INFLUENCE OF COATINGS AND ALLOYING ON COLD WELDING DUE TO IMPACT AND FRETTING

A. Merstallinger, E. Semerad, B. D. Dunn *

ARC Seibersdorf research, A-2444 Seibersdorf/Austria, andreas.merstallinger@arcs.ac.at
** Materials and Processes Division, ESTEC, Noordwijk/The Netherlands, barrie.dunn@esa.int*

ABSTRACT

This paper shall present a survey on a vacuum or space related effect, which is referred to as “cold welding”, “adhesion” or “sticking”. It refers to “welding or sticking” of contacting bodies which shall open vertically (no sliding), i.e. acc. to ECSS “separable contact surfaces”. Starting from a reported failure on a spacecraft, test facilities were developed and a verification study was done to show relevance between the test results and the reported failure. In the following, a standardised test method was set-up, in order to compare different space relevant materials and coatings for their tendency to cold welding. Within several studies, common experience and numerical results were gained on space relevant combinations of materials and coatings. Based on this knowledge, recommendations for use of certain combinations will be drawn. Adhesion forces under fretting were found to exceed the loading forces. As example, nickel containing stainless steels shall be avoided. An assessment of coatings for steels and Aluminium (e.g. hard anodising, Keronite) is given.

1. INTRODUCTION

On spacecrafts, a variety of engineering mechanisms exhibit ball-to-flat surface contacts which are periodically closed for several (thousands of) times. An impact during closing can eventually degrade the mechanism's surface layers whether they are natural oxides, chemical conversion films or even metallic coatings. This can dramatically increase the tendency of these contacting surfaces to "cold-weld". Fig. 1 shows an example for such a mechanism. The anchor was actuated from it’s resting position (middle) electromagnetically, and impacted on both end stops. Finally, an anomaly from the flight model of this mechanism on a satellite was reported, that the anchor kept blocked on the left side (as shown in Fig.1). Another even more dangerous effect is fretting: vibrations occurring during launch or during movement of e.g. antennas in space, can lead to small oscillating movements in the contact, which is referred to as “fretting”. This lateral motion causes even more severe destructions compared to impact and adhesion forces may increase by factor of ten !

In order to set-up experience in these effects, two special devices - called "impact facility" and “fretting facility” - have been developed at ARC Seibersdorf Research (ARCS) 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 [5] were carried out to show the influence of the main parameters impact energy and static load (contact pressure). These results have been used to set up a standard test method with fixed parameters.

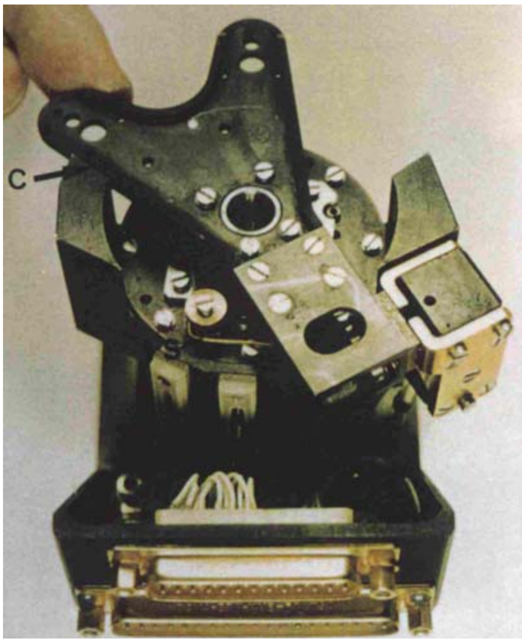

Fig. 1 Mechanism of a satellite: anchor was actuated from it’s resting position (middle) electromagnetically. It impacted on both end stops. Finally, an anomaly from the satellite was reported, that the anchor kept blocked on the left side. It was “cold welded”.

2. STATE OF THE ART

Under atmosphere surfaces are generally covered by physically or chemically absorbed layers. Even in the absence of absorbed water, grease or other macroscopic contaminants there remain surface layers, e.g. oxide and nitride layers, which are formed under terrestrial conditions on pure metal surfaces and which can be regarded as natural protection layers against cold welding.
Under vacuum or in space environment, once removed by wear, these layers are not rebuilt and the exposed clean metal surfaces show a higher cold welding probability. So, adhesive and tribological behaviour under space environment or vacuum differs significantly from terrestrial conditions and the use of data collected under latter conditions is rather restricted. Secondly, a modelling of the adhesion forces suffers from the unknown degree of real metal-metal contact, which is linked to the destruction of the surface layers. This effect is strongly affected by the contact situation. Moreover, scientific studies are mostly based on atomically clean surfaces. However, surfaces of spacecrafts exhibit “normal engineering composition”.

As discussed in previous papers, [1], [5], contact situations may be classified in three different types: static, impact and fretting. In a cyclically closed and opened contact, the amount of destruction of surface layers increases in order mentioned above. This is followed by increasing adhesion forces. Fig. 2 shows three plots of the adhesion force as function of cycles (=openings). The three plots refer to three contact types applied to a pairing of titanium alloy (IMI834) and Stainless steel (AISI440C) [1]. In fretting conditions the maximum adhesion force during the whole test was 9.5N (2.5 times the load of 4 N), under impact 0.96 N (load 29 N), whereas in static contact after 25.000 cycles adhesion of less than 0.1 N occurred (29 N load).

