INSPECTION OF SEPARABLE SURFACES – LESSONS LEARNED

Sebastian Schwarz (1), Ingo Köker (1), Lionel Gaillard (2), Harald Langenbach (1)

(1) Airbus Defence & Space GmbH, Claude-Dornier-Str., 88090 Immenstaad, Germany, Email: Sebastian.Schwarz@airbus.com
(2) ESTEC, Keplerlaan 1, PO Box 299, AG Noordwijk, THE NETHERLANDS, Email: Lionel.Gaillard@esa.int

ABSTRACT

One of the major critical items for satellite mechanisms, especially for launch lock and separation mechanisms, has always been the proper functionality of separable surfaces. To avoid mission critical effects such as fretting, cold welding or adhesion in general, the separation partners need to be carefully designed, qualified and controlled. Typical test scenarios, from equipment to satellite level, include a high number of handling, integration and test activities that could all affect surfaces and tribological coatings and need to be assessed wrt. the virgin surfaces.

In this context, the paper starts with lessons learned from inspections of disassembled qualification models with more detailed methods, such as scanning electron microscopy or optical microscopy. This is followed by several examples of surfaces on flight models, where the inspection has been performed at satellite level under limited accessibility and documented only by photographs. These examples highlight the difficulties, encountered during the inspection process, and the challenges of determining whether potential defects are critical or acceptable.

Based on this experience, a common set of rules is proposed to support future decisions of whether a separable interface is flightworthy or not.

1 INTRODUCTION

The majority of separable contacts on satellite mechanisms are metallic - only few designs use polymer or ceramic materials. With metallic contacts however, adhesion has to be avoided. Best practice is the use of dissimilar materials and material pairs that are not prone to fretting. In addition, a lubricative coating is recommended to reduce friction induced damages, such as fretting, abrasive wear, etc. A typical cross section of such a material setup is shown in Figure 1, where the metallic bulk material or substrate is protected by several layers with different functions. On top of the plastically deformed zone, which is usually a result of the manufacturing process, oxide layers are formed on most metallic materials. To further improve hardness and/or corrosion protection, the oxide layer thickness can be increased or replaced by a hard coating, such as Ematal, Tioxal, etc.

The final layer with the lubricative function, is provided by e.g. MoS2 or graphite powder, held in place by organic or inorganic binders.

In some cases grease is used as final layer although this is not very common since it can be wiped away, pressed out of the interface and collects particles, etc.

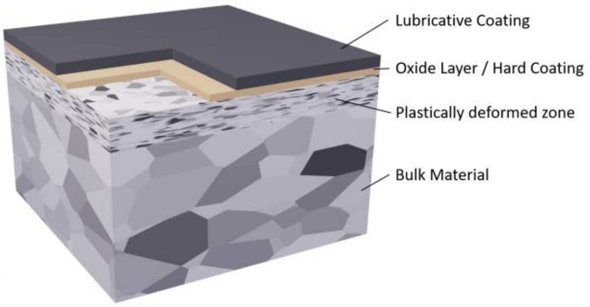


Figure 1. Material setup of a typical contact element

In this general setup, failure of the separation function due to adhesion is prevented by several redundancies, where direct metal to metal contact occurs only, if all coatings and layers are removed.

In real space mechanisms however, the contact situation is not always simple and fully predictable, leading to test scenarios with e.g. local gapping or sliding and possibly the removal of dry lubricants and hard coatings.

Due to this, a careful inspection of the separable surfaces is important to identify design weaknesses after qualification and to prevent failures during flight.

2 CATEGORIES OF DEFECTS

After qualification and acceptance testing, different effects on separable contact surfaces have been found. Not all of these effects have an influence on the separation function or adhesion in general. To assess the criticality, it is helpful to start with a classification of the affected layer and the loading situation that caused the defect – some examples are shown in Figure 2.

