



Cold Welding in Hold Down Points of Space Mechanisms Due to Fretting When Omitting Grease

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Abstract: Cold welding refers to an effect related to space (vacuum). The heavy vibrations during a launch subject interfaces (hold down points) to oscillating motions which may lead to formation of a kind of “friction weld”. If so, these mechanisms may get stuck, and deployment will be hindered. This may endanger the functionality of the mission (instruments) or even the whole spacecraft (if solar panels do not open). Several studies have been done to characterize material combinations (including coatings) for their ability to cold welding in space. Meanwhile, also during launch grease free contacts are demanded. If grease has to be omitted, the risk of cold welding under fretting was found to increase (when testing in high vacuum). To rate this risk under launch conditions, the test method was recently extended for testing under launch conditions. The new tests procedure consists of fretting applied in the sequence in air, low vacuum and high vacuum. The paper shall present first results gained with this new method of testing in launch conditions and compare them to previous studies done in vacuum. Following the need of space industry on mechanisms for launch and in-orbit life, a first set of combinations of materials and coatings were selected for this new test sequence where fretting is now applied in a sequence of air, low vacuum and high vacuum. Under this sequence, the measured levels of adhesion and its evolution was found to differ strongly from tests done formerly. The paper outlines these first results and compares them to existing data.

Keywords: tribology; fretting; cold welding; HDRM (Hold Down and Release Mechanisms)



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1. Introduction

On spacecraft and satellites, a variety of mechanisms have to open (deploy) items after launch into orbit. The most known are solar panels and antennas that are simply too big to fit unfolded into the launcher. Hence, these items are folded up and held in position by so-called Hold Down and Release Mechanism (HDRMs). They often exhibit a ball-to-flat contact which can move laterally: under the heavy vibrations during launch, they can perform small oscillating motions (so-called fretting). This lateral motion can cause severe surface destructions and it may lead to cold welding effects, i.e., the contacts might get “friction welded”, which can be an effect similar to bonding techniques. If such welds are formed, the force to separate the surfaces may increase to values being higher than the forces available for opening the mechanism. An example of such a failure due to cold welding after fretting occurred on the Galileo spacecraft [1]. The high gain antenna had the shape of an umbrella. Each of the ribs was locked for launch by a HDRM. The high gain antenna could not be fully opened (1991). Investigations on spare parts have shown that fretting during ground transport and during launch caused cold welding of the ribs to their hold down points. The resulting adhesion forces were too strong for the opening springs, hence some of the ribs were stuck and the antenna did not open. Luckily, the mission could be flown by using the secondary antenna.

Due to the general problem of mass saving, those mechanisms are preferably made of light metal alloys (Al, Ti), which strongly tend to adhesion. Further, also for gears

stainless steels are required from point of view on corrosion and stress corrosion cracking. Unfortunately, the austenitic steels show higher tendencies to cold welding than, e.g., martensitic steels [2,3].

Fretting occurs also in terrestrial applications, due to the presence of oxygen causing an effect which is well known as fretting corrosion (in German “Passungsrost”). The small motion causes permanent tribo-corrosion, the oxides fill-up tight clearances, which leads to the blocking of shafts. The main difference in space is the missing atmosphere (oxygen). All metals exhibit natural reaction layers on their surface (oxides, carbides, ...). They are not removed by simple evacuation, hence if just a static contact between such two pieces of “engineered metallic parts” is maintained, they do not stick measurably. In order for them to stick, the surfaces must be cleaned, i.e., the surface layers must be removed. For space applications, metallic surfaces are simply milled surfaces with cleaning by fluid means, i.e., no specific sputtering, etc. is done. Hence, when mounted on a spacecraft, all metallic parts still have their natural surface layers. However, the vibrations during launch cause fretting, which wears away these layers. That creates “clean metallic surfaces” which enable a “friction weld” to the opposite metallic part. Additionally, during cruise of a spacecraft to a planet or during service life of a satellite, both lasting several years, vibrations caused by motion of antennas or solar panels may lead to fretting followed by cold welding effects. Nowadays not only the loss of the function of a satellite is a topic. The satellite may then not perform its final demise (i.e., to slow down and burn-off during re-entry). Such dead satellites are a dangerous waste in orbit, and endanger other spacecraft and human spaceflight.

2. Background

2.1. Overview

In order to derive representative data for this very specific space application, in the 1990s, two special devices—called “impact facility” and “fretting facility”—were developed and were used to investigate several combinations of bulk materials and coatings for their tendency to “cold-welding”. The test philosophy is based on repeated closing and opening of a pin-to-disc contact. In an impact test, in each cycle, the contact is closed by an impact with defined energy (no fretting applied). During a fretting test, the contact is closed softly (without impact), and while being closed, fretting is applied to the contact. For both tests, the adhesion force, i.e., the force required to re-open the contact, is measured at each opening. Basic studies [4] were carried out to show the influence of the main parameters impact energy and static load (contact pressure). These first results have been used to set up a standard test method together with ESA to fix parameters for establishing a kind of a data-base to compare typical material combinations used for spacecrafts [2]. In the following years, tests were conducted and results were published [3]. For ESA-member states, data can also be obtained [5]. This effect may also be found with items such as sticking, stiction or adhesion.

However, space programs on Earth observation with scanners and cameras raised the need for very clean contacts in HDRMs, too. It is very common to use space approved greases for lubrication in those contacts. This avoids cold welding too, since the grease is re-spread over the contact zone during vibrations and avoids exhibiting clean metallic surfaces. However, grease may evaporate in vacuum (outgassing), and these vapors may condense on optics, causing their failure. Therefore, it is required more often to design HDRMS without greases, which increases the risk of cold welding.

Hence, in contrast to previous tests which were done in high vacuum only, the so called “launch-tests” presented herein were performed in multiple environments. The fretting was not run in (only) high vacuum for long duration (5000 cycles), but a sequence was established where the tests are run for short intervals in air, then in low vacuum and finally in high vacuum. For each environment, this fretting duration refers to 30 cycles, i.e., approx. 5 min fretting. This sequence was seen as more representative for a hold down point than the previous method of long-term in high vacuum. This is seen as the basic

tendency to cold welding, but it was not known so far if there are “pre-damages” caused by on-ground testing (vibrations tests on shakers) and the launch. Launch starts in ambient pressure, and it takes some 10–30 min to arrive in orbit (vacuum). Launch may even last for some more hours, days, or weeks in space if higher orbits are envisaged.