Consequently contaminant layers (oxides) are removed under impact and fretting much more quickly when compared to static contacts, and cold welding occurs much earlier than expected. This may not only reduce the life time of a satellite but also can endanger space missions, e.g. any opening or ejection mechanism may fail due to cold welded contacts. A typical opening/closing mechanism fails, if the adhesion force exceeds the force which is available to open this mechanism, e.g. by a spring. This „blocking“ value may be much lower than the applied load. The blocking of the mechanism (fig. 1) under impact condition was reported with an adhesion force in the range of 0.3 N. This value was confirmed by a first verification study of the impact device [2].

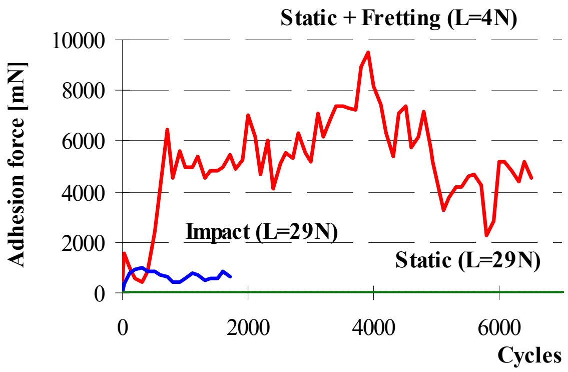

Fig.2 Adhesion force as function of cycles (i.e. one closing-separation) [1]. Comparison of adhesion in static (load 29N), impact (load 29N) and fretting (load 4 N) condition under vacuum. Danger and severity of adhesion increases with type of contact: static- impact – fretting. (Max. adhesion in static 0.1 N after > 25,000 cycles, in impact 0.96 N, in fretting 9.5 N.)

3. EXPERIMENTAL

In general, a pin is closed onto a disc for several thousand times. At each opening the force required to separate pin and disc is measured. 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.
To enable comparison of cold welding tendency between different material pairings, the following testing philosophy was set-up at ARCS (it is described in detail in an in-house specification of ARCS [3]): the parameters static load and impact energy are fixed for each pairing with respect to elastic limit (EL) of the contact materials. 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): if the load (contact pressure) exceeds this EL, plastic yield would occur. Similarly, for the impact energy a limit (W_Y) can be deduced above which yielding occurs [3], [4]. Based on parameter studies [1], [5], the ARCS-standard was defined: the static load is selected to achieve a contact pressure of 40, 60 and 100%EL. An impact test is started with a static load, which achieves 40% of EL. After 10000 cycles, the load is increased to achieve 60%EL. After, another 5000 cycles 100% are applied. The impact energy is kept constant to 40 times the W_Y. This stepwise increase of load enables to get data within one test. (From the point of possible irreversible plastic deformations, loads may be increased but must not be decreased. In the latter case, work hardening of material might have increased hardness, and therefore the actual contact pressure is lower than calculated.) For fretting

tests, only one static load (related to 60%EL) is applied for 5000 cycles. If no coatings were applied, the specimen were freshly ground to Ra<0.1µm before testing [3]. The contact is closed and opened for 10 seconds, each. At impact the base pressure of vacuum was less than 5.10^{-8} mbar, i.e. surfaces are not recovered during opening. During fretting test, a base pressure of 5.10^{-7} mbar is sufficient.

The European Co-operation for Space Standardisation (ECSS) has released specifications on contact surfaces. In the ECSS - E-30 Part 3A, section 4.7.4.4.5 "Separable contact surfaces" [6], following main requirements are stated:

b) 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.)
d) ... the actuator shall be demonstrated to overcome two times the worst possible adhesion force ...

Therefore, results obtained from cold welding tests acc. to the ARCS-in-house-specification [3], can be used to address the necessary opening forces for actuators in mechanisms. (Both, impact and fretting test are done at 60% EL.)

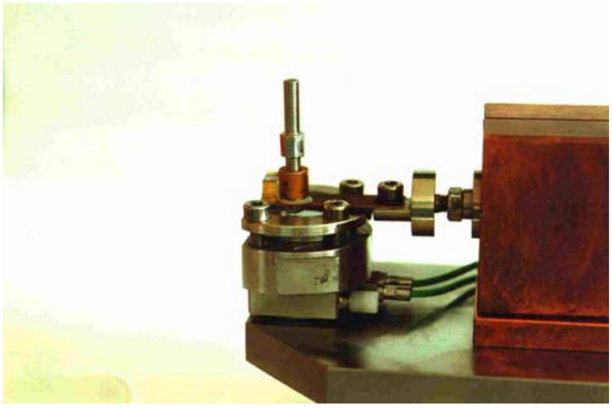

Fig.3 Fretting device: Detail showing the fixation of pin (upper rod) and disc (mounted directly on a force transducer). Right side: piezo actuator for generation of fretting movement.