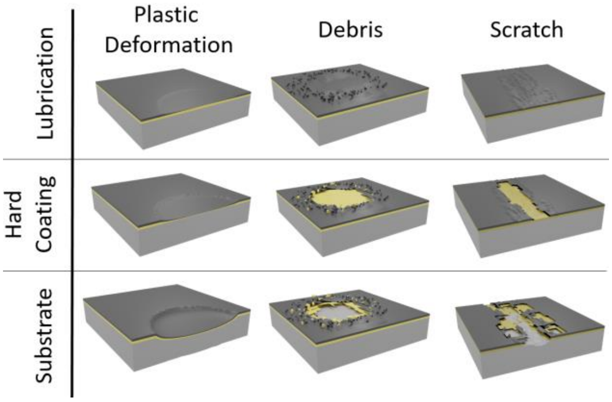


Figure 2. Categories of Defects

In case of a static loading situation, mainly plastic deformation occurs. This is seen often in more complicated contact geometries (such as prismatic, spherical, etc.) where a poor conformity of the surfaces leads to local stress concentrations and finally to plastic deformation. As long as the substrate is not stressed beyond its capability, this is typically acceptable. More problematic are the gapping and sliding load cases, where the protective layers could be removed. The result are scratched surfaces and/or debris down to the various layers.

With such a categorization, it is possible to identify heritage mechanisms with similar contact situations and defects. In this case, similarity with e.g. successfully flying interfaces could be identified or solutions and design changes from previous investigations can be implemented.

In the following chapters different examples of such investigations are shown, explaining also the corresponding way forward and conclusion.

3 INSPECTIONS AFTER QUALIFICATION

After the mechanism qualification campaign, (incl. life test) disassembly into the tribological parts and visual inspection is required. In contrary to the inspections performed on highly integrated flight mechanisms, the post qualification inspections are possible in much more detail, using e.g. optical microscopes, UV light, surface profilometry, SEM (Scanning Electron Microscopy) and EDS/EDAX (Energy Dispersive X-Ray Analysis) or metallurgical cross sections. With such advanced inspection techniques, critical conditions can be identified with much higher precision. These conditions could be for example:

- Loss of lubricative coating and metal to metal contact.
- Surface defects into the bulk material, such as pitting, plastic deformation and wear marks.
- Corrosion effects, especially after e.g. accelerated aging in damp-heat conditions.
- Chemical deterioration of fluid lubricants.

In the following chapters, examples of post qualification inspections with different test method are presented and the conclusions are discussed.

3.1 Surface inspections using SEM-EDX

Since the appearance of hard coatings is often quite similar to the metallic blank surface underneath, it is very difficult to distinguish between compression marks with intact coating or wear with removed coating.

One of the most accurate methods to identify such defects is the SEM. With this test method, surface defects can be determined with high resolution and accuracy.

The example in Figure 3 shows very accurately the details of a hard anodized aluminium surface where the top layer was destroyed due to fretting.

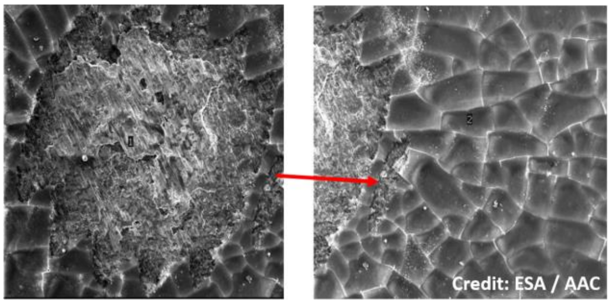


Figure 3. Breaking of hard anodized top layer

With an optical microscope, an identification of a defect at this scale is very difficult.

3.2 Pyramidal Interfaces under Gapping and Sliding

On a pyramidal locking interface for a large deployable antenna, several coating combinations were tested during environmental qualification. At high vibration loads, the interfaces were subjected to both, gapping and sliding, which has caused in some cases severe degradations of the surfaces in contact.

In the first example, an aluminium bracket with a Tioxal hard coating was lubricated with Everlube®620C and tested against a titanium counterpart. As shown in Figure 4, on the left side, coating material was worn away and has accumulated locally. Another area is shown in comparison on the right side with only compression – here the coating is fully intact.