2.2. State of the Art

The initiating point of starting the abovementioned development of this test method was lack of data for efficient design of spacecrafts. A wide literature survey done around 1995 with the emphasis on “adhesion/cold welding”. (This very first literature survey revealed that the term “cold welding” should be used for this effect, because searching by the term “adhesion” reveal almost paper related to “adhesion of coatings to substrates”, and the few papers on “adhesion = cold welding was hard to separate. This survey focusing on vertical separation (“cold welding”) and not the lateral separation (“static friction”) was done within a PhD [6]. It revealed intense research and publications from the 1960s (more basic) to 1970s (many of them related to NASA, e.g., [7]). It showed among other things that the level of adhesion in vacuum is strongly dependent on “size”. Experiments ranged from microscopic level (contact loads of a few mN, [8,9]), to medium scale (loads in range of N, [7]) up to very high loads (linked to the use of rotation welding machines, thereby exceeding elastic regimes in the specimen [10]). It had to be concluded that the level of adhesion cannot be reliably transferred between “levels of dimension”. Therefore, in focus on space, the “range of N” was targeted as it fits best to the space applications. The experimental work within the PhD [6] put emphasis on pure static contact with contact loads in range of 10–40 N causing Hertzian contact pressure from 10–100% of the elastic limit. Both pins and discs were conventionally machined from commercial materials and cleaned with solvents for space hardware. No in situ vacuum-cleanings were applied. The level of adhesion forces in pure static contact was found to be negligible to space applications: adhesion forces up to a few hundreds of mN at loads in range of Newtons [6]).

Combining the static loading with an impact led to an increase of the adhesion forces (“up to a few N”), which was explained by “breaking” natural surface layers as the impact caused plastic deformations. By that, an in-orbit failure of an instrument could be explained [4]. Reported failure from the Galileo spacecraft [1] led to the conclusions that fretting is even more dangerous to space instruments. Following that, a new test device was setup by the authors that allowed fretting to be applied via a pin-on-disc contact with the option to separate the two in a vertical direction (see Section 3). Together with ESA, a test philosophy was also agreed to compare different materials (as their mechanical properties differ strongly, between “soft” aluminium and “hard” steel [2]). Experimental data gained with this setup confirmed the previous assumption that fretting causes much higher adhesion forces up to a range of 10 N [3]. The adhesion force of several material combinations in high vacuum was measured and is available via [3,5]. This data is mainly for in-orbit operation.

As mentioned above, during recent years, the need to provide data on adhesion forces for design of HDRM has become apparent. Herewith, the question on the vacuum level that is related to the onset of cold welding.

A new literature review was performed in 2020 combining cold welding, fretting and vacuum (space). It revealed several publications before the 1970s, which is related to the start of space flight. Many of them are based on research by NASA, most of them were already identified during the very first literature survey done in 1995 and discussed above [6]. There were only a few more publications between the early 1970s and this the recent one (2020). Two NASA papers finally did not cover fretting as motion type, but only sliding friction and did not evaluate adhesion forces in vertical separation [11,12]. Macroscopic sliding is not representative for the vibrations during launch, because the oscillatory motion with small stroke (fretting < 0.1 mm) causes a different wear mechanism. Finally, the measurement of friction (lateral shearing) is not seen representative for a vertical

separation (tensional rupture). Several more papers placed emphasis on the investigation of wear mechanisms in fretting (mostly not in vacuum), but did not measure adhesion forces [13,14]. The latter publication deals with the change of the microstructure of the subsurface inside the contact zone caused by the fretting motion, which is referred to as “Tribologically Transformed Structure”. This mechanism is seen also after vacuum fretting tests; however, as this effect occurs only when protecting measures failed, and it is of secondary interest to space applications. Two papers presenting results on adhesion forces are based on tests done together with the authors, but are not relevant to space applications [15,16]. Finally, the following three papers seem to be of interest to cold welding [17–19]:

- Investigating tin coated electrical contacts under fretting, a relation was established between the partial pressure of oxygen and the test duration [17]. The lifetime was defined as an increase of the electrical contact resistance, which was due to oxidation: with increase of the oxygen partial pressure from 0.1 to 100 mbar, this lifetime decreased by roughly 2 orders of magnitude [17]. No cold welding was measured, but it could be deduced that the wear mechanism is already changing from adhesive to oxidative.
- A recently published paper [18] compares wear volume in fretting between air and Argon. Assuming the Argon to be purity 5.0, the ratio of impurities can be estimated to 10^{-5} . This amount of impurities may be estimated into a vacuum pressure range of 10^{-2} mbar, which is roughly about 10^{-5} of ambient pressure. Based on that assumption, it might be extrapolated that the transfer from oxidative to adhesive wear in pairing of steel-steel and steel-Ti4Al4V is in “low vacuum (range 10^{-2} mbar)”.
- Finally, the most interesting paper with regard to this transition from oxidative to adhesion wear is [19]. This is despite the fact that, again, no adhesion forces were determined, but friction under fretting was investigated in contact of stainless steel SUS304 against itself. They report that the friction coefficient starts to increase when the pressure decreases beyond 1 mbar. They state that the transition from oxidative to adhesive wear occurs in a range of 0.1 mbar.

Surveying the revealed literature, no publications measuring the adhesion force—i.e., vertical separation force—under fretting in vacuum were identified. Moreover, even NASA papers from the 1960–1970s only measure adhesion under vacuum in static contacts [7] or derived friction forces. On the other hand, several papers investigate wear mechanisms under fretting. A few of them may let us extrapolate that under fretting the transition from oxidative to adhesive wear mechanism occurs already in “low vacuum”, range of 10^{-1} to 10^{-2} mbar. As from theory, adhesion—cold welding—needs two “clean metallic surfaces”. Oxidative wear contaminates the contact, thereby preventing a clean surface. On the opposite side, an adhesive wear mechanism is expected to create clean metallic surfaces. It is of minor relevance, if the microstructure is the “original polycrystalline one of an engineering alloy” or already a kind of “TTS” (Tribological Transformed Structure, [11]). The main issue is that metal atoms are on the outer surface enabling interaction with opposite metal atoms and thereby formation of a weld.

From the view of space applications, the conclusion is that not only the high vacuum phase of the launch is to be considered for assessment of cold welding, but the complete launch. A very first part of wear lifetime happens at ambient pressure (including also vibration tests on shaker), and during launch also a low vacuum phase has to be considered for the new test approach (Section 3).

3. Experimental

The test method reported herein is based a cyclic contact. A pin is placed into contact with a disc for several (thousand) cycles. At each opening, the force required to separate pin and disc is measured. (See Figure 1.) This force is referred to as “adhesion force” of this cycle. The adhesion force is plotted as function of cycles. Comparison of different materials is based on the maximum value of adhesion found during a whole test. In addition, the

friction force is derived during the fretting motion. However, it was experienced that compared to standard pin-on-disc-tribometers this data is too noisy to reveal reliable friction coefficients. Finally, it is used to qualitatively indicate if a lubrication is effective ($\mu < 0.2$) or not ($\mu > 0.2$). Following that, friction coefficient is only derived for a reduced number of cycles.

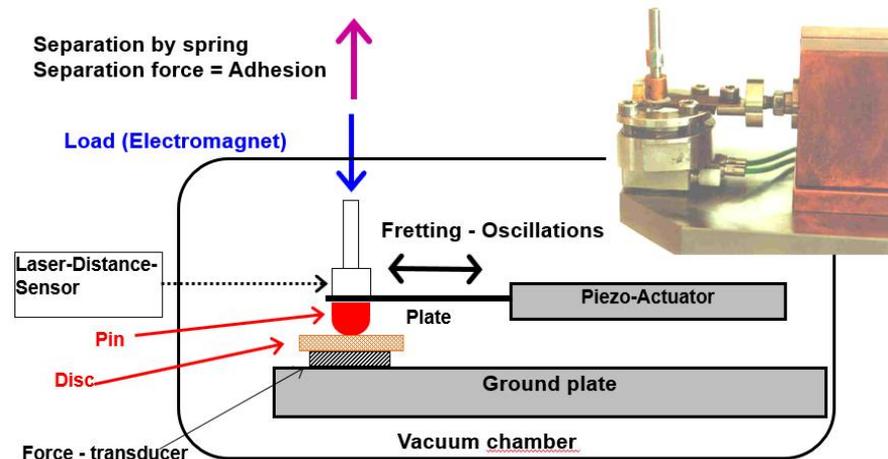


Figure 1. Fretting device: working principle showing the fixation of pin (on upper rod) and disc (mounted directly on a force transducer), piezo actuator for generation of fretting movement. Inset shows the real setup.

