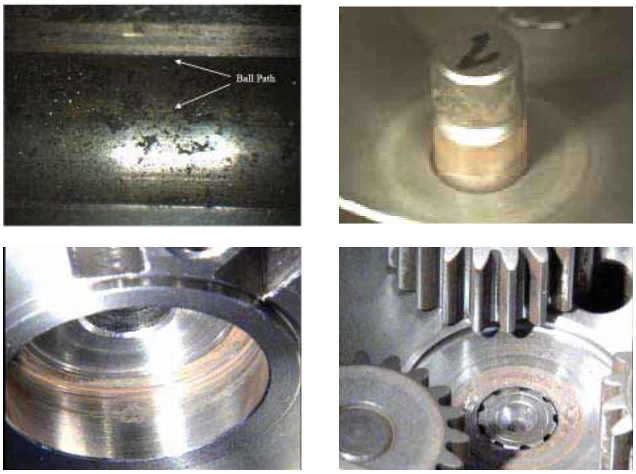


Figure 3—Lubrication failure of first actuator after life test. Visible corrosion results from the exposure of the blank metal to air after disassembly of the actuator.

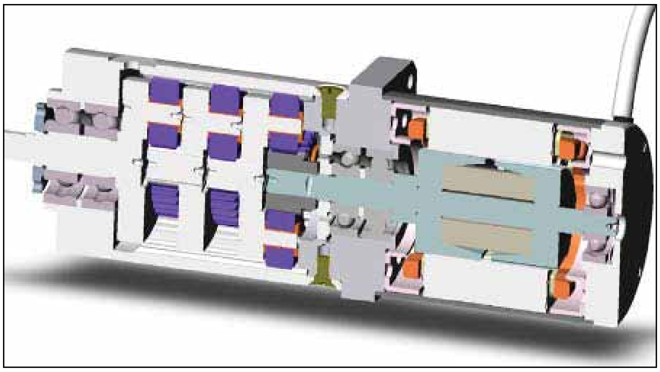


Figure 4—New design RMA actuator.

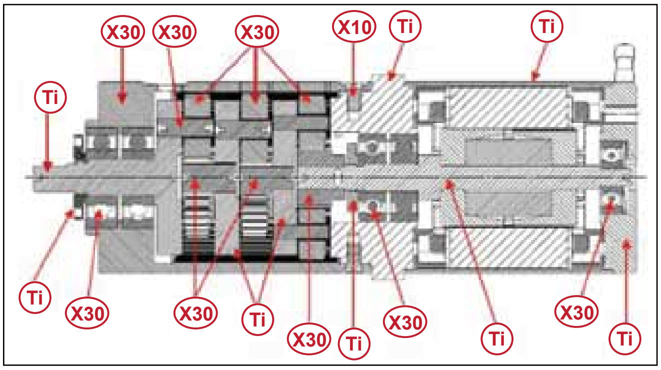


Figure 5—New material concept.

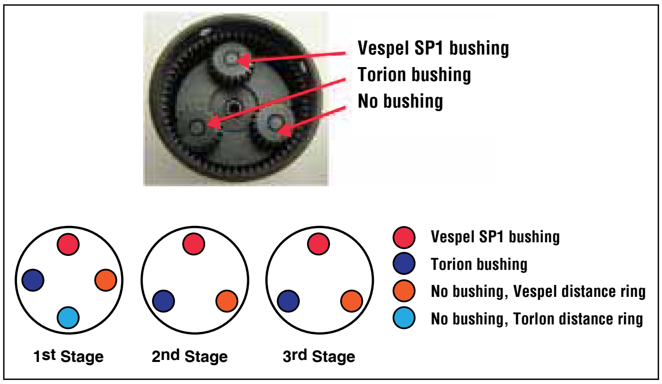


Figure 6—Pre-QM1 design (MoS_2–lubricated).

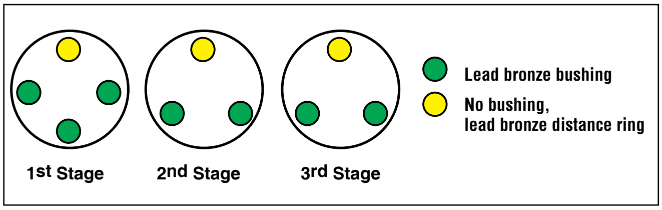


Figure 7—Pre-QM2 design (lead-lubricated).