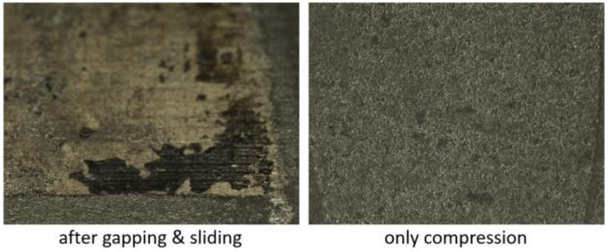


Figure 4. Lubricant accumulation and intact surface

Although the degradation appeared severe, the Tioxal layer was not affected and the coloration suggested that there is still residual lubricant left on the compromised surfaces. Under the optical microscope, it was however not possible to confirm the presence of any residual lubricant. For the flight model, this coating combination was not selected, since the presence of residual lubricant is not assured and to avoid any adhesion due to the accumulated lubricative coating itself.

As a second combination, Dicronite®DL5 was tested on the same aluminium + Tioxal combination. In this case, the lubricative function was not sufficient and could not prevent wear marks down into the bulk material, as shown in Figure 5.

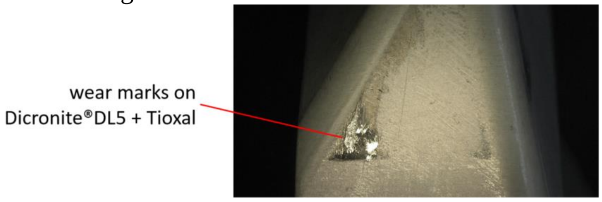


Figure 5. Wear marks into the aluminium

Due to the severe wear through all layers, this combination was not selected for the flight model.

In the third combination, Braycote grease on the Tioxal coated aluminium was tested under identical conditions. As shown in Figure 6, only small and shiny marks on the Tioxal were observed in combination with an accumulation of dark grease.

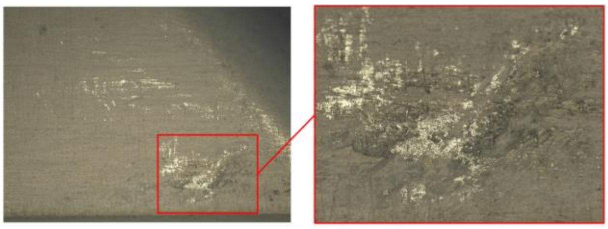
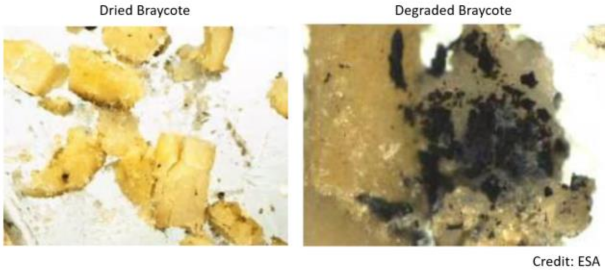


Figure 6. Small grinding Marks on Tioxal/Braycote

This configuration showed by far the best results, which demonstrates that in a sliding and gapping scenario grease provides better performance than a solid lubricative coating.

The coloration of the grease was linked to a chemical reaction of the fluorine atoms in the PFPE fluid with the substrate. This has been investigated before at ESA, as shown in Figure 7.



Credit: ESA

Figure 7. Braycote degradation patterns

To avoid degraded grease on this interface for flight, cleaning and re-lubrication is proposed in case the coloration occurs after testing. This was not observed after the acceptance campaign.

3.3 Planar Interfaces under High Pressure

On this planar interface of a highly preloaded hold down and release mechanism, a material combination of aluminium to titanium was used in combination with Everlube®620C on both sides. After full environmental qualification and life testing of the release function, the pressure has smoothed the matte black surfaces so that the contact areas appeared shiny and almost metallic blank, as shown in Figure 8. By a detailed visual inspection however, it could be confirmed that the lubricative coating is still present in its original amount.

