

Development of an Actuator for Ambient to Cryo Application

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Abstract

During the qualification campaign of the NIRSpec Instrument Mechanism, the actuator could not achieve the expected life time which was 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 such that the function of the mechanism would not be endangered and thus the overall function of the NIRSpec instrument. The modification included the 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 6 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 subunit carrying highly sensitive mirrors (see Figure 1).

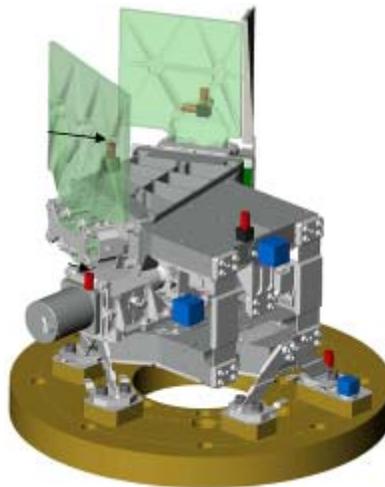


Figure 1: Refocusing Mechanism Assembly

The high non-operational temperature range of 296K as well as the low operational temperature of 30K requires 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

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In order to keep the development risk (both technical 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 of the instrument 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 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 3 stages.

The most important requirement is the large 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-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 Midstroke 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 after life time that has to be prevented in any case. 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 subunit 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 but 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 coefficient of thermal expansion (CTE) at 30K varying between 7.5×10^{-6} 1/K (ball bearings) and 15×10^{-6} 1/K (gearbox housing). This design was based on the experiences 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 have to be pursued.

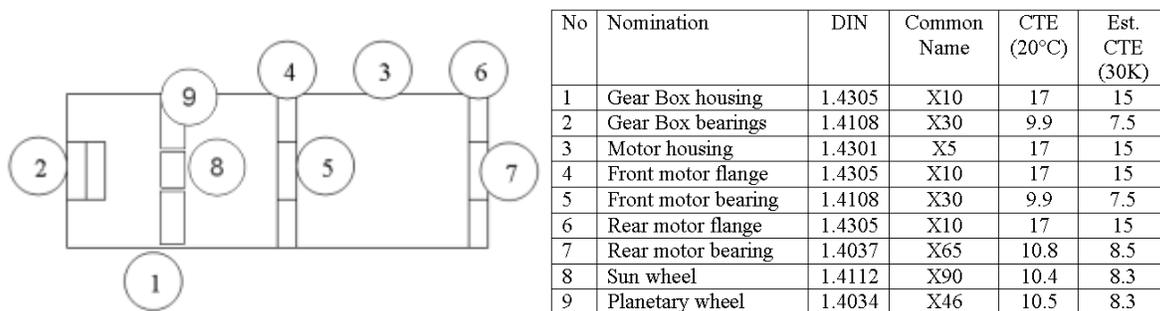


Figure 2: Material concept of first actuator

The shrinking at cryo is likely to have caused increased friction and therefore affected the life-time significantly. The lubricant used, Diconite, showed significant signs of abrasion after life test (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.



Figure 3: Lubrication failure of first actuator after life test¹

Motor current measurements during the life test demonstrated that the actuator lubrication would have survived the nominal life time but due to life time 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 (iso-static 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.

¹ Visible corrosion results from the exposure of the blank metal to air after disassembly of the actuator.

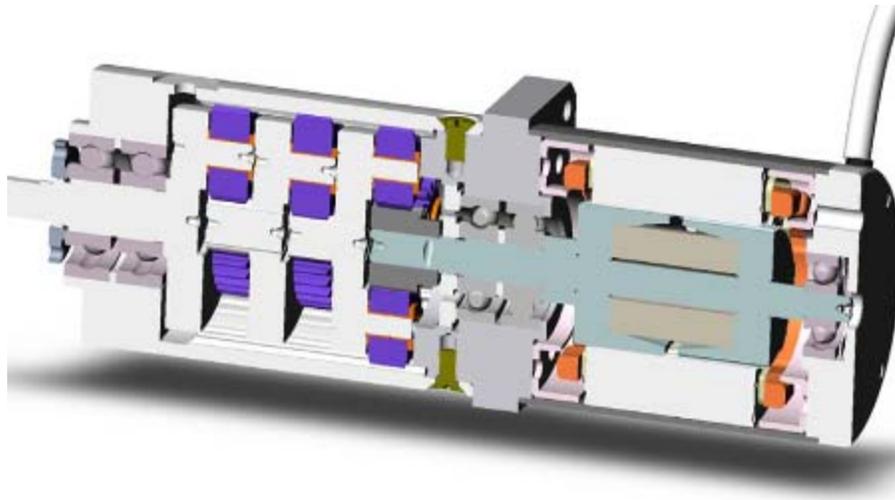


Figure 4: New Design RMA Actuator

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.