To enable comparison of cold welding tendency between different material pairings, the following testing philosophy was defined (it is described in detail [2,3]): the parameter static load is fixed for each pairing with respect to the elastic limit (EL) of the contact pairing. Hertz' theory is used to calculate to contact pressure in the ball-to-flat contact. Using the yield strength of the softer material, the "von MISES-criterion" defines an elastic limit (EL) [20]. For fretting tests, one static load related to 60% EL is applied.

This value of 60% is derived from the European Co-operation for Space Standardisation (ECSS), who has released specifications on contact surfaces. In the ECSS-E-30 Part 3A, Section 4.7.4.4.5 "Separable contact surfaces" [21], the following main requirements are stated:

Peak Hertzian contact pressure shall be below 93% of the yield limit of the weakest material. (This refers to a contact pressure of 58% of the elastic limit, EL.)

The actuator shall be demonstrated to overcome two times the worst possible adhesion force.

Uncoated specimen are freshly ground to $R_a < 0.1 \mu\text{m}$ before testing [2]. The contact is closed and opened for 10 s each. Fretting tests are done at a pressure of 5×10^{-7} mbar as high vacuum level. Test duration is typically 5000 cycles in high vacuum. (Multiplying the 5000 cycles by a fretting frequency 200 Hz and holding of each cycle for 10 s means that the total number of lateral fretting motions in this test is 10 million.)

Fretting parameters are a stroke of $50 \mu\text{m}$ and frequency of 200 Hz. These parameters were agreed with the European Space Agency when setting up the test standard STM-279 [2]. The stroke was defined to $50 \mu\text{m}$, which is about the range of fretting $< 0.1 \text{ mm}$ (general tribological definition). The frequency range 100–500 Hz was recommended by ESA being a result of an analysis of vibrations on satellites during in-orbit-life. The value of 200 Hz were finally agreed as average. Of course, the fretting test is a strong simplification for a HDRM, the same applies for the "Pin-on-disc test (tribometer)" for common tribological applications. It is a simplified model test, whose results need to be interpreted carefully.

The test approach was changed in order to consider effects of the environment for a HDRM. The test duration was reduced, and the environment was changed to the following sequence: fretting in ambient air, then fretting in low vacuum (range 1 mbar) and then fretting in high vacuum. Duration in each environment was 30 cycles (times 10 s each, refers to 0.6 million fretting revolutions per environment). In total, 15 min for launch. This is not an exact launch profile, but it is in the order of, and it was agreed with ESA to enable comparison of the effect of fretting in ambient and low vacuum on the onset of cold welding in high vacuum.

Following the need for current applications two groups of candidates were selected for a recent test campaign funded by ESA: six different alloys (without any coatings), and a first selection of coatings. (See Table 1.) This selection was driven by the need for space application. PH-steels are often used in space mechanisms for their resistance to corrosion (for that reason none of the conventional nitriding steels used in ground application is allowed for space.) Bearings made of steel AISI440C are used in space, and this steel tends to low adhesion under fretting in vacuum [3,5]. Ti6Al4V is commonly used for housing in space, but tends strongly to cold welding. MuMetal is used for flexible cable isolations, and due to its austenitic character, it is expected that it tends also to high adhesion (like, e.g., austenitic steels, SS316L [5]). Results are benchmarked with tests using space qualified grease based on PFPE (Braycote 601). For Tungsten, Silver and Copper commercial pure grade was used.

Table 1. Survey of tested combinations.

Disc Material	Disc Coating	Pin Material	Lubricant
AISI440C	–	Ti6Al4V	Braycote (PFPE)
AISI440C	–	Ti6Al4V	–
AISI440C	MoS ₂ (PVD)	Ti6Al4V	–
Steel 17-7PH	MoS ₂ (PVD)	Ti6Al4V	–
Steel 17-7PH	Nitrided	Ti6Al4V	–
MuMetal	–	MuMetal	–
Tungsten	–	Tungsten	–
Silver	–	Silver	–
Copper	–	Copper	–

4. Results

4.1. Reference Testing on Grease as Inhibitor to Cold Welding

The combination of hard chrome steel AISI440C with Ti-alloy (Ti6Al4V) was tested under grease lubrication, with and without an additional solid lubricant coating (MoS₂) on the steel disc. Figure 2 shows the adhesion force as function of cycles (one cycle covers 2000 fretting motions, in total 10 million motions were done). It can be seen that the adhesion is within the range of “noise” typical for this test setup. This leads to the conclusion that cold welding can easily be avoided if grease is applied. Figure 3 shows on the left plot (a) the evolution of adhesion if both contacts are blank, i.e., they exhibit the typical engineered surface quality of a space part. The adhesion is reasonable with peaks up to ~4.000 mN. It has been seen over the past years that the value of adhesion varies from one cycle to the next. This can be related to the fact that the contact for the subsequent cycle is not made (microscopically) at the same point. Such severe cold welding must be avoided in space applications. If grease is not allowed, coatings would be a solution. However, using MoS₂ (PVD, approx. 1 µm thick) is found not to be the solution: the coating fails early, and the measured adhesion forces are similar to the uncoated pair, in fact slightly higher (~5000 mN, Figure 3b).