4. RESULTS ON IMPACT

Typical space materials under impact

In the following, comparison of data will be based on the worst case of impact (100%EL). A table in the ANNEX details the materials and the abbreviations used. A survey of adhesion forces found for a selection of typical (uncoated) space materials is shown in Fig. 4. Highest adhesion is seen for stainless steel SS17-7PH versus itself (Fig.4) or Al AA 7075 versus itself (1744 mN). This is an unexpected experience, since usually titanium is regarded as the most "dangerous" contact material. From scientific view, cubic fleet centered metals are more prone to adhesion: Fe, Al. This is due to their ductility. A study [7] on the adhesion of different working materials to a cutting tool made of high speed steel indicated a relation between adhesion force and Ni-content. Regarding standard tests done on different steels to themselves, show that the standard bearing steel (AISI 52100) has negligible adhesion. For the AISI440C (no Ni) certain adhesion under impact was found. (This is also opposite to fretting results. Hence re-testing is under way.)

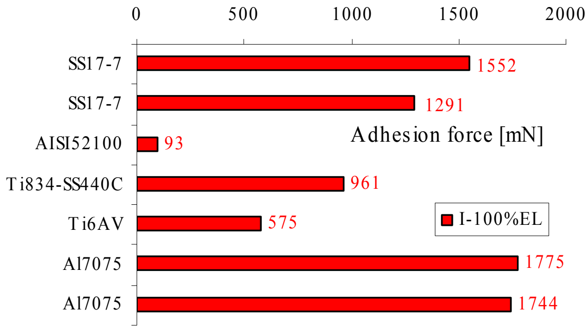

Fig.4 Adhesion force under impact for materials in contact to themselves. Highest adhesion for stainless steels with Nickel (e.g. SS17-7PH), Inconel, Titanium alloys (IMI834) and Al alloys (Al AA7075). Low adhesion for bearing steel AISI 52100 (no Ni).

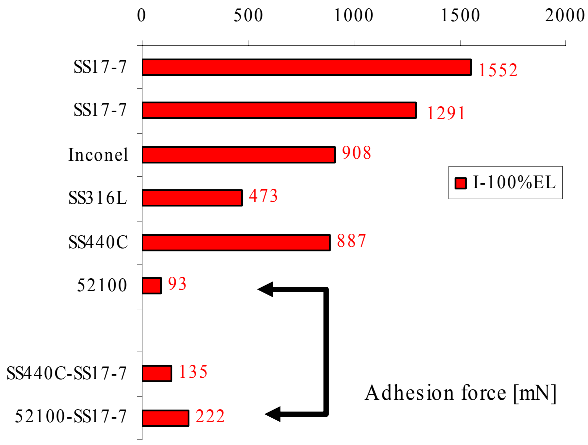

Fig.5 Adhesion force under impact for different types of steel versus itself: austenitic structure and Ni seem to promote high adhesion: SS17-7ph (7%), AISI 316L (11%), Inconel 718 (52%). No adhesion for AISI52100 versus itself ("52100"). High adhesion of AISI440C has to be proven. Combinations of different steels: adhesion seems to increase in contact to steels with higher tendency to cold welding (arrow).

Influence of coatings

For comparison some SS17-7PH discs were coated with TiC and MoS_2 and investigated for their ability to reduce adhesion. These coatings are related to two types of coatings: hard and soft. The efficiency of the first group - **hard coatings** - depends on the load bearing capacity of the underlying bulk: if it is too soft, it is deformed under impact, and the hard coating breaks [8]. Herewith, the underlying metal or inter-layer (Ti) is set free, pieces of the hard coating (TiC, or inter-layer TiN) are transferred and may act as additional abrasive particles. Hence, adhesion is decreased in comparison to bare metal surfaces, but since destructed surfaces areas cannot be „re-coated“ adhesion is still found. An example for this is the **TiC** (2000 HV) on the SS17-7PH (only 441HV), the coating decreased the adhesion force by approx. four times, but could not avoid it. (See. Fig.6.)
Hence, for use of such a hard coating, another steel type which enables a higher hardness should be targeted, e.g. AISI440C or AISI52100 (up to 700 HV). By use of steel AISI52100 in contact to SS17-7PH lower adhesion can be achieved (222 mN, Fig.5). This can further be reduced by application of coatings: DLC by VITO [9]. However, despite of the deformation of the AISI 52100 substrate, the hard **DLC-film** did not (visible) peel off and no adhesion during more than 37.000 cycles was measured. Some small amount of steel was transferred from the (un-coated) pin to the DLC-coated disc.
Secondly, a **soft lubricant** coating on SS17-7PH could avoid any adhesion to another SS17-7PH pin. Hence, under impact soft lubricant coatings on stainless steels reveal higher efficiency in prevention of cold welding.