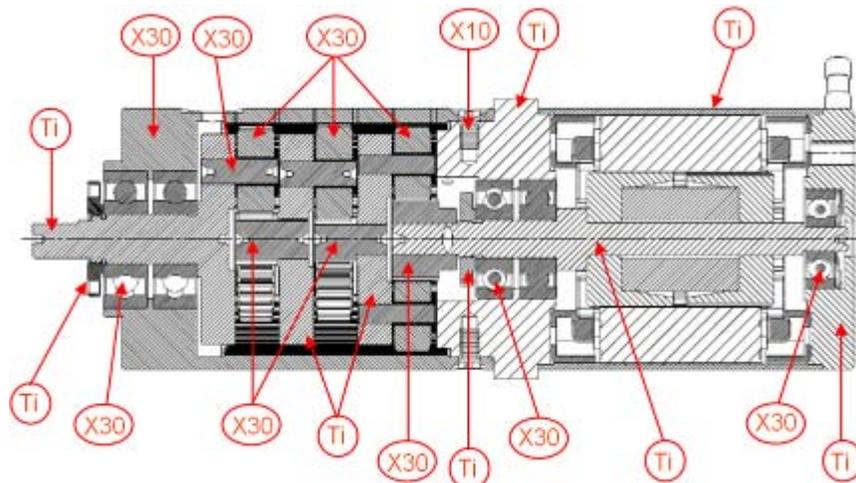


Figure 5: New Material Concept

Coating for Solid Lubrication

After the failure of the Diconite coating during life test, a solid lubricant concept had to be selected that is well known 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 backup 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 MoS₂ 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 tolerance such 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 to be implemented 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 MoS₂ 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 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 in particular 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% MoS₂ or 30%, respectively.
- PGM-HT contains of PTFE filled with glass fibers (15%) and MoS₂ 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 MoS₂ powder should give a first impression of the tribological behavior. While Vespel SP1, Victrex and Torlon showed a 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 the 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 to be implemented in one of the breadboard models in order to allocate a backup solution.

Development Concept and Success-Oriented Approach

A success-oriented approach has been chosen due to programmatic reasons: 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, so called 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 MoS₂ lubricated and contains bushings of Vespel SP1, Torlon and planet axes without bushings according to Figure 6. Pre-QM2 is lead lubricated with bushings of lead bronze assembled or no bushings, respectively (Figure 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.

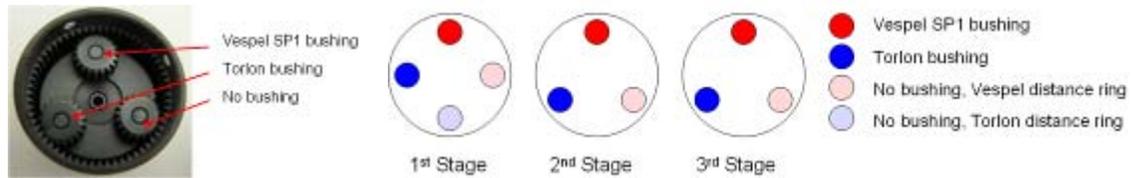


Figure 6: Pre-QM1 design (MoS₂ lubricated)

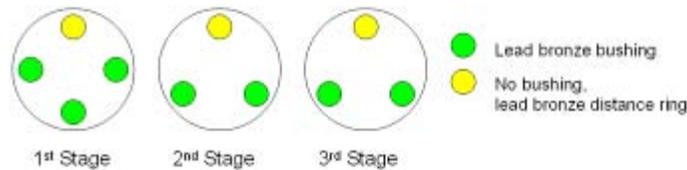


Figure 7: Pre-QM2 design (Lead lubricated)

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 subunit at a time 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 the best.