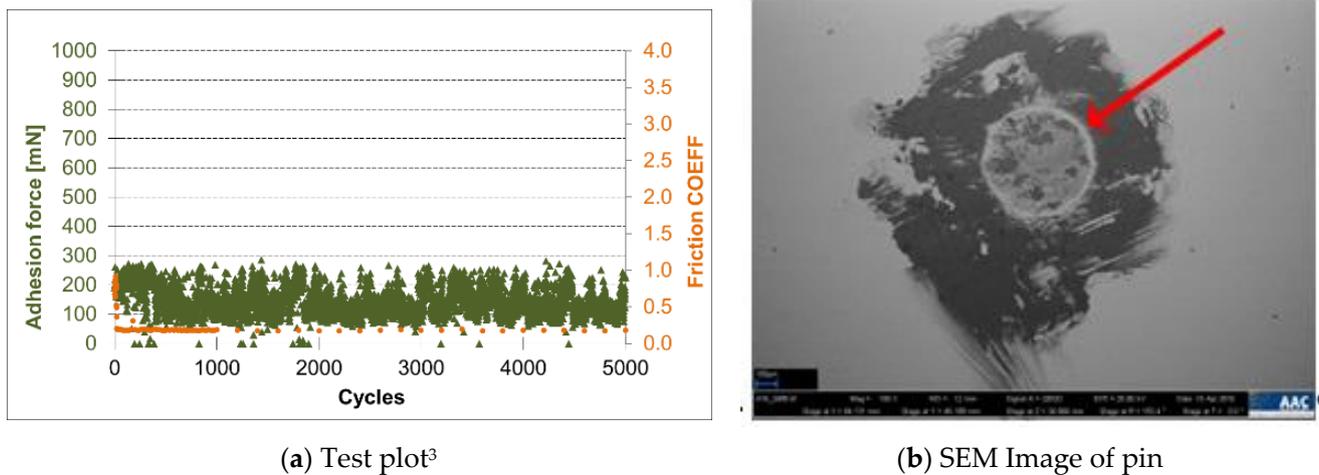


Figure 2. Fretting test (high vacuum): (a) adhesion as function of cycles for AISI440 (disc) to Ti6Al4V (pin), grease Braycote 601EF was applied. (b) SEM image of contact zone of Pin (Ti6Al4V blank), the circular wear zone is clearly visible (→), but EDS confirms that the contact surface is covered by the grease.

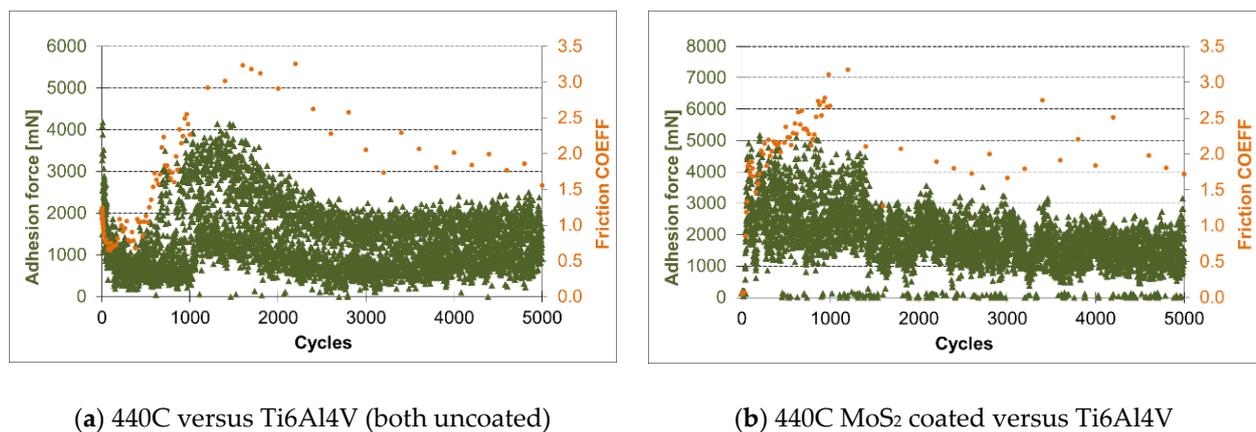


Figure 3. Fretting test (high vacuum): adhesion as function of cycles for AISI440 (disc) to Ti6Al4V (pin): (a) disc and pin blank, no lubricant, (b) Disc AISI440C coated with MoS₂, Pin Ti6Al4Vblank.

4.2. Results for Some Bulk Materials in HighVac and Launch High Vacuum

Under high vacuum, a typical behavior for many materials used in space is seen with Mumetal (Fe-based austenitic alloy). If in contact with itself and fretted in high vacuum, high adhesion forces with peaks up to almost 14,000 mN can be found. These high forces are typical for austenitic Fe-alloys, but also for face-centered-cubic materials (Cu, Al, ...). Although the test materials were poly-crystalline, the ductility is seen as the reason for forming high “clean real contact areas” and therefore higher adhesion forces. Contact area may be divided into: nominal contact being the macroscopically visible one in a flat-to-flat contact or the one calculated from Hertzian theory (assumes perfect smooth surface). Due to roughness, only a few tips are in mechanical contact, this shall be referred to as “real contact area”. Finally, even this area might be covered by oxides, etc. which inhibit cold welding. Hence, the cold welding will be established only on a sub-part of that: the “clean real contact area”. SEM image in Figure 4b shows a morphology typical of for adhesive wear.

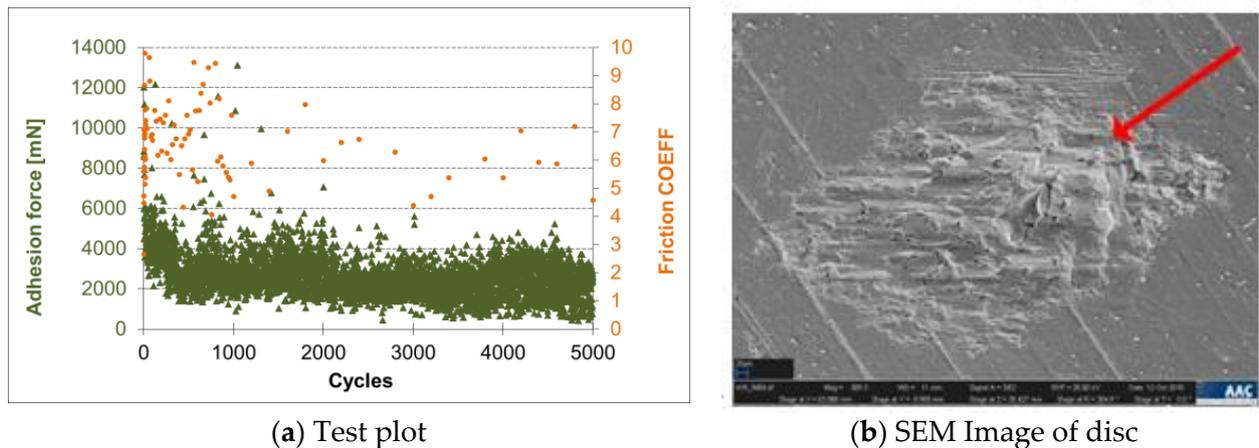


Figure 4. Fretting test (high vacuum): (a) adhesion as function of cycles for Mumetal to itself (not coated). (b) SEM image of contact zone of disc, irregular wear zone (→) is clearly visible without debris, but strong adhesive marks are present.

A quite unexpected behavior was found for technically pure tungsten in contact with itself. Although disc and pin are blank, the fretting motion does not lead to formation of significant welds. The adhesion force stays hardly above the noise of the test, even in high vacuum. SEM images show that the material itself is strongly worn, and a lot of loose debris are attached close to the contact zone. Such a material would not be an alternative to grease lubrication, as this debris can also contaminate the spacecraft (Figure 5).