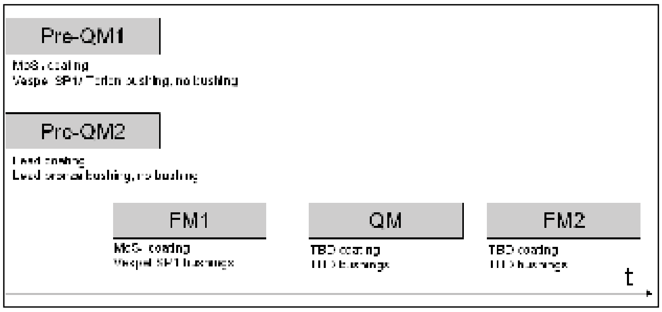


Figure 8—Development concept and success-oriented approach.

for space applications due to the short time frame of development. Sputtered molybdenum disulphide (MoS_2) seemed to be the most suitable lubricant, as it has proven its reliability in numerous space applications. In order to have a back-up solution during the development program, a lead-lubricated breadboard model was set up, tested and compared to the MoS_2-coated model before starting the qualification program. This development approach is explained later on.

Plain Bearing Bushings

Sputtered MoS_2 is well known as a solid lubricant for ball bearings where the predominant relative movement is a combination of sliding and rolling friction. However, this experience cannot be found in a gearbox lubrication application. The planetary wheels are rotating around the pins pressed into the planet carriers. This journal bearing was one of the critical areas where the Dicronite coating wore off. Therefore a redundancy was requested for this function. Plain bearing bushings made of plastics have been found to fulfill this requirement for increased safety against abrasion. In case of local lubrication failure, these bushings fulfill journal bearing functions and prevent direct metal-to-metal contact.

The bushings were toleranced in such a way that they shrink onto the planet axis in cryo in order to gain a defined sliding surface. That requires a small low-temperature embrittlement at temperatures down to −246°C, relatively low CTE and good sliding properties in cryo—all not self-evident for organic plastics.

Different materials have been considered in this application:

- Vespel SP1/Vespel SP3. Vespel is a well known plastic material used in space applications; type SP3 is self-lubricating by containing small particles of MoS_2 while SP1 represents the unfilled material.
- Copper metal matrix composite (Cu-MMC). The self-lubricated Cu-MMC has been developed by Austrian Research Centers for use in tribological sliding contacts under vacuum. It is based on a copper matrix with inclusions of solid-lubricant particles, and one of its highest advantages compared to plastics is its low CTE.
- Victrex PEEK 450G is supposed to be applicable especially for cryogenic applications.
- Torlon 4203 PAI stands out due to its high ductility—even at cryogenic temperatures.
- Sintimid 15M/30M is a sintered polyimide designed for cryogenic applications and filled with either 15% MoS_2 or 30%, respectively.
- PGM-HT contains of PTFE filled with glass fibers (15%) and MoS_2 particles (5%) and is often used for ball bearing cages.

Bushings have been manufactured of all the materials as well as sliding samples for friction coefficient comparison. Friction tests under ambient in combination with MoS_2 powder should give a first impression of the tribological behavior. While Vespel SP1, Victrex and Torlon showed good machinability, Sintimid, Cu-MMC and Vespel SP3 were very brittle during manufacturing (the higher the filling percentage or the bigger the particles, the worse was the machinability) and some of the bushings broke during machining. It turned out that filled material is not suitable for this application as the marginal wall thickness and particle size are in the same range.

The bushings were assembled onto the planet axes and exposed to a liquid nitrogen dip test. Sintimid bushings cracked or indeed broke during the test and therefore failed. Victrex material was undamaged, in principle, but showed slight white marks after removal of the bushings that are suspected to be material degradations.

Based on the experiences with Vespel in an Astrium space application, this material has been selected for the FM1 model, but Torlon has been considered for one of the breadboard models in order to allocate a back-up solution.

Development Concept and Success-Oriented Approach

A success-oriented approach has been chosen due to programmatic reasons: i.e., the FM1 was produced and tested with the design described above without the qualification program having started yet. In order to gain confidence, two breadboard models—or pre-qualification models—have been set up. As every stage of the planetary gear has three (1st stage four, respectively) planet axes that are equally loaded, different bushings could be assembled and their behavior during life test can be compared.