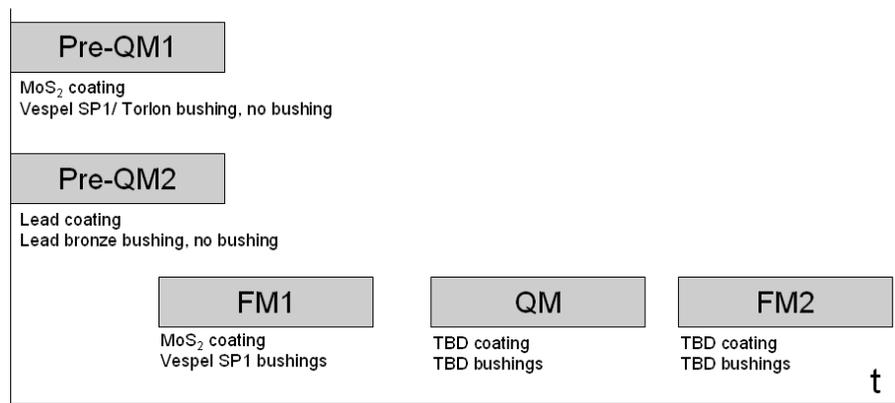


Figure 8: Development concept and success oriented approach

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 (Figure 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 is very accurate.

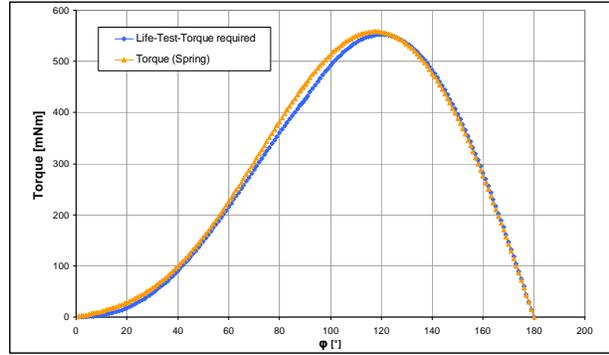
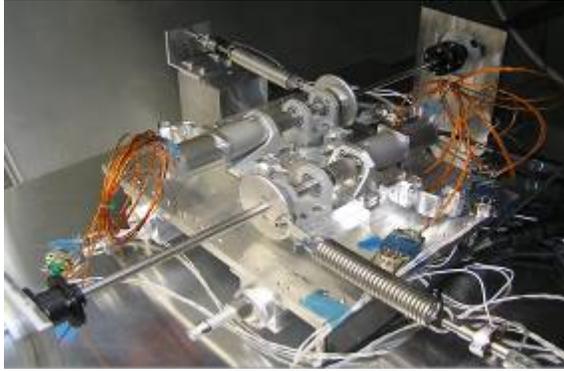


Figure 9: Pre-QM Life Test (left), Load application during life test by spring assembly (right)

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 nor the change in material properties between these two temperatures is high compared to their absolute values.