On the other hand, (hard) **finishes on the soft aluminium** showed breaking and removal of the upper layers, but did not enable cold welding. Tests were run up to 50.000 cycles without finding significant "break-throughs" in terms of sudden increases of adhesion forces. Fig. 7 shows a comparison of the maximum adhesion forces of Al AA7075 versus itself (uncoated: Al7075-Al7075) and the influence of selected coatings. No adhesion was found for combinations: Al AA7075 hard anodised versus stainless steel SS15-5PH ("Al7075(anod)-SS15") and Al AA7075 CrNi-coated versus Al AA7075 hard anodised ("Al7075(CrNi)-Al7075(anod)"). However, an Alodine 1200 coating on only on the disc is not sufficient to prevent adhesion (Al7075(alod)-Al7075, adhesion force of 336mN). A recently developed coating, named "Keronite", did not show any adhesion. But the main advantage was that no surface destruction or formation of debris was found. (For details to Keronite refer to [10].)

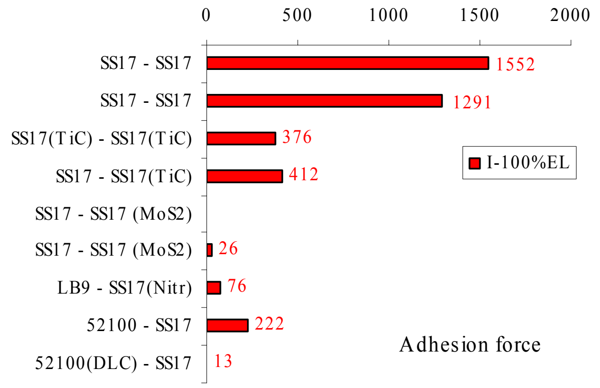

Fig.6 Adhesion force as function of static load for different coatings on steel: lowest adhesion for SS17-7PH (SS17) with MoS_2.Hihger adhesion for TiC (coatings was broken). Negligible adhesion between bronze (LB9) and SS17-7PH (LB9-SS17(Nitr)). Low adhesion between AISI52100 and SS17-7PH, can further be decreased by use of DLC coating ("52100(DLC)-SS17").

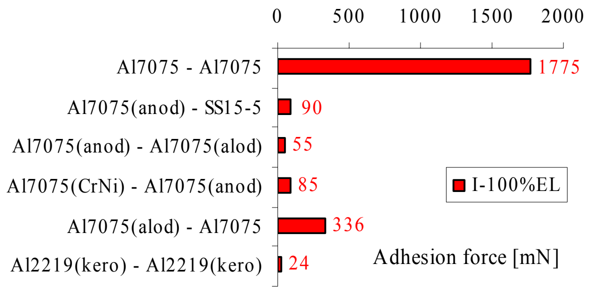

Fig.7 Maximum adhesion force under impact for different coatings on aluminium (AA7075): negligible adhesion for combined coatings "Hard anodised (anod)", CrNi-plated (CrNi), Alodine 1200 (alod) and Keronite [10], Alodine alone is not sufficient to prevent cold welding (336mN). (For details on Keronite coating refer to [10].)

MoS_2 coatings versus MoS_2 composites

The investigations included also two composites materials containing MoS_2 particles: Vespel SP3 (Polyimide with 15m% of MoS_2) and a silver alloy "$AgMoS_2$" (with 15v% MoS_2). Vespel shows negligible adhesion against both, stainless steel SS17-7PH and Al AA7075. The silver alloy shows some small adhesion 117 mN. (The combination Ag10Cu versus $AgMoS_2$ is used in slip rings.) SEM-inspection showed the counter-surfaces (partially) to be covered with MoS_2 flakes, which were pressed out of the matrices. This effect is assisted by the fact that adhesion is mainly driven by bonding between two metals. In case of Vespel SP3 no metal is present. In case of silver, the very low shear strength enables easy braking of the bonds. Hence, beside coatings also composites provide efficient prevention of cold welding, due to their ability to re-form, i.e. at each impact a new lubrication layer is formed and coating free areas are re-coated.

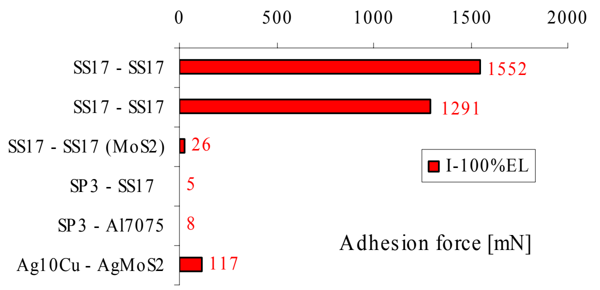

Fig.8 Adhesion force under impact for different combinations with MoS_2:coatings and composites provide good prevention of cold welding (SP3 = Vespel SP3, Ag10Cu = coin silver, $AgMoS_2$ = silver composite with 15v% MoS_2) .