Pre-QM1 is MoS_2-lubricated and contains bushings of Vespel SP1, Torlon and planet axes without bushings (Fig. 6). Pre-QM2 is lead-lubricated with bushings of lead bronze assembled or no bushings, respectively (Fig. 7). If no bushing is assembled on one of the planet axes, a distance ring is necessary to prevent the appropriate planet gear from moving along the axis.

These breadboard models have been manufactured first and the FM1 production has been started during their test campaign, as displayed in Figure 8. Indeed the FM1 has been assembled into the sub-unit at a time for which the actuator has not been fully qualified; as the pre-QM1 and FM1 are not assembled completely identical and the pre-QM life test was in some ways simplified but equivalent at best.

Life Test Pre-QMs

As the pre-QMs had to be life-tested without being integrated into the RMA, an equivalent test set-up had to be designed in order to load the actuators correctly.

Springs connected to a disc (Fig. 9) load the actuators with the torque corresponding to the load the real blades are generating in the RMA mechanism. Figure 9 illustrates that the maximum torque at 120° from launch position and the load represented by the spring set-up are very accurate.

The cryogenic temperature during pre-QM life test was not 30K (liquid helium) but 80K (liquid nitrogen) due to facility reasons. This temperature is justified by the fact that neither the shrinking or the change in material properties between these two temperatures are high compared to their absolute values.

The expected lifetime of the RMA actuator is about 400,000 motor revolutions, including ECSS margins. As Figure 10 illustrates, in the case of pre-QM1 the so-called success current—indicating the friction—does decrease during lifetime up to the end of life test at about 430,000 motor revolutions. The MoS_2 coating seems to be properly run in at this time. Lead-coated pre-QM2 showed some degradation starting between 320,000 and 380,000 motor revolutions, but is still within the ECSS success criteria at end of life. The detailed visual inspection of the bushings (Figs. 12–13) did not show significant differences in abrasion on bushings

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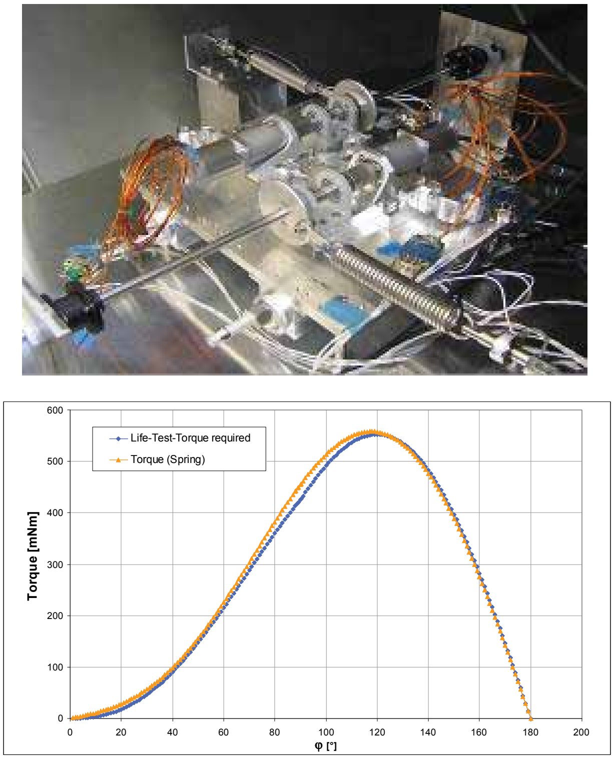

Figure 9—Pre-QM life test (top); load application during life test by spring assembly (bottom).

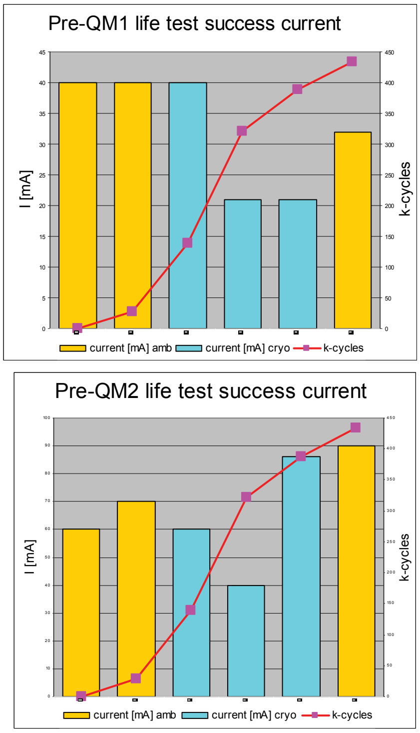

Figure 10: Results of Pre-QM life test.

made of Vespel SP1 and Torlon.