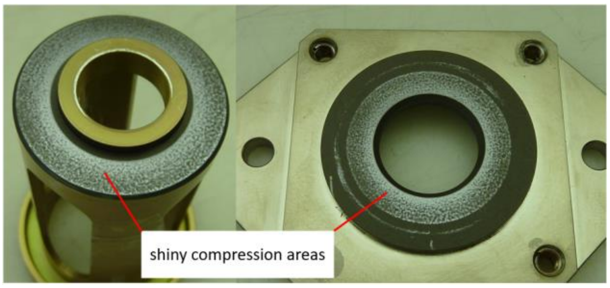


Figure 8. Planar HDRM interface with shiny compression zones

It is noticeable that the lubricative coating in contact to itself does not show any adhesion, even after high pressure, vibration and thermal vacuum was applied. During the entire program, no adhesion forces or other effects, such as material transfer or flaking were detected. This demonstrates that the use of Everlube®620C on both sides of a separable contact under high preload works well.

3.4 Hirth Coupling with Local Sliding

For the transfer of high torques and forces through a locked scanning mechanism, a Hirth coupling interface has been pre-developed. The bulk material for both separation partners was made from hardened martensitic steel with a hardness of approx. 340HV. The lubrication in this case was provided by a small amount of Braycote grease. Due to local sliding at high vibration loads, local grease spots were observed during visual inspection after the environmental tests. As shown in Figure 9, the dark lubrication spots could not be finally removed and the metallic surface remained compromised.

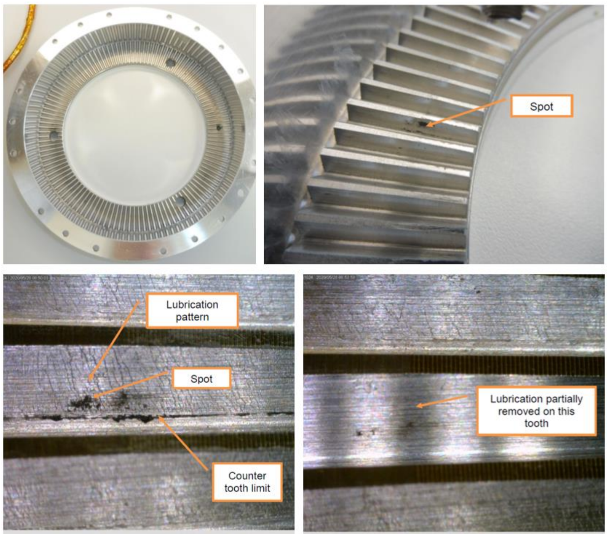


Figure 9. Hirth coupling lubrication after sliding

Although cold welding patterns could not be observed, it was decided as a risk mitigation, to apply a plasma nitriding on the surfaces to increase the hardness up to 1350HV. This was implemented successfully on the following EQM and FM units.

4 FLIGHT MODEL INSPECTIONS

Compared to the inspections done after qualification, the challenges on instrument or satellite level are completely different. The accessibility of the surfaces under inspection is often very poor and light conditions complicate the unambiguous identification and documentation of damages. Furthermore, decisions have to be made under consideration of the programmatic situation of the project. This could be that e.g. a detailed microscopic inspection is not possible, since it would require dismantling of parts of the satellite, causing unacceptable delays, etc.
Within this context, examples of flight model inspections are presented in this chapter, including the decisions made and the lessons learned.

4.1 Prismatic Boom HDRM Interface

To lock all degrees of freedom on a deployable boom, a symmetric arrangement of two prismatic interfaces, as shown in Figure 10, has been used. The material partners in this case were titanium and aluminium with Everlube®620C as lubricative coating, applied to both parts.

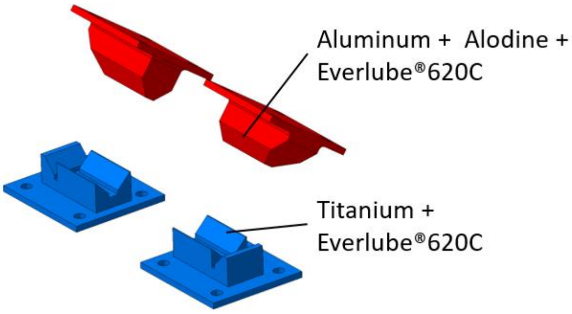


Figure 10. Prismatic Locking Interface

After the environmental test campaign, the appearance of the lubricant, especially on the titanium part, changed significantly from the black matte finish to a shiny surface in the areas under high contact pressure. Although this effect is well known and was expected, the strong change of the appearance raised the question whether there is still sufficient lubricant left on the surface. As flaking and lubricant transfer to the other surface could be excluded by the inspection, it was concluded that the lubricant is still in place and no repair action is required.