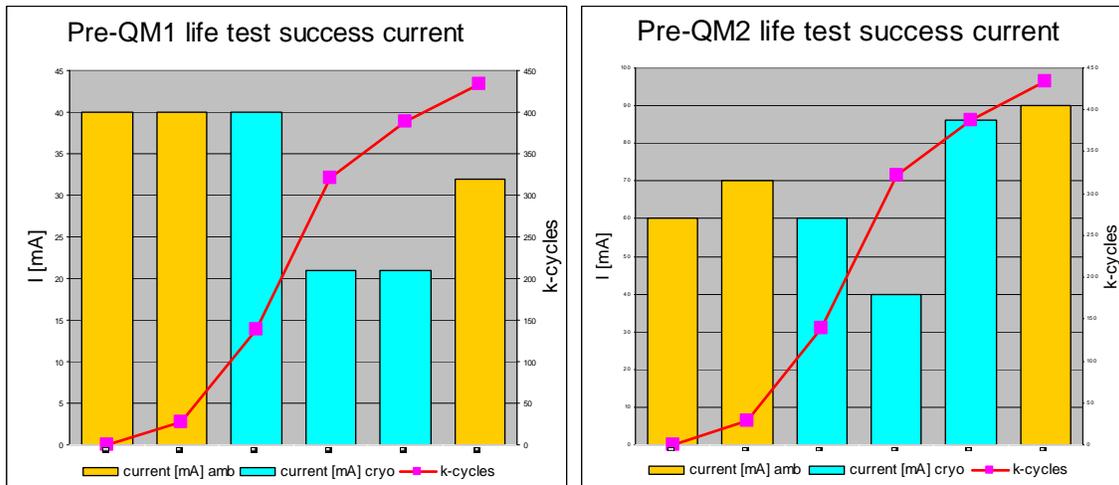


Figure 10: Results of Pre-QM life test

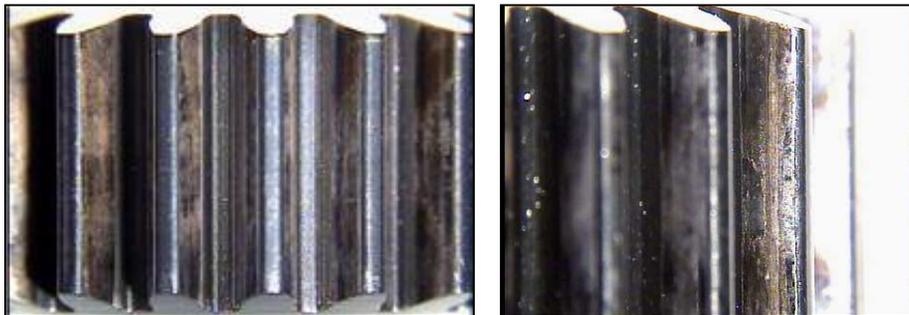


Figure 11: MoS₂ Gearbox inspection after life test

The expected life time 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 life time up to the end of life test at about 430,000 motor revolutions. The MoS₂ 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 (Figure 12 and Figure 13) did not show significant differences in abrasion on bushings made of Vespel SP1 and Torlon.



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

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 gear-box's performance, the surfaces look smooth and properly run in after life test (Figure 11) and XRF measurement at ESTL revealed a remaining MoS_2 layer of at least 0.14 microns.

The visual inspection of the lead-coated Pre-QM2 gearbox revealed as well a 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 show that in all but one case the minimum thickness was less than $0.1 \mu\text{m}$, being as low as $0.03 \mu\text{m}$ in one case. However, it should be stressed that very little lead is required – particularly on polished steel surfaces - to provide effective lubrication.



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

As with the MoS_2 -lubricated gears, the wear of the lead coatings was uneven across the teeth. This is illustrated in Figure 15 for a planetary gear from Stage 3 where it can be seen that the lead coating in the center of the tooth is virtually unworn whereas elsewhere wear of the lubricant has clearly taken place.

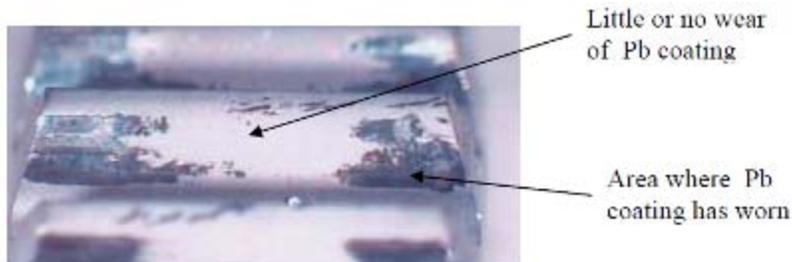


Figure 15: Uneven distribution of remaining lead coating on the planet teeth

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 MoS₂ – a fact consistent with the observation that no anomalously high coating thicknesses were observed for the MoS₂-lubricated gears.

Technical Difficulties and Challenges

Planet carriers and gearbox housing

The initial approach was a design containing some parts made of unhardened Cronidur®, namely the planet carriers and the gearbox housing. It is impossible to shrink-fit hardened pins onto hardened carriers and the risk of deformation due to hardening of the hollow wheel (→ ovalization) was supposed to be too high. But Cronidur® is not corrosion-resistant in the unhardened condition and therefore a substitution of the material or heat treatment had to be considered.



Figure 16: Failed pressing trial results

To replace the Cronidur® the planet carriers have been manufactured from titanium and extensive trials have been performed in order to identify the necessary oversize for press fit to transmit the required torque loading to the sun wheel on the one hand but not to exceed the ultimate strain of about 7% of titanium (Figure 16 and Figure 17). In the case of 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.



Figure 17: Passed pressing trial results with 40 μm oversize

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 considered to be an alternative but due to its sensitivity against stress corrosion cracking its usage would have required advanced fatigue analyses.

Sticking to the previous concepts still offers two opportunities: harden the entire gearbox housing (Figure 18 right) or manufacture a hollow wheel ring from Cronidur[®] (Figure 18 left), harden it and assemble it in an integrated design to a titanium housing (Figure 18 middle). Both methods have been tested; entire gearbox and hollow wheel ring have been hardened and 3D-measured afterwards with the following result: the hollow wheel was ovalized but the gearbox stayed stable!