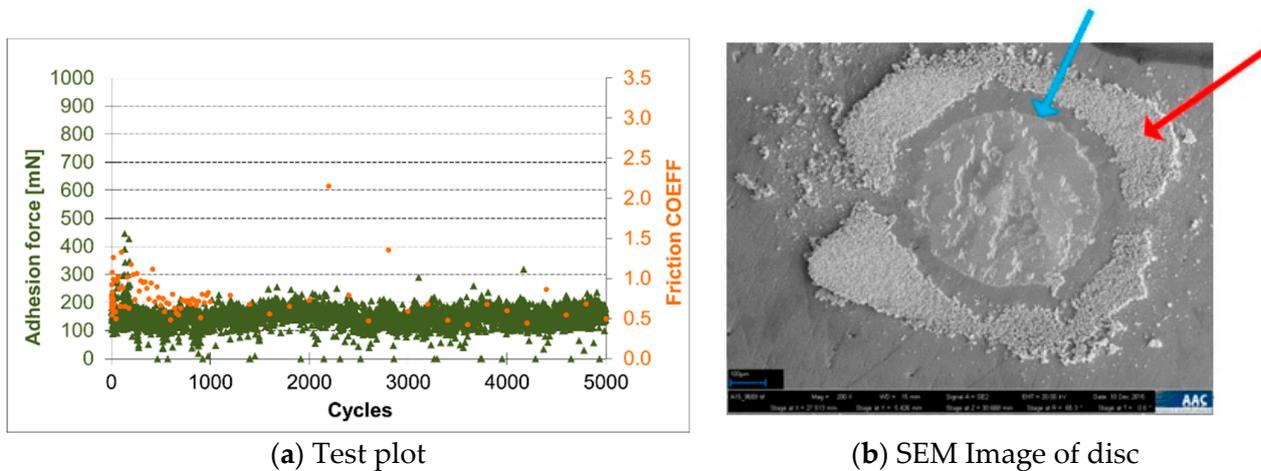


Figure 5. Fretting test (high vacuum): (a) adhesion as function of cycles for tungsten to itself (not coated). (b) SEM image of contact zone of disc, circular wear zone (→) is clearly visible with highest amounts of loose debris around it (→).

4.3. Launch Environment

When testing similar combinations (blank alloys against themselves) in a launch environment, the behavior was found to change. Figure 6 shows the adhesion of Mumetal to itself during a fretting test in launch mode: the fretting was done for 30 cycles in air, then it was evacuated to low vacuum (1 mbar) and another 30 cycles were run. Finally, it was evacuated to high vacuum, and the last 30 cycles were run. It can be seen that the onset of cold welding in high vacuum is delayed, and lower adhesion forces would be visible in a launch (overall just about 15 min = 90 cycles). The SEM-image also shows that the wear mechanism is not “adhesive”. At least, it is “not yet” adhesive, as remaining oxide layers inhibit cold welding so far.

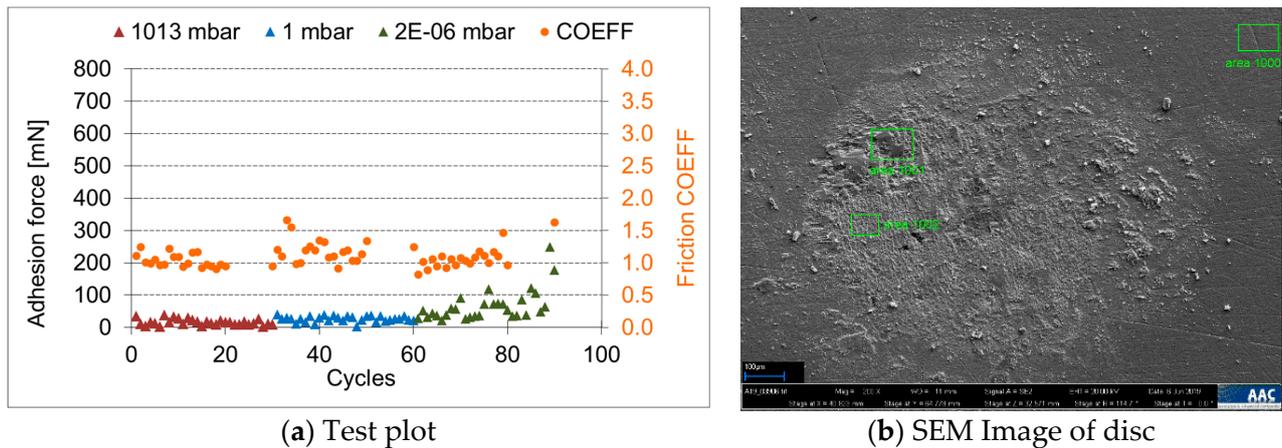


Figure 6. Fretting test (launch): (a) adhesion as function of cycles for Mumetal to itself (blank). (b) SEM image of contact zone of disc, wear zone does not show typical signs of adhesion (Compare Figure 4, (→)).

An example of high adhesion even under launch conditions is seen in contact of silver against itself. Adhesion is already seen in low vacuum (from approx. 40 cycles in total). It then increases strongly after reaching high vacuum to values that almost exceed the test devices' separation forces (Figure 7). Additionally, the SEM image showing typical marks for adhesion underlines that high adhesion. (These high adhesion forces are similar to the results from a test done in fully in high vacuum.)

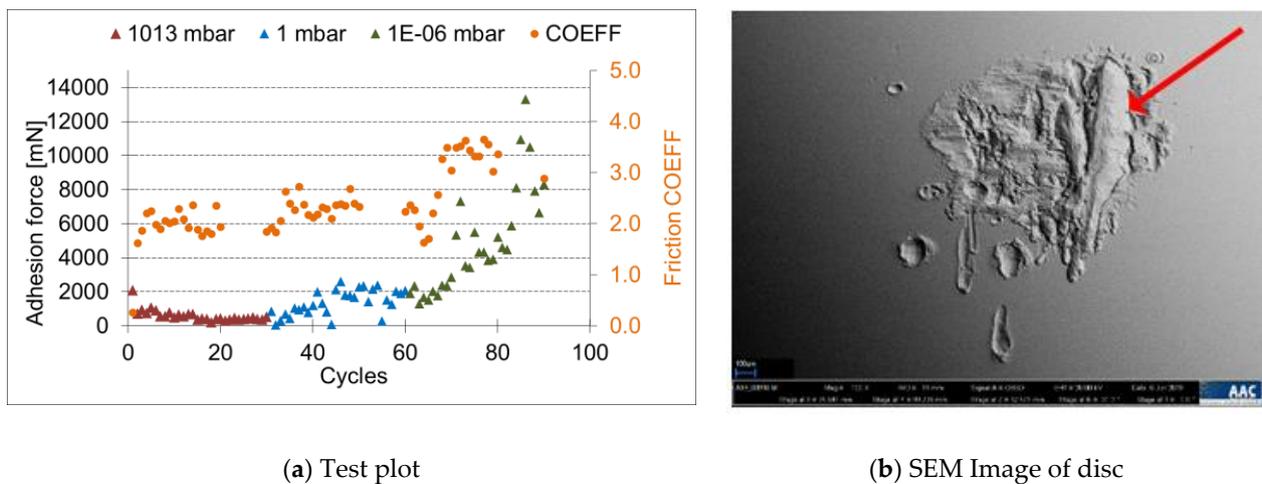


Figure 7. Fretting test (launch): (a) adhesion as function of cycles for silver to itself (not coated). (b) SEM image of contact zone of disc, wear zone show severe signs of adhesion (→).