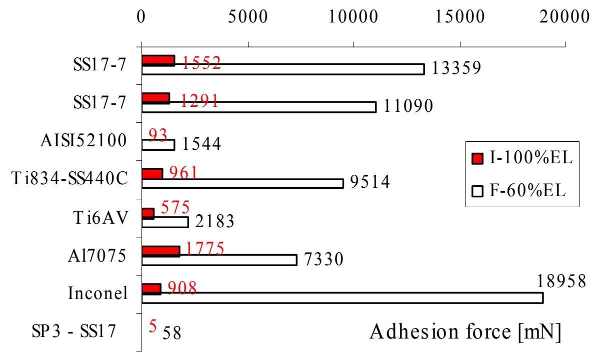

Fig.9 Comparison of adhesion force under impact (I) and fretting (F): Adhesion between metals under fretting are up to tenfold higher than under impact. Highest adhesion for Ti, Al-alloys, stainless steels containing Ni and Ni alloys (Inconel 718). No adhesion between polymer composite (VESPEL SP3: Polyimide with 15m% MoS_2) and steel (SS 17-7PH).

5. RESULTS ON FRETTING

Comparison of impact and fretting contact

A survey of adhesion forces found under fretting and under impact is given in Fig.5. (Data from [9], [11], [13], [1].) As mentioned in the introduction, the fretting movement which is a small sliding, was expected to cause sever surface destructions. In highest allowed contact pressure at impact (100%EL), typical adhesion forces range up to approx. 2000 mN. Under fretting conditions at even lower contact pressure (60%EL), the adhesion forces exceed these values by factor of up to 10. Stainless steel SS17-7PH versus itself shows adhesion of approx. 1500 mN under impact, but more than 11000 mN in fretting (Fig.9 “SS17-7”). For other metal-metal contacts similar behaviour is found: Ti-IMI834-AISI440C, Al AA7075 versus itself. The highest adhesion was found for Inconel 718 (Ni alloy). No adhesion is found for polymer to metal contact: VESPEL SP3 (polyimide with 15m% MoS_2) versus stainless steel SS17-7 PH.

As mentioned in section 4, the adhesion of different working materials to a cutting tool made of high speed steel indicated a relation between adhesion force and Ni-content in fretting conditions [7]. Standard fretting tests [3] done on different steels versus themselves, show this basic relations too (Fig.10). Adhesion decreases in the order Inconel 718 (52%Ni), SS17-7PH (7%Ni) and AISI 316L (11%Ni), down to AISI 52100 and even lower for AISI440C (no Ni). The bearing steels (AISI 52100 and SS440C) show lowest adhesion under fretting. (The high adhesion of the AISI440C (no Ni) under impact is still under investigation.)

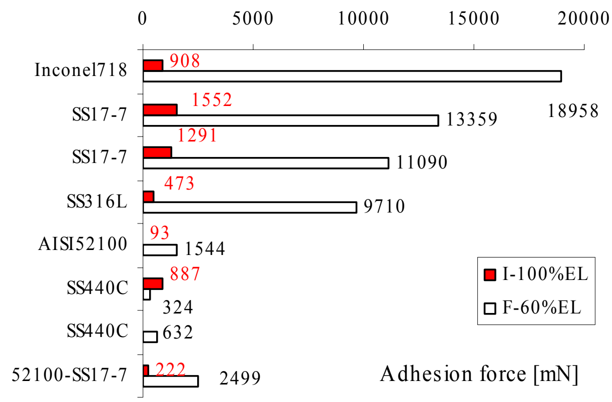

Fig.10 Comparison of adhesion force under impact (I) and fretting (F) for different steels and Ni-alloys versus themselves: Adhesion under fretting decreases with decreasing content of Ni as indicated by [7]. Combinations of different steels seem to be dominated by the one with higher adhesion: AISI52100 to SS17-7ph. (52100-SS17)

Influence of coatings on fretting

Coatings were investigated for their ability to prevent cold welding under fretting. Results for **coatings on steel** are compared to contacts of bare materials in Fig.11. Applying a **MoS_2 coating** to one of the two SS17-7PH counterparts could not prevent adhesion: in two tests after only 50 (20) cycles, i.e. 8 (3) minutes fretting or 100000 (42.000) strokes lubrication effect was lost. This is combined with a distinct increase of adhesion force. High adhesion forces of up to 5870 mN were found. This refers to a reduction of the max. adhesion forces of approx. 50 % (compared to SS17-7

without coating). (See Fig. 11.) The same tendency can be seen for one **TiC coating** between two SS17-7ph counter parts (Fig.12: “”SS17-SS17(TiC)”). Adhesion is only reduced to approx. one third of the uncoated combination. SEM images and EDAX analyses confirm the breaking of the coating and adhesive wear.
The influence of **nitriding** SS17-7ph surface was investigated: no significant reduction of adhesion is visible (still 8517 mN, Fig.11: “SS17-SS17(nitr)”.) Based on this result, the low adhesion between nitrided SS17-7 and bronze LB9 (500-1087 mN) may be due to the lubrication effect of the lead (known for tribological applications).
Applying a **DLC coating** on AISI52100, reduces adhesion in contact to SS17-7ph from 2499 mN to 856 mN.
The effect of **grease** (Braycote 601) was tested in a contact AISI440C to itself. No significant effect is visible. Hence risk of contamination due to outgassing is superior to the efficiency in avoiding adhesion. (Fig.11: “440C(bray)-440C”.)