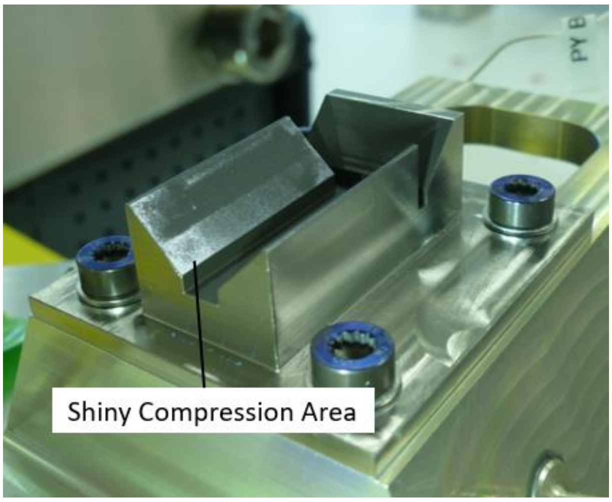


Figure 11. Shiny Compression Area

A more critical damage however was found on the aluminium part, as shown in Figure 12.
On this location, the sharp edge of the titanium part has left scratches on the aluminium prism. The root cause of these scratches could be clearly linked to a handling operation, where the boom was guided manually in its launch lock for stowing.

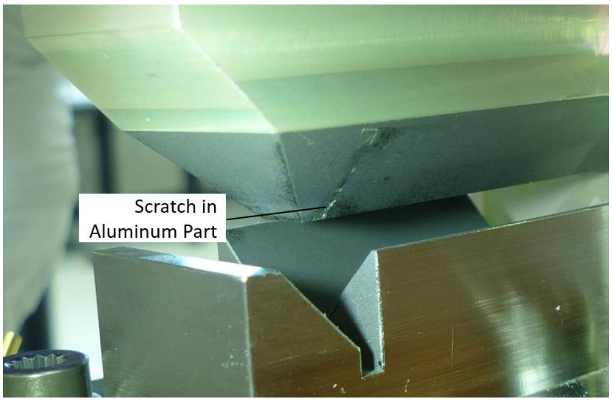


Figure 12. Scratches on Aluminium Part

To avoid scratches in the future, sharp edges will be rounded, especially on the titanium part and special attention will be given to mating processes, such as boom stowing.

In this case however, it was decided to use this interface for flight, since the scratch does not show a material deformation that extends out of the surface of the prism. With this, no sharp aluminium particles are trapped and preloaded between the separable surfaces during launch.

4.2 Spherical Interfaces on Antenna Pointing Mechanism

On an arrangement of spherical interfaces, which lock the azimuth and elevation stages of an antenna pointing mechanism, copper beryllium and stainless steel was used, as shown in Figure 13. The lubrication was provided by Everlube®620C on both parts.

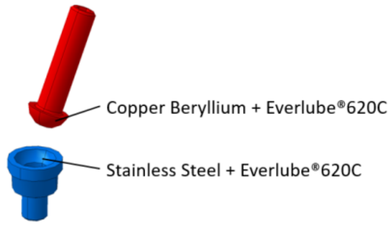


Figure 13. Spherical Locking Interfaces

With four of these interfaces, the launch lock is mechanically overdetermined. This is required to achieve the necessary stiffness in launch configuration, however increases the risk of local gapping and sliding, since the preload is depending on the alignment precision and the stiffness distribution.

As a consequence of this, sliding on the edge of the ball joint occurred with local wear marks on the coating of both parts were detected.