These test results provide high confidence in the selected material combination. Flakes of coating have been delaminated during vibration (this issue is explained later in detail) from gear teeth on planets, suns and hollow wheel. This damage did not affect the gearbox's performance, and the surfaces look smooth and properly run in after life testing (Fig. 11), and XRF (X-ray fluorescence) measurement at ESTL (NASA Electronic Systems Test Laboratory) revealed a remaining MoS$_2$ layer of at least 0.14 microns.

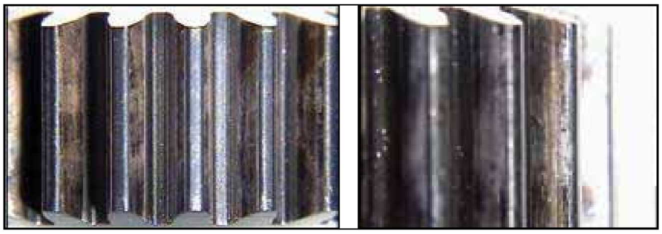
Figure 11—MoS$_2$ gearbox inspection after life test.


Figure 12—Pre-QM1 Vespel SP1 bushing and distance washer after life test.


Figure 13: Pre-QM1 Torlon bushing and distance washer after life test.


Figure 14—Lead-coated gearbox and lead-bronze bushing after life test.

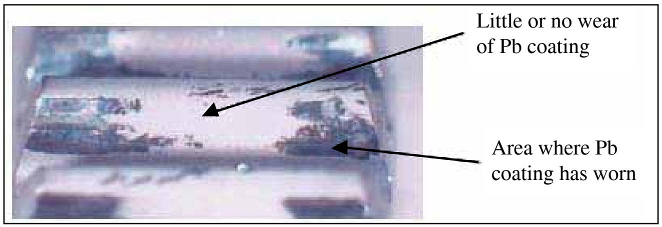

Figure 15—Uneven distribution of remaining lead coating on the planet teeth.

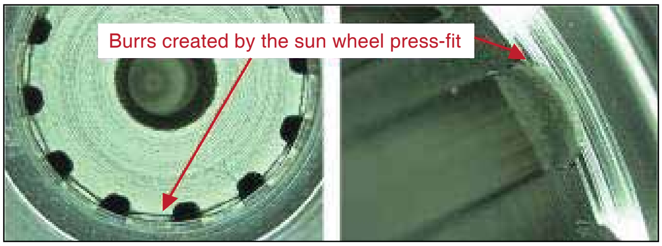

Figure 16—Failed pressing trial results.

In addition, a visual inspection of the lead-coated pre-QM2 gearbox found it in good condition with no evidence of metallic wear of the steel surfaces. XRF measurements confirmed that lead remained on the gear teeth, but that in several areas it was extremely thin. Examination of the thickness values shows that in all but one case the minimum thickness was less than 0.1 µm, and as low as 0.03 µm in one instance.

However, it should be stressed that very little lead is required—especially on polished-steel surfaces—to provide effective lubrication.

As with the MoS$_2$-lubricated gears, wear of the lead coatings was uneven across the teeth. This is illustrated in Figure 15 for a planetary gear from stage 3; note that the lead coating in the center of the tooth is virtually unworn, but elsewhere lubricant wear has clearly taken place.

It was also apparent that lead had transferred during tooth-to-tooth contact, leaving patches where the thickness of the lead was greater than the thickness of the coating, as initially applied. This effect accounts for the relatively large patch width (>2 mm) occasionally observed. It should be noted that lead transfers more efficiently than MoS$_2$—a fact consistent with the observation that no anomalously high coating thicknesses were observed for the MoS$_2$–lubricated gears.

Technical Difficulties and Challenges

Planet carriers and gearbox housing. The initial approach was a design containing a number of parts made of unhardened Cronidur—i.e., the planet carriers and the gearbox housing. It is impossible to shrink-fit hardened pins onto hardened carriers; the risk of deformation due to hardening of the hollow wheel (→ ovalization) was considered unacceptable. But Cronidur is not corrosion-resistant in the unhardened condition, so a substitution of the material—or heat treatment—had to be considered.