An example of the influence of fretting in air (oxygen) under launch conditions is seen in contact of copper against itself. Adhesion is already seen in low vacuum (from approx. 50 cycles in total). It increases after reaching high vacuum, but does not reach values found during testing solely in high vacuum. The SEM image shows typical marks for tribo-corrosion of the copper surface, those oxides are strongly contaminating the surface. The adhesion forces are definitely lower than the results from a test in only high vacuum (Figure 8).

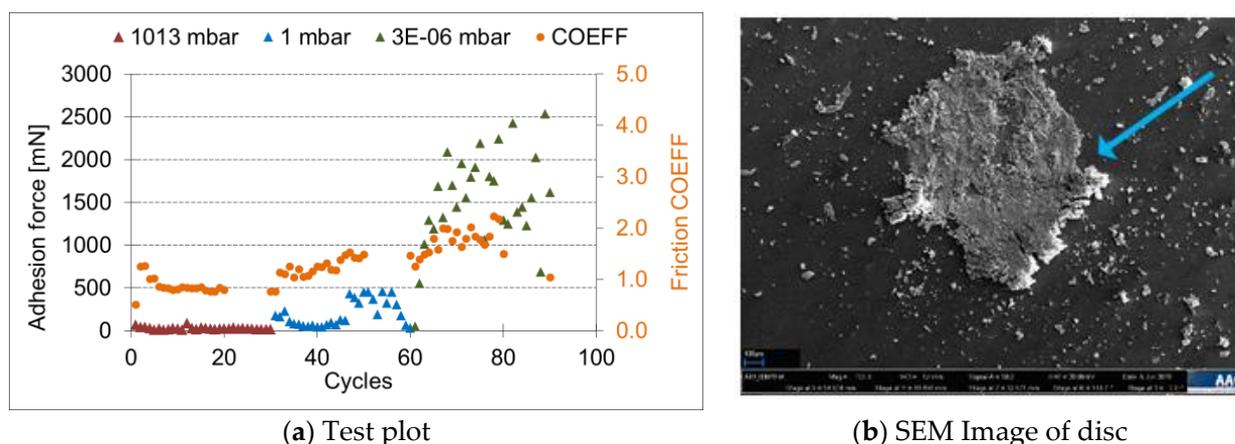


Figure 8. Fretting test (launch): (a) adhesion as function of cycles for copper to itself (not coated). (b) SEM image of contact zone of disc, wear zone shows signs of tribo-corrosion (\rightarrow) not those of adhesion (as, e.g., shown in Figure 4, (\rightarrow)).

4.4. Some Results from Coatings Compared for HighVac and Launch

High Vacuum

In space, tribological parts like gears are often based on PH-steels, as the conventional nitriding steels used in terrestrial gears are not allowed for space. On the other hand, hard chrome steels (440C) are not accepted either. A combination that could be found in gear applications in space is PH-Steel 17-7 with MoS₂ coating against Ti6Al4V (blank). The fretting test in vacuum exhibited very high adhesion followed by early failure of the coating (Figure 9). Enlarging the first part of this test (Figure 10a), it can be seen that the coating inhibited cold welding (in high vacuum) just for about 40 cycles (this equals 400 s of fretting). Launch test of the same combination (but new specimen) revealed that the coating may even fail earlier: the onset of adhesion is only after some 12 cycles in high vacuum (120 s net fretting).

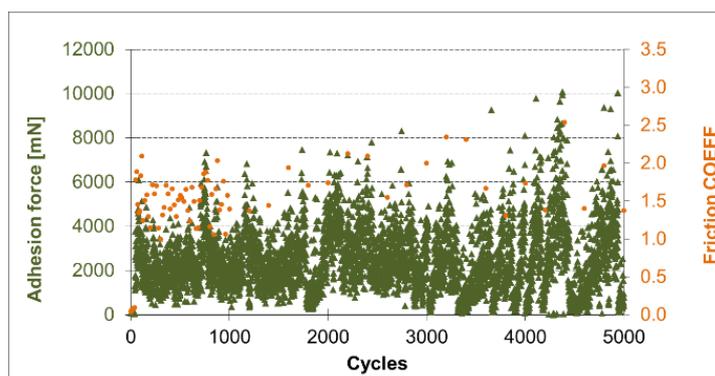


Figure 9. Fretting test (high vacuum): PH-Steel 17-7 with MoS₂ coating against Ti6Al4V (blank).

In the case of proper pre-treatment of the steel by plasma nitriding, no cold welding during the whole launch test was found. Nevertheless, some Ti6Al4V was found as wear on the nitrided steel disc (Figure 11).

A fretting test under high vacuum between AISI440C and Ti6Al4V (both uncoated) was shown in Figure 3. Reasonably high adhesion was measured. This could not be avoided by coating the steel disc with MoS₂. The same combinations were finally also tested under launch condition (Figure 12b). The MoS₂ coating on the hard steel AISI440C does not avoid adhesion in launch conditions either: Even in low vacuum, the onset of cold welding is visible (Figure 12b). Comparing this result to the test on the same combination, but without MoS₂ coating (Figure 12a), it has to be concluded that the coating does not

give any improvement to this material combination, as there is also adhesion visible in the launch test. Moreover, using the coating, the onset of adhesion is even earlier (Figure 12b, in low vacuum). Without coating, the onset of adhesion is later (in high vacuum, Figure 12a) and only starts in high vacuum. Hence, it might be anticipated that the coating preserves the steel surface from some tribo-corrosion, which can enable formation of a protective layer that delays the onset of cold welding in vacuum. (The friction coefficient in range of 1 indicates that the lubrication by MoS₂ is already lost at the very beginning of the test in air, Figure 12b.)

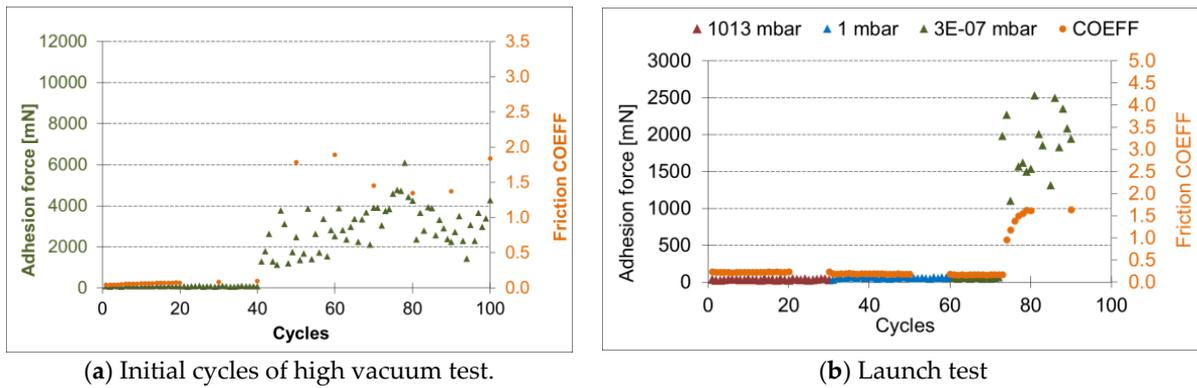


Figure 10. Fretting tests: PH-Steel 17-7 with MoS₂ coating against Ti6Al4V (blank), (a) Initial cycles of high vacuum test from Figure 9, (b) Launch test.