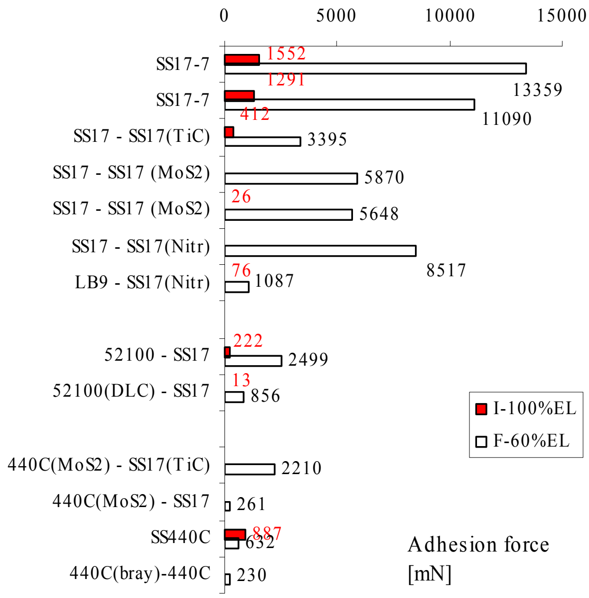

Fig. 11 Adhesion force of steel based coatings (I=impact and F=fretting): coatings in general reduce adhesion. For SS17-7PH no tested coating of the disc could decrease adhesion significantly (TiC, MoS_2 or nitriding). In contact of AISI440C to SS17-7ph, TiC shall be avoided. Efficiency of grease (Braycote601) is not significant in contact of AISI440C to itself. Efficiency of MoS_2 coating under fretting is limited to a low endurance.

MoS_2 coating in a special pairing (AISI440C+MoS_2 vs. SS17-7PH+TiC): MoS_2 + TiC resulted in a breakthrough (at 366 cycles = 61 minutes = 700,000 strokes) and medium adhesion forces of up to 2210 mN. Applying only MoS_2 on a AISI440C disc and performing test versus SS17-7PH only very low adhesion forces were found. (Compare AISI440C vs. itself without coating, Fig.11: “SS440C”.) Therefore the conclusion could be drawn that the TiC destroys the surface layers of the AISI440C which could have been regarded as adhesion prevention layers.

Selected combinations of coatings on **aluminium** were tested under fretting: no adhesion was found between Al AA7075 hard anodised and Al AA7075 NiCr-plated. (See Fig. 12.) Al AA7075 hard anodised in contact to non-coated SS15-5PH showed negligible adhesion. This is in contrast to the fact, that SEM-images show breakthrough and pealing off of the conversion layer on the Al. But results are in accordance to impact tests done in [11]: despite of a breakthrough of the layer, no adhesion was measured. Coating of only the disc with Alodine, did not prevent from cold welding, medium adhesion of 2036 mN was found. (Fig.12: “Al7075(alod)-Al7075”) A recently developed coating named “Keronite” offers not only no adhesion to steel AISI52100, but also did not peel off during fretting [12]. (The coating is described in [10].)

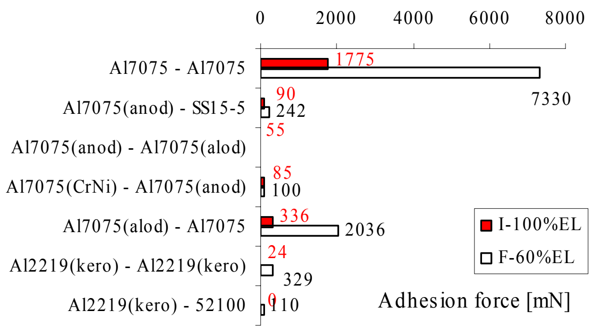

Fig. 12 Adhesion force of aluminium based coatings (I=impact and F=fretting): Adhesion between Al parts is strongly reduced by hard anodising (anod), CrNi-plating (CrNi) and Keronite [10],[12]. A single Alodine coating (alod) is not efficient in prevention of cold welding.

6. SURFACE MORPHOLOGY AFTER IMPACT AND FRETTING

Surface is strongly changed due to impact and fretting. After impact testing, a SS17-7ph pin shows plastic flow, which can be seen by the piling up at the edges of the pin’s contact area (Fig.13a). On the other hand, fretting of a SS17-7ph steel versus itself shows strong surface destructions due to adhesive wear. Material is torn out of the surface, and pressed back or adheres to the contact partner. (Fig.13b)

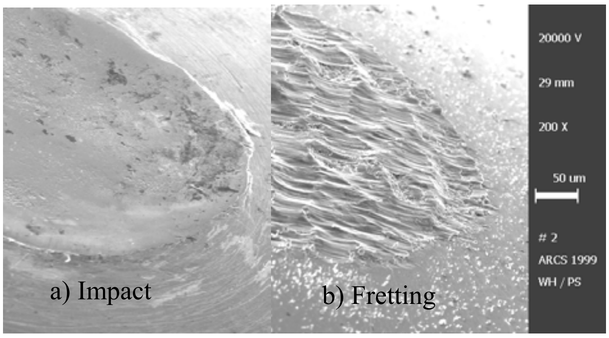

Fig. 13 Surface of a pin (SS17-7ph) after impact and fretting. Impact: only some plastic flow visible by piling up of edges. Fretting: strong destruction of surface, adhesive wear combined with high adhesion forces (Compare to Fig.10 for adhesion forces: "SS17-7".)

