Static Adhesion in Preloaded Contacts subjected to Long-Term Vacuum Exposure.

S.Gill and R.A.Rowntree

European Space Tribology Laboratory (ESTL),
AEA Technology, Risley, Warrington, UK

ABSTRACT

The onset of static adhesion between contacting materials during a spacecraft mission has always been of concern to mechanism designers. The evidence to prove that static adhesion has actually occurred in space is limited, yet the data to reassure designers is not available. To support ESA missions, ESTL is currently building a facility to investigate the sensitivity of material combinations to differing contact stress levels during long term exposure to vacuum conditions. The facility allows measurement of the static adhesion forces in vacuum. The materials investigated will be those of most relevance to the mechanism designer, and the time periods under consideration will be up to ten years.

Keywords: Static Adhesion, Cold Welding, Vacuum, Lubrication.

1. INTRODUCTION

A particular concern, in long term space applications, is the tribological behaviour of mechanical components such as bearings, clamps and gears which have been under static load for long periods in vacuum, because of the threat of cold welding or static adhesion.

Some mechanisms can be operated at periodic intervals to mitigate these effects, however items which must not or cannot be displaced prior to deployment pose a difficult tribological design problem. There are an increasing number of European missions in development, which will require the optimum design of, and the flawless operation of, such mechanisms after extended dormant periods in space, under load. Examples of such mechanisms include spring-actuated spin and eject devices (SED), or the sample acquisition system devices (SAS).

A literature review reveals that a large quantity of research was performed during the 1960's, however the data was taken over short time spans, usually less than two years, and the materials used were, in the main, not the engineering materials of direct relevance to the spacecraft mechanism designer.

Recent inspections of the Long Duration Exposure Facility (LDEF) hardware, retrieved in early 1990, after seventy months of exposure in low Earth orbit have not revealed any evidence of static adhesion. Indeed one experiment, FRECOPA, was specifically designed to test static adhesion in engineering contacts and revealed no signs of cold welding apart from one gold/gold control specimen.

This paper gives a brief resume of the literature currently available, before describing a test rig currently being designed at ESTL. The aims of the test programme will be to investigate the differing contact stress levels, when employing various engineering materials, before static adhesion forces are registered, when operated in vacuum.

2. LITERATURE REVIEW

2.1 Laboratory Studies

The majority of relevant references are based on work performed by NASA during the 1960's. The main reason for the emergence of well founded static adhesion data at this time, was the major advance being made in the standard of vacuum systems and related technologies.

Some of the earliest work performed on this topic dates back to the 1930's, and was performed at Cambridge by Bowden, Tabor and their associates. Reference 1 described early experiments with copper and other pure metals, when high adhesion forces were generated between clean surfaces brought into contact in a vacuum environment.

Winslow et al (Ref. 2) compared the adhesion performance of standard spacecraft materials whose cleanliness (vapour degreased in trichlorethylene) and surface finish (~32 microinches RMS) were typical of spacecraft hardware. Samples used were loaded under vacuum (levels ~5x10^{-9} torr), with static loads up to 80% of the compressive yield strength at temperatures of 500 C for periods up to 70000 seconds (nearly 20 hours). At some of the test conditions, high bond strengths were reported for copper/copper and aluminium alloy/aluminium alloy interfaces. Lower strength bonds were registered for the aluminium alloy when in contact with other materials. A titanium alloy/titanium alloy sample also showed some adhesion force at high temperature and pressure.

Hordon and Roehrig (Ref. 3) investigated the adhesion, welding and friction of annealed copper, titanium and tungsten at vacuum levels better than 10^{-9} torr for ultrasonically-cleaned diamond-polished surfaces. They concluded that the tendency for self-adhesion and friction was strongly dependent on the cleanliness of the contact surfaces and the mechanical strength of the material. The more tenacious oxide present on the titanium was suggested as the reason for it registering the lowest tendency of the three materials to weld, whilst the relative weakness of the copper relative to the tungsten led to its higher adhesion forces.

A major symposium was held in Toronto, Ontario, Canada on 1-2 May 1967, entitled "Adhesion or Cold Welding of Materials in Space Environments". The next three references are from the proceedings.

Hordon reported on further testing in reference 4. He tested a number of metals, from which he ascertained the following ranking of adhesive strength, highest first. Lead, silver, nickel, copper, gold, iron, cobalt, tantalum and titanium. It was noted that metals with a face centred cubic (fcc) crystalline structure produced stronger bonds than those with body-centred cubic (bcc) or hexagonal close-packed (hcp) types. The degree of plastic compression and temperature also increased the adhesion, but no well defined relationship was established between adhesion and the mutual solid-solubility.

Gilbreath (Ref. 5) measured adhesion coefficients for clean surfaces prepared by the fracturing of notched specimens (1.25cm in diameter notched to 0.6cm) in high vacuum at pressures < 10^{-10} torr. His ranking was as follows; lead, aluminium, copper, silver, titanium, zirconium, magnesium, 2014 Al alloy, 17-4PH steel, alpha brass and bismuth. This compares well with Hordon's results, except for the titanium whose tenacious oxide film was probably not removed. Metals with an fcc crystal structure again gave the highest adhesion. Gilbreath concluded that any parameter which tends to increase the effective area of contact will increase adhesion.