To replace the Cronidur, the planet carriers have been manufactured from titanium. Extensive trials have been performed to identify the necessary oversize for press fit. By doing so, the required torque loading is transmitted to the sun wheel on the one hand—but not to exceed the ultimate strain of about 7% of titanium (Figs. 16–17). As for the gearbox housing, a material substitution has been widely discussed with many experts, but the number of materials in the same CTE range of Cronidur is very limited.

Using titanium for the gearbox housing is out of the question as the gear supplier is not able to cut the internal gear from titanium. The steel 17-4PH has been deemed an alternative but, due to its sensitivity against stress-corrosion cracking, its usage would have required advanced fatigue analyses.

Nevertheless, adhering to the previous concepts offers two distinct opportunities:

- Hardening the entire gearbox housing (Fig. 18, right)
- Manufacture a hollow-wheel ring from Cronidur (Fig. 18, left), harden it and assemble it in an

integrated design to a titanium housing (Fig. 18, middle)

Both methods have been tested; the entire gearbox and hollow-wheel ring have been subsequently hardened and 3-D-measured with this result: the hollow wheel was ovalized but the gearbox remained *stable*.

Influence of surface quality on coating adhesion. As indicated previously, both pre-QM1 and FM1 showed signs of coating delamination on the gear teeth of planets, sun wheel and gearbox housing after vibration testing, which was detected during subsequent inspection (Fig. 19). This finding raised three main questions:

1. Does a remaining layer of MoS_2 still exist on the gear teeth?
2. Is the lubrication sufficient?
3. How can the generated particles be prevented from emerging from the gearbox and possibly contaminating optical equipment on the instrument?

Investigations at ESTL revealed a minimum MoS_2 layer of 0.14 micron-thickness existing on the affected surfaces, and the successful pre-QM1 life tests justify confidence in the coating quality. Nevertheless, an investigation has begun to find out whether the chosen pre-treatment electro-polishing and defined surface roughness do in fact represent the ideal parameters.

Samples have been manufactured with varying surface qualities between 0.1 micron and 0.5 micron, as well as electro-polished/not electro-polished. The deflating conclusion of the pin-on-disc test following the coating process was that surface roughness does not significantly influence the quality of the coating adhesion, but electro-polishing treatment reduces the endurable revolutions in pin-to-disc testing down to 20%–30% of those samples that were not electro-polished.

Influence of proper run-in on friction/torque. Molybdenum disulphide is, to an extremely high degree—hygroscopic. When exposed to ambient atmosphere/humidity, it absorbs water and binds it molecularly, which alters the coating's microscopic structure, and friction increases. Because the process is not completely reversible by simply drying MoS_2 in a vacuum, mechanical pressure via a run-in must be applied in order to overcome this initial peak-torque in the gearbox and ball bearings. Evacuating throughout the weekend resulted in better torque value than evacuating only overnight; a proper run-in even increased the torque margins.

While this effect is not unknown in the technical world, many experts are of a very different opinion on how to deal with a MoS_2-coated actuator, and that good communication with all suppliers is essential in sensitizing every employee to this issue.

Conclusions and Lessons Learned

The first flight model with the MoS_2 dry lubrication and Vespel SP1 bushing has been successfully implemented into the flight model RMA. The RMA has performed its acceptance program and is currently mounted onto the NIRSpec optical bench. We are confident of having supplied an actuator that will safely provide the required functionality throughout the lifetime of the NIRSpec instrument.

During the very short time frame of the execution of this seven-month development program, we have learned a great deal about not only development programmatic, but material and lubrication technologies as well. Some key lessons learned are outlined here, not all of them new.

Programmatic lessons learned:

- Do not change too many technical parameters at the same time; it may become impossible to identify the reason for both improvement and deterioration.
- Postponing tests and planning to combine them with other tests due to programmatic reasons may be a shortsighted decision. Both technical and programmatic reasons might eliminate the possibility of performing a particular test at a later time. Certain measurement results can be generated at only one specific time; once this time frame is closed, the opportunity for measurement might be missed forever.
- Ensure that your suppliers are fully aware of their contribution to the development success. This key success factor ensures that the suppliers provide their utmost technical capabilities and are extremely flexible with the necessary modifications that are normal in such a development program. Access to the supplier's expertise can only be acquired if they feel part of the team and understand the final application of their contributed part. As an example, Gysin (gear box) should be mentioned as they succeeded in providing a gear tooth surface quality far beyond standard industrial needs by the proper setting of the standard machinery.
- A success-oriented approach initially has the allure of saving time and money, but always contains high risk of failure, such as doubling the cost at the end as