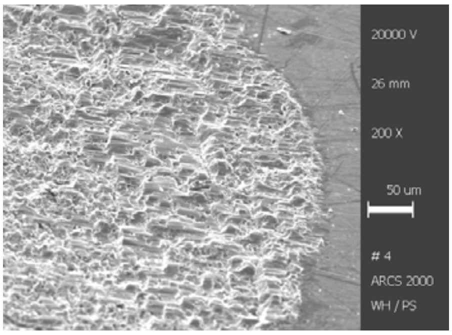

Fig. 14 Surface of disc SS17-7ph with MoS_2 coating after fretting tests (compare to Fig. 11 for adhesion forces): lubrication effect was lost after less than 200 second fretting movement (confirmed by EDAX-mapping: no Mo present in contact area).

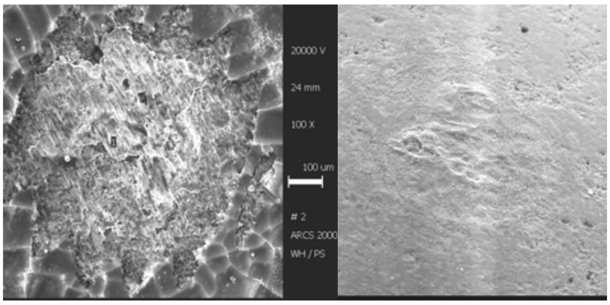

Fig. 15 Comparison of Al-coatings under fretting: Left: Hard anodising on Al7075 was broken. Right: Keronite coating on Al AA 2219 does not show fretting marks. (Compare to Fig. 11 for adhesion forces).

As mentioned above, MoS_2 coating on SS17-7ph could not prevent from cold welding. The lubrication effect was lost after 20 cycles (200 seconds fretting, 42000 strokes). Afterwards, adhesion up to 5870 mN was found. Fig. 14 shows strong surface destruction of the MoS_2 coated disc, which is similar to the uncoated (Fig.14). EDX-distribution of Mo taken from the disc shows, that no Mo is present in the contact area after 7000 cycles. Both, pin and disc, show fretting wear scars which are similar to those without MoS_2 coating.

In contrast to all coatings investigated until now, the Keronite on Al AA2219 was the only one which prevents adhesion and which was not destroyed under fretting conditions. Hard anodising of Al AA 7075 prevented adhesion, but much loose debris was found. (Fig.15.)

4. CONCLUSION

The **first aim** was to set up expertise and test devices on cold welding. **A verification study** [2]**,** has proven that the devices offer a reliable simulation capability. They enable to make a step forward in cold-welding effects from „common experience“ to measurable numbers, useful for designers of spacecraft applications.

The **second aim** of these activities was to set up a base knowledge on the influence of impact energy and subsequent static load on the adhesion force. Therefore, a wide range of pairings covering metal-metal (SS17-7 PH versus itself and Al alloy AA 7075 versus itself), metal-polymer (SS17-7 PH versus Vespel SP3), as well as several coatings for steels and aluminium were investigated under impact and fretting conditions.

Several tests have revealed, that the range of adhesion forces in metal-metal-contact with typical engineering surfaces and without coatings **depend on the contact type**: in static contact adhesion forces were below 0,5 N, in impact adhesion force up to 2 N, and under fretting adhesion forces in excess of 18 N were found.

Generally, **coatings** reduce adhesion in case of impact and fretting. **Hard coatings** (TiC) may break and, therefore, adhesion is lower but still found. **Soft coatings** made of solid lubricants (herein MoS_2) can repair themselves during impact, i.e. prevention of adhesion is more efficient than for hard coatings. Under fretting none of the investigated coatings is able to avoid cold welding of stainless steel (SS17-7ph). Also MoS_2 is not effective in fretting, lubrication is lost soon. In contrast to steel, anodisation coatings on aluminium prevent adhesion in both impact and fretting. However, much loos debris is formed. A new developed "Keronite" coating avoids debris formation.

Composites containing solid lubricants (polymer Vespel SP3, or silver based with MoS_2) can be regarded as a second choice after solid lubricant coatings.

Hence, the ARCS devices can offer the appropriate simulation capability to make a step forward in cold-welding effects from „common experience“ to measurable numbers, useful for designers of spacecraft applications. It is recommended that these tests are performed whenever critical contact surfaces are identified, and possible surface treatments shall be selected in early states of projects. Moreover, an internet data base is in preparation.

REFERENCES

[1] A. Merstallinger, E. Semerad, B.D. Dunn, "Cold welding due to fretting under vacuum, Helium and air", Proc. 7h European Space Mechanisms and Tribology Symposium, ESTEC Noordwijk (NL), Oct. 1997. (ESTEC-Contract 8198/89/NL/LC, WO 46, 1996.

[2] Merstallinger A., Semerad E., 'Tribological properties of Ga3Z1', ESTEC Contract No 8198/89/NL/LC, WO 32, 1995.