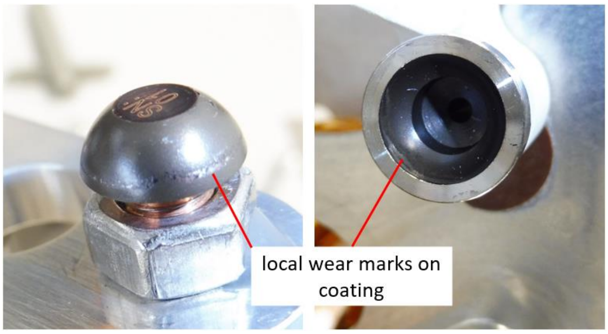


Figure 14 Wear marks on coating

With the dissimilar materials of the interface parts and since no plastic deformation or debris was detected, this effect was accepted and several of these mechanisms released successful in orbit.

4.3 Reflector Launch Lock Final Inspection before Launch

For a large unfurlable reflector, the locking of deployable reflector panels is provided by 36 individual aluminium brackets, arranged in a circular configuration. To provide locking in all degrees of freedom, the brackets are designed with a form fit, which is preloaded by a circumferential clamp band. With the form fit, a complicated contact geometry with prismatic surface contacts is created. These contacts slide on each other during release and stowing, which is done several times (also manually) as part of the acceptance campaign. During final stowing, prior to launch, scratch marks were detected on these sliding interfaces, as shown in Figure 15.

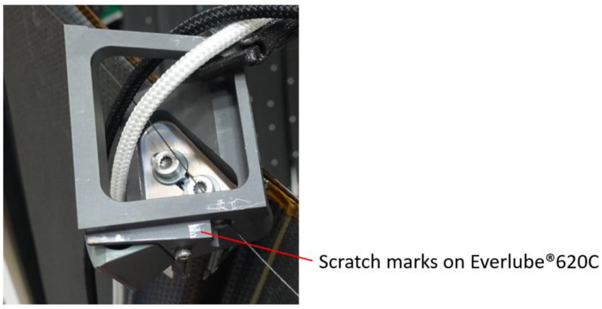


Figure 15. Scratch marks found prior to flight

Due to the final configuration, the inspection itself was challenging. With the launch lock brackets on top of the antenna and the satellite, photographs had to be taken on a movable platform at ~5m with some distance to the hardware. In this configuration, it was very difficult to identify shiny scratch marks by eye, since changing of the view angle was limited. As a consequence, also the photographic documentation of the shiny scratch marks was found very difficult.

As a precaution and to avoid disassembly of the launch configuration, a thin layer of Braycote has been applied by a brush to the scratched areas, to avoid direct metal to metal contact. With this, the reflector has successfully deployed in space.

4.4 Example Cup-Cones Inspection

On the Sentinel-1 C SAR Instrument, cup-cone assemblies were inspected after a misaligned installation of panels. The cones in this case were made from titanium with a Vitro-Lube coating. The counterpart is an aluminium cup with Ematal.

Due to the misaligned installation, the cup-cone connection was statically loaded and exposed to vibration and thermal cycles. During visual inspection, local shiny rings were observed, as shown in Figure 16 on the left. On previous assemblies, as shown in the same figure on the right, the shiny compression marks are distributed more uniformly over the entire cone. Since these compression marks alone are not critical, the cones were examined for plastic deformation. This was done with rulers and LED light from the opposite side. With this method, no plastic deformation of the shiny ring area was found.

Figure 16. Cones with different compression marks

On the cup side, the inspection could not identify plastic deformation either but transfer of the MoS2 lubricant from the Vitro-Lube, as shown in Figure 17. In case the binder material would be transferred as well, this would be critical. For the Vitro-Lube however, the binder is ceramic and only small amounts of MoS2 powder is transferred, which is commonly observed.

Figure 17. MoS2 transfer to the aluminium cup

5 PROPOSED GUIDELINES

In the following chapter, a set of guidelines are proposed, that are the result of a long lasting experience in the inspection of separable surfaces. The guidelines are neither exhaustive nor claim to be used as a standard.

5.1 Inspection Guidelines

With the many different designs and possibly a high amount of separable interfaces on complex mechanisms, it is helpful to classify the adhesion risk in categories and apply the level of inspection accordingly. In the past, the following scheme was found helpful, which is explained hereafter.

In the first step, the material pairing is categorized, as shown in the table below.