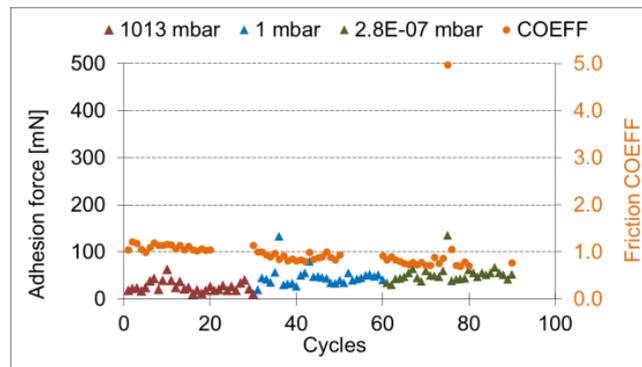


Figure 11. Fretting tests (launch): Steel 17-7 PH nitrided against pin Ti6Al4V (blank).

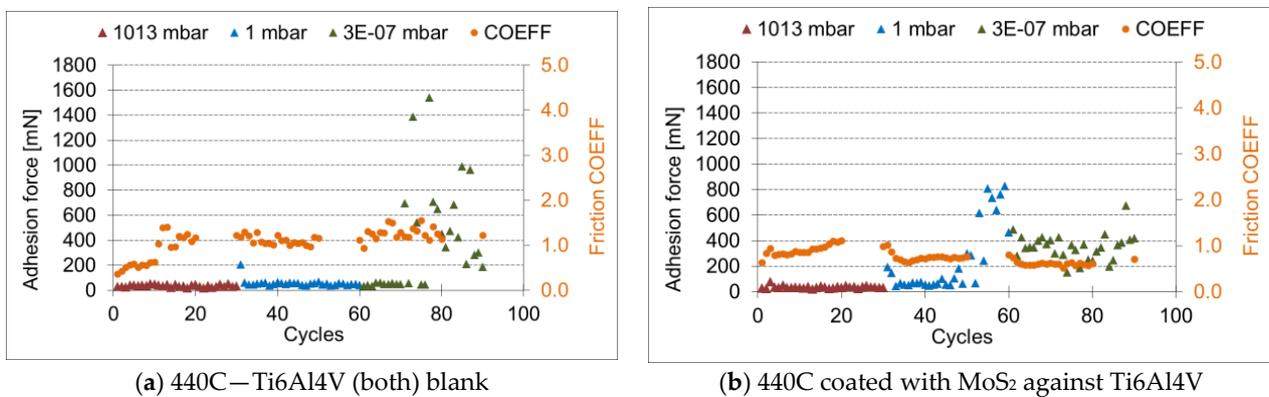


Figure 12. Fretting tests (launch): (a) Steel AISI440C (blank) against pin Ti6Al4V (blank). (b) Steel AISI440C (coated with MoS₂) against pin Ti6Al4V (blank).

Coming back to the initial reference test (Section 4.1). This test between 440C and Ti6Al4V in high vacuum showed no adhesion when a grease was used, but high adhesion forces were found for contact between both being blank (in Figure 3a) and with the steel disc being coated with MoS2 (in Figure 3b). Finally, this combination was also tested as a reference for fretting in launch conditions: also the use of grease protects against cold welding in launch condition (Figure 13).

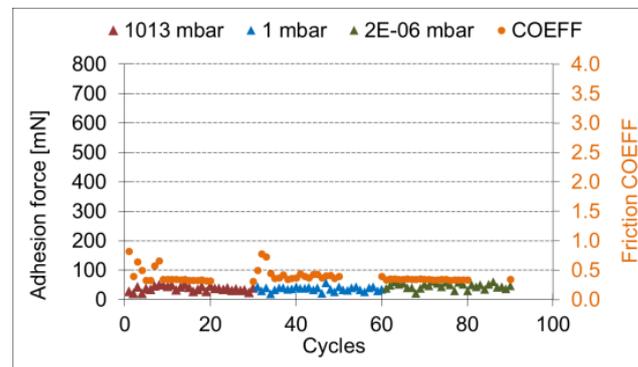


Figure 13. Fretting tests (launch): AISI440C against pin Ti6Al4V (blank), lubricated with grease Braycote.

5. Discussion

Some test results from “blank” materials in contact with themselves are compared in Figure 14. The selected approach is to compare the maximum values found. This is a risky approach due to high uncertainty, but it was chosen for assessment for space application, as the highest value leads to the failure of a mechanism. For the launch test, the highest value out of the three environments is considered, but is in the current results related to the 3rd environment of high vacuum. In the plot, three “groups” of behavior can be seen (Figure 14):

1. High/Low: Mumetal and Invar (both austenitic Fe-alloys) show very high adhesion in high vacuum, but very low (maximum) adhesion in launch, the SEM analysis has shown typical signs for adhesive wear in high vacuum. EDS exhibited formation of oxides during the launch test.
2. Low/low: tungsten and also molybdenum show low adhesion in both test environments. For tungsten, strong wear was identified creating much loose debris, which seems to act as a kind of 3rd body not enabling the formation of a friction weld.
3. High/high: high adhesion is found for silver in both conditions, in high vacuum the weld was so strong that the test device failed to re-open (therefore > 10,000 mN). In launch condition the adhesion was found in a similar range (~13,300 mN). SEM shows for this contact shows adhesive wear marks even in launch conditions. This may be related to a less strong tribo-corrosion and the more noble character of silver. Copper in contact with itself shows higher adhesion in launch, but when investigating the wear zone by SEM, the high amount of corrosion products (oxides) would fit also to the first group mentioned above (high/low).

Summarizing the result found for coatings does not yet reveal a clear trend. Hence, only some spotlights (or working hypotheses) may be proposed:

- Reference is seen in the use of grease (PFPE based like, e.g., Braycote 601). No adhesion was found in long term tests in high vacuum (until 5000 cycles). Additionally, no adhesion is seen in launch tests (3×30 cycles).
- Subsurface treatments offer a somewhat promising approach. They improve the hardness, not only on the very surface (like thin PVD-coatings), but offer a graduated increase into the subsurface zone. One example of nitriding PH-Steel 17-7 was successful in inhibiting adhesion to Ti6Al4V (which is known to tend to cold welding).

- Solid lubricant coatings of MoS₂ made by PVD are widely used in space. However, the fretting tests shown above indicate that in very small oscillating motion, the coating is not offering to suppress cold welding. Failing in launch tests can be argued with the susceptibility of MoS₂ to degradation by humidity: sliding in humid ambient condition is reported to decrease the life time in ball bearings in high vacuum (space). Comparing test data from launch to high vacuum is not in contradiction, but due to missing parallel testing it cannot be argued as “confirmed”. Finally, fretting tests done fully in vacuum show early failure, too. Hence, for this type of solid lubricant, the small motion (fretting) is also critical to life.