[3] Merstallinger A., Semerad E., „Test Method to Evaluate Cold Welding under Static and Impact Loading", In-house-Standard by Austrian Research Centre Seibersdorf, Issue 1 (1995), Issue 2 (1998).

[4] Johnson K. H., 'Contact mechanics', Cambridge University Press, 1985.

[5] Merstallinger A.; Semerad E.; Dunn B.D.; Störi H., „Study on cold welding under cyclic load and high vacuum", 6th Europ. Space Mechanisms & Tribology Symposium, Zürich, Proceedings ESA SP-374, 1995.

[6] European Co-operation for Space Standardisation (ECSS): ECSS - E-30 "Mechanical", Part 3A "Mechanisms" , section 4.7.4.4.5 "Separable contact surfaces", page 32, Pre-Print Version June 2000.

[7] U. Persson, H. Chandrasekaran, A. Merstallinger, "Adhesion between some tool and work materials in fretting and relation to metal cutting", WEAR 249 (2001), p. 293-301.

[8] A. Merstallinger, E. Semerad, B.D. Dunn, "Influence of impact parameters and coatings on cold welding due to impact under high vacuum", Proc. 8th European Space Mechanisms and Tribology Symposium, Toulouse (F), Oct. 1999. (ESTEC Contract No 11760/95/NL/NB, CO 12, 1998.)

[9] A. Merstallinger, E.Semerad,P.Scholze,C.Schmidt, "Screening of contact materials for cold welding due to fretting", ESTEC Contract No 11760/95/NL/NB, CO20, Materials Report 3150, 2001.

[10] S. Shrestha, A. Merstallinger, D. Sickert and B. D. Dunn, "Some preliminary evaluations of black coating on aluminium AA2219 alloy produced by Plasma Electrolytic Oxidation (PEO) process for space applications", to be published: Proceedings ISMSE, ESTEC, 2003.

[11] A. Merstallinger, E. Semerad, P. Scholze, C. Schmidt, "Influence of coatings on adhesion under impact", ESTEC Contract No 11760/95/NL/NB, CO21, Materials Report 2663, 2000.

[12] A. Merstallinger, E. Semerad, W. Costin, "Assessment of Keronite for Cold Welding and Friction", ESTEC Contract No 11760/95/NL/NB, CO39, Metallurgy Report No. 3522, October 2002.

[13] A. Merstallinger, E. Semerad, W. Costin, "Influence of steel types on cold welding under fretting and impact", ESTEC Contract No 11760/95/NL/NB, CO40, to be finished, 2003.

ANNEX

Abbreviation	Designation	Composition	Condition	HV daN/mm²	Yield MPa	Poisson	E GPa
Al7075	Al alloy Al AA 7075	2.1-2.9Mg1.2-1.6Cu0.18-0.28Cr5.1-6.1Zn	T7351	170	654	0.33	72
Bronze LB9	Bronze LB9 BS 1400 LB4	Cu-4-6Sn-8-10Pb-2Zn-0.25Fe-0.01Al-0.2Mn-2Ni-0.5Sb-0.1S	AR	160	130	0.34	80
SS15	Stainless Steel SS15-5 PH	14-15.5Cr3.5-5.5Ni0.15-0.45Nb<0.07C2.5-4.5Cu	H1025	393	1000	0.27	196
440C	AISI 440C	Fe-1.01C-0.47Si-0.56Mn-0.014P-<0.002S-17.81Cr-0.27Ni-0.48Mo	Harden	700	2692	0.283	200
SS17	Stainless Steel SS17-7 PH	17Cr-7Ni-1Al	PH	441	1697	0.29	210
Ti834	Ti-IMI 834	Ti5.8-Al4Sn-3.5Zn- 0.7Nb-0.5Mo-0.35Si- 0.06C	AR	334	1285	0.32	112
Ti6AV	Ti-IMI 318	Ti6Al4V	AR	338	850	0.32	105
Vespel SP3	Vespel SP3	85PI-15MoS2	AR	18	68	0.41	2.5
$AgMoS_2$	Ag/MoS2	Ag 15v% MoS2	AR	26	138	0.367	71
Ag10Cu	Ag10Cu	Ag10Cu	AR	150	620	0.367	82.7
Inconel718	Inconel718 / ASTM B 637)	Fe-53.6Ni-18.9Cr-5.3Nb-3Mo-0.98Ti-0.03C-0.13Si-0.12Mn-0.008P-0.001S-0.49Al-0.2Co-0.06Cu-0.004B	AR	348	1338	0,25	211
SS316L	AISI316L	Fe-0.011C-0.41Si-1.42Mn-0.031P-17.3Cr-11.2Ni-2.09Mo-0.05W-0.098Co-0.041V-0.026S	austenitic	175	675	0,28	190
52100	AISI52100 (SKF)	Fe-1C-0.3Si-0.4Mn-0.03P-0.03S-1.6Cr-0.3Ni-0.3Cu	AR	700	2692	0,28	200
AL 2219	AL AA 2219	6.3Cu-0.3Mn-0.18 Zr-0.1V-0.06Ti	T851	138	531	0,33	73,8