Figure 18: Hollow wheel ring and integrated design vs. gearbox housing completely made of Cronidur[®]

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 test, which was detected during subsequent inspection (Figure 19). This finding raised two main questions:

1. Does a remaining layer of MoS₂ still exist on the gear teeth and is therefore the lubrication sufficient?
2. How can the generated particles be prevented from emerging from the gearbox and possibly contaminating optical equipment on the instrument?



Figure 19: Coating damage after vibration

Investigations at ESTL revealed a minimum MoS₂ layer of 0.14-micron thickness existing on the affected surfaces and the successful Pre-QM1 life tests supports the confidence in the coating quality. But nevertheless an investigation has been started in order to find out whether the chosen pre-treatment electropolishing and the defined surface roughness represent indeed the ideal parameters.

Samples have been manufactured with varying surface qualities between 0.1 micron and 0.5 micron as well as electropolished / not electropolished. The deflating conclusion of the pin-on-disc test following the

coating process: the surface roughness does not influence the quality of the coating adhesion significantly but the electropolishing treatment reduces the endurable revolutions in pin-to-disc test down to 20 to 30% of the un-electropolished samples.

Influence of proper run-in on friction / torque

Molybdenum disulphide is to an extremely high degree hygroscopic. While exposed to ambient atmosphere / humidity it absorbs water and binds it molecularly. Thereby the coating changes its microscopic structure and friction increases. This process is not completely reversible by drying MoS₂ in vacuum but mechanical pressure by performing a run-in has to be applied in order to get over this initial peak torque in the gearbox and ball bearings. However, evacuating throughout the weekend resulted in better torque value instead of evacuating only overnight; a proper run-in even increased the torque margins.

This effect is not unknown in the technical world but it turned out that many experts are of very different opinion how to deal with an MoS₂-coated actuator and that good communication with all suppliers was necessary in order to sensitize every employee to this issue.

Conclusions and Lessons Learned

The first flight model with the MoS₂ dry lubrication and Vespel SP1 bushing has successfully been implemented into the Flight Model RMA. The RMA has performed its acceptance program and is currently mounted onto the NIRSpec optical bench. Though the full qualification program at the end of 2009 is not yet finished 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 development program (7 months), we have learned a lot both about development programmatic as well as about material and lubrication technologies. Some key lessons learned shall be outlined here - some of them not really new

Programmatic lesson learned:

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

Technical lessons learned:

1. MoS₂ 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 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 (see Figure 19) is still not understood and shall be further investigated (see last chapter "Outlook").

2. When we initially saw those areas of lubrication loss on the gear wheels (see Figure 11) we were sure that this was the end of the story. Thanks to ESTL, who had great confidence in their sputtering process and was confident according to measurements performed to still have sufficient MoS₂ 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 MoS₂ layer survived. It is the intention to continue the life test on the pre-QM (see last chapter "Outlook")
3. Witness samples for process control for any kind of surface layer generation 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 has also an impact on the surface treatment, the witness sample should have also a similar geometry.
4. Keeping MoS₂ surfaces either in a dry environment or ideally in vacuum or in constant N₂ atmosphere is state of the art knowledge to prevent moisture absorption of the MoS₂. 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 MoS₂ to escape from the mechanism and to 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 needs to be properly planned at the beginning of the project to prevent pollution effects.

Outlook

In a very short time frame of 7 months a dry-lubricated actuator for ambient and cryo application was developed with a complete new combination of materials. Though the development was a success, some questions are still open and shall be further investigated.

As outlined in the lessons learned, the material treatment process does have an important impact on the sputtering process success. The observed partial loss of lubricant on the gear wheels is still not understood. From the pin-on-disc test results, we do have clear indications that the electro-polishing 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 be assessed also for different standard gear box or bearing materials. Astrium wants to initiate a program with ESA, ESTL and further 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 gear box. So Astrium will continue the life test on the pre-qualification models (both the MoS₂ and the lead lubricated ones). Life test stop criteria will be a certain current threshold (still TBD) which 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 shall be reported at the next ESMATS to be held at Astrium premises in Friedrichshafen in September 2011.

Acknowledgment

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

- Phytron GmbH - motor development and the overall assembly and functional testing
- Gysin AG - gear box components
- GRW - bearing manufacturing and Cronidur® hardening
- ESR - MoS₂ and lead lubrication