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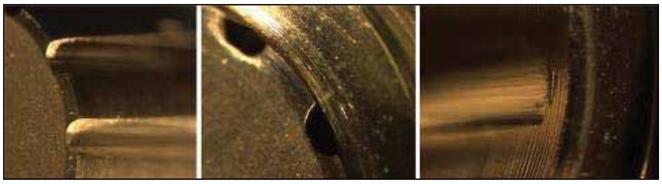

Figure 17—Passed pressing trial results with 40 µm oversize.

Figure 18—Hollow-wheel ring and integrated design versus gearbox housing made entirely of Cronidur.

Figure 19—Coating damage after vibration.

the work had to be done twice. We must confess that we had good luck that the selected combination of materials for the FM1 was the right choice, as this combination was found to be the best as a result of the pre-QM life test. In many other development programs similar results could not be achieved.

Technical lessons learned:

- MoS_2 lubrication might be seen as a state-of-the-art dry lubrication. We learned that the processes applied to the materials prior to coating do in fact have a relevant influence on the sputtering process; even the sequence of processes seems to be of importance. The initial loss of sections of dry lubricant on the gear wheels—as observed after vibration testing (Fig. 19)—is still not understood and will be further investigated (see last section, "Outlook").
- When we initially saw those areas of lubrication loss on the gear wheels (Fig. 11), we were sure that this was the end of the story. But thanks to ESTL's confidence in their sputtering process and the measurements performed showing sufficient MoS_2 on the teeth to survive the life test, we decided to continue. The life test was a success. Those observed areas increased, but the residual MoS_2 layer survived. It is the intention to continue the life test on the pre-QM (see last section, "Outlook").
- Witness samples for process control for any kind of surface layer generation; they should be of the same material and should have been exposed to the same processes and sequence of processes as the units to be treated. In some cases where geometry also impacts the surface treatment, the witness sample should also have a similar geometry.
- Keeping MoS_2 surfaces in either a dry environment or, ideally, in a vacuum or constant N_2 atmosphere, requires specific knowledge of how to prevent moisture absorption of the MoS_2. Permanent purging of mechanism elements like bearings is one of the methods applied if the outer environment is not adequate. In the vicinity of optical surfaces at temperatures below those of the mechanism (cold traps), purging or even open venting holes might allow particles from the MoS_2 to escape from the mechanism and pollute the optical surfaces. As seen from the life test, particle generation cannot be avoided. Consequently the purging process, purging direction and venting-hole definition need to be properly planned at the beginning of the project to prevent pollution effects.

Outlook

In a very short time frame of seven months, a dry-lubricated actuator for ambient and cryo application was developed with a complete combination of new materials. Though the development was a success, some questions are still open and require further investigation.

As outlined in the "lessons learned," the material treatment process does have an important impact on the success of the sputtering process. The observed partial loss of lubricant on the gear wheels remains unexplained. From the pin-on-disc test results we do have clear indications that the electropolishing is of negative influence, but the physical or chemical nature of such an effect is still not completely understood. Other effects like the order of hardening and polishing might be also of influence. These effects need to also be assessed for different standard gearbox or bearing materials. Astrium hopes to initiate a program with ESA, ESTL and technical surface coating experts to further investigate this issue.

Though we did initially lose some lubricant on the gear surfaces, they survived the life test and it would be of interest to determine the final life of such surfaces in the gearbox. Therefore, Astrium will continue the life test on the prequalification models (both the MoS_2 and the lead-lubricated ones). Life test stop criteria will be a certain current threshold (TBD) that would be equivalent to a certain increase of the friction torque of the unit (e.g., 50%). A dedicated inspection program of the units will follow the life test, and results will be reported at the next ESMATS to be held at Astrium in Friedrichshafen, September 2011.

Acknowledgment

Astrium would like to thank their partners in this development program for their utmost efforts provided in terms of technical quality, adherence to the very tight schedule and their expertise and support at every phase of this project.

- Phytron GmbH—motor development and the overall assembly and functional testing
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- (German-based) GRW—bearing manufacturing and Cronidur hardening
- (UK-based) ESR—MoS_2 and lead lubrication