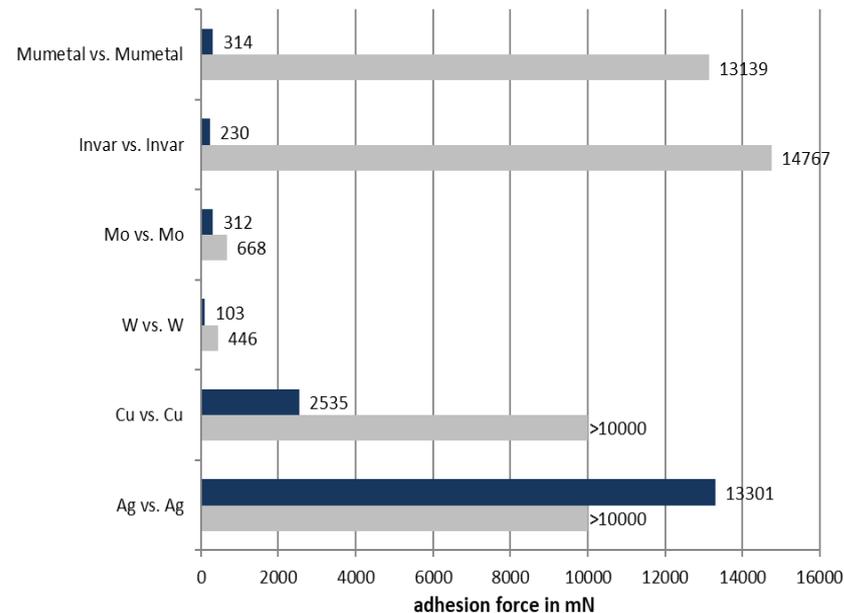


Figure 14. Maximum adhesion force from tests in high vacuum (dark blue) and in launch conditions Air-lowVac-highVac (light grey). Adhesion forces and wear mechanisms depend strongly on the materials.

6. Conclusions

Although the current results are only a first highlight, some conclusions may be drawn:

- First fretting tests in “launch conditions” were done on several selected blank metals and on coatings typically used in space.
- The clear conclusion is that behavior in high vacuum (deployment in orbit) is influenced by the “pre-life” on ground (fretting in ambient, e.g., when doing vibration tests on a shaker), i.e., testing in a full environment needs to be done to assess life in space reliably.
- The need for replacement of grease in HDRMs caused by, e.g., optical payloads can more likely cause failure, as the results show that coatings do not guarantee 100% success compared to the use of grease. Hence, detailed work on a suitable replacement is needed and will probably lead to certain coating-application-correlations.
- Additionally, the option “no coating” was found to be worth considering: some alloys do not show high adhesion forces in the high vacuum phase of a launch test. The fretting in air (and maybe low vacuum) leads to tribo-corrosion, forming reaction layers that inhibit cold welding. However, it has to be expected from future tests that this might become a risky approach, as no reliable life will be expectable, as those layers are not reproducible.

The selection of materials/coatings was driven by the need for space application. The results seem to raise more questions than answers. It will be an aim of coming studies to step-by-step answer those questions in scientific terms. More work is foreseen to improve

the understanding of the wear mechanism in order to reliably predict working material combinations for separation mechanisms when being forced to avoid use of grease.

7. Annex—Example for a “HDRM”

Hold-down-And-Release-Mechanisms (HDRMs) are a very common part of a satellite, like a clutch in a car. Comparing to automobiles, a very similar mechanism is the “hood latch” in high-end cars: they are actuators (pyro-technical) that open the front hood, which softens the frontal section of the car in case of collision with pedestrians.

An example for a HDRM based on a bolt is shown in Figure 15. The spherical area on the bolt is the contact zone (diameter few cm). The material is steel [22]. The bolts are cut by several methods: by explosives, or simply by thermal expansion (thereby overstressing a notch, middle of Figure 15).

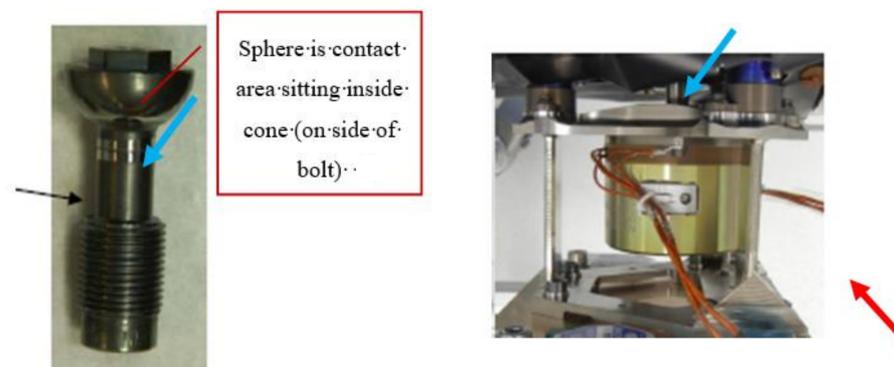


Figure 15. Left: Bolt extracted: contact is the sphere [22], for release it is cut (at black arrow →). Right: HDRM [23] example for a product from Figure 16, not using exactly the bolt shown on the left, location of that bolt is indicated by blue arrow →).

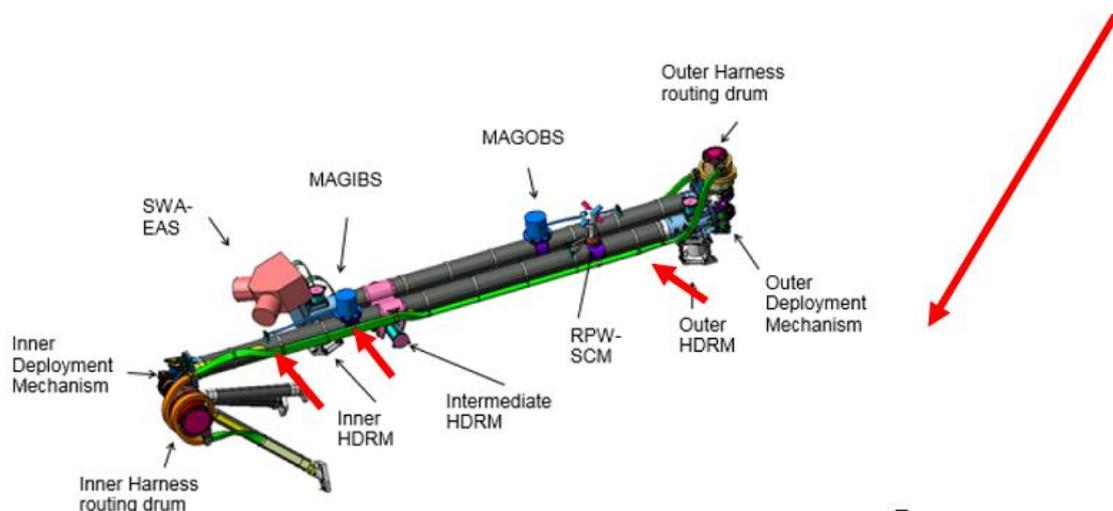


Figure 16. Overview for example of deployable boom (2 × 2.4 m) [23]. Red arrows indicate the location of the HDRMs (3×).

Another example showing a complete HDRM is shown in Figure 15 (right, this is based on a different type of bolt, but principle is similar): three of them are used to hold down two large booms during launch. In orbit, the HDRMs are released, then the booms are deployed to keep the instrument (“SWA-EAS”) apart from the satellite (Figure 16).

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