Cat.	Adhesion Risk	Material Pairing	Examples
1	none	Dissimilar material classes (metal to plastics…)	Aluminium to Vespel®
2	small	Dissimilar metallic materials with small adhesion	Stainless steel to bronce
3	medium	Dissimilar metallic materials prone to adhesion	Aluminium to titanium
4	severe	Similar metallic materials	Aluminium to aluminium

It is noted that hard coatings or any lubrication is not considered in this categorization, in order to assess the adhesion risk in case of failure of these layers.

The material pairing category is then plotted against the contact situation, which is either static, impact or fretting. With this adhesion criticality matrix, the level of inspection can be defined in a generic manner.

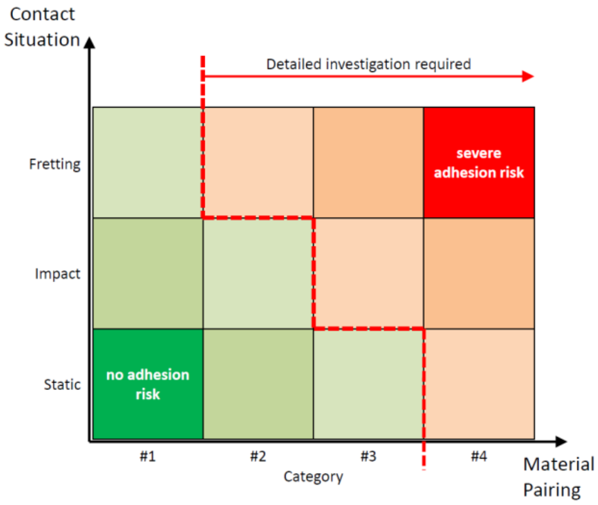


Figure 18: Adhesion Criticality Matrix

As an example, it might be sufficient to inspect an aluminium to Vespel® interface, used in a static contact situation only visually by eye after qualification.

On the other side of the matrix, an aluminium to aluminium contact with local gapping or sliding certainly requires a very careful microscopic inspection or the use of SEM/EDX to verify that the lubricative- and hard-coating are still in place.

5.2 Design Guidelines

From the many qualification campaigns and lessons learned during post-test inspections, a number of general design rules are concluded, that could help to improve the design of future projects:

- Material transfer and accumulation of a solid lubricant coating in certain areas is not acceptable since the lubricative function is no longer assured and the accumulated lubricant material can lead to adhesive forces itself. In this case, the design of the lubrication system has to be changed.
  It is noted that this applies only if the binder is transferred together with the lubricant. As shown in chapter 4.4, transfer of MoS2 powder w/o the binder is a common and acceptable phenomenon.
- Avoid sharp edges in e.g. prismatic interfaces to reduce the risk of scratching the lubricant during handling and stowing operations.
- On interfaces where local gapping or sliding cannot be avoided, grease works better than a dry lubricative coating.

5.3 Decision Guidelines for the Flight Model Inspections

For an occurrence on a flight model, after acceptance testing, it is essential to identify if the root cause is linked to the environmental test loads or a result of mishandling. If environmental loads have caused the occurrence, a design weakness or a difference to the qualification model might be the root cause, which could result in a modification of the design and subsequently to a major impact on the flight model itself.

If mishandling has been identified as the root cause, the situation could often be solved by a repair or a use as is decision.

6 CONCLUSION

The provided examples and lessons learned show that during the inspection of separable surfaces, different phenomena have to be evaluated and decisions have to be made, often based on limited information.

As a consequence, it is important to involve experts of the relevant areas of expertise in the investigations and foster an open discussion among the tribology and space mechanism community. In the future, this could lead to a better and more common understanding of the topic and the definition of best practices for the inspection of separable surfaces.

7 REFERENCES

1. Merstallinger, A., Sales, M., Semerad, E., Dunn, B.D., Assessment of Cold Welding between Separable Contact Surfaces due to Impact and Fretting under Vacuum. ESA STM-279 November 2009

2. Paul, Elena Cristina, Hardware Post Test inspection; Pass/Fail criteria, 3rd Advanced Mechanism Design Course, September 2021

3. European Co-operation for Space Standardisation (ECSS): ECSS-E-30 “Mechanical”, Part 3A “Mechanisms”, section 4.7.4.4.5 “Separable Contact Surfaces”