Kellogg (Ref. 6) reported on work designed to provide materials information for the SNAP nuclear reactor and specifically examined their tendency to self-weld when in contact under load for long periods at high temperature and in ultra-high vacuum.

Twenty independent test chambers were used to perform 110 initial screening tests on a simple geometry simulating flat surfaces (a square with half inch sides) in contact. All tests were conducted in vacuum below 10^{-7} torr, and at raised temperature levels of 370-700 C for varying lengths of time up to 3500 hours. Samples were well cleaned, except for those employing precoated films, before testing. Kellogg tested a wide range of metallic materials, various coatings and also some ceramics. In addition various "contaminant" films applied at the interfaces were also tested. Kellogg concluded that all the metal versus metal pairings showed self-welding under these conditions. Even the metallic pairings showing apparently immeasurable adhesion force showed material transfer in post test examinations.

On the basis of his results, Kellogg suggested that designers should employ the high-strength alloy materials needed structurally and then separate the moving parts with a thin film of low-shear contaminant that will not sublimate, or otherwise allow intimate contact between the metal surfaces during the design life.

A further series of tests were then reported by Kellogg, employing beryllium and 316 stainless steel over extended contact periods up to 10,000 hours. Half were bare metal whilst the remainder were coated with colloidal graphite. The coated samples showed no adhesion, apart from one which had a concave surface causing minor adhesion at the edges. Kellogg concluded that the colloidal graphite inhibited, almost totally, adhesion between the mating parts. The uncoated surfaces showed measurable adhesion forces and material transfer from the beryllium to the stainless steel.

A further aspect of static adhesion forms a major part of the relevant literature. This is the technique of diffusion bonding welding, which described simply is the joining of surfaces by applying heat and pressure to cause comingling of atoms at the joint interface. Since a requirement is for clean surfaces, this process is often carried out in a vacuum chamber.

Kazakov, who is credited with the invention of the process, extoled the virtues of the technique and listed many interfaces which have been created, many of which cannot be generated in any other known manner, in his book "Diffusion Bonding of Materials" (Ref. 7).

Partridge (Ref. 8) described the application of diffusion bonding to aerospace structures, and reviewed the process variables which affect bond quality and strength with reference to bonds between Ti-alloys, Al-alloys and dissimilar metals.

2.2 Spacecraft Experiences

Recent results following the stripdown of the LDEF, after seventy months in low Earth orbit, have generated surprise in that no static adhesion was registered during the deintegration, and that no signs of static adhesion were present in an experiment called FRECOPA where various samples were loaded together in columns by belleville washers. Contact pressures are quoted as being between 25 and 135 MPa, and samples tested included aluminium alloys, copper alloys, titanium alloys and stainless steel. With the exception of a gold/gold control specimen no signs of static adhesion were registered (Ref. 9).

The deintegration of LDEF is reviewed by Dursch and Spear (Ref. 10), along with the results of a literature search into previous on-orbit cold-welding experiments and a review of on-orbit spacecraft anomalies. The authors concluded that there have be no documented cases of a significant on-orbit spacecraft cold-welding event occurring. Seizures of several mechanisms were reported as being due to vibration caused fretting or galling caused by loss of lubricant. Nevertheless the authors still advise that precautions should be taken to ensure that not only does cold welding not occur in the space environment, but that seizure does not occur in the pre-launch or launch environment.

2.3 Implications of Previous Work

The literature reveals that while considerable work has been performed into understanding the adhesion of pure metal surfaces, the majority of testing has been done over short time periods under clean conditions in vacuum. The technique of diffusion bonding welding has shown that most substances, under suitable conditions, are susceptible to static adhesion. The sensitivity of adhesion to subtle changes in the surface chemistry and the cleanliness has been shown to be of great significance.

Little work has been performed on typical engineering contacts, and no reported work has dealt with timescales greater than two years. It has been shown however that at elevated temperatures most metal-metal interfaces will suffer adhesion over the relatively short period of a few months. Both soft interface barriers and hard coatings have been shown to be effective as diffusion barriers, which will maintain low adhesion values over periods of a year or so (i.e. up to the limit of existing tests).

From an adhesion standpoint, the worst case conditions are usually at elevated temperatures (say >200°C). However it is very unlikely that such temperatures would be experienced by envisaged missions (deep-space, near-earth or sun-orientated), since thermal shielding would be expected to protect against such levels of temperature. In practice typical temperatures of loaded interfaces will be at or below ambient, with low, if any, thermal variation.

Current experience gained from spacecraft experiments and deintegration suggests that static adhesion is unlikely to occur. The operation of long-term preloaded contacts in vacuum has not been evaluated however, and it is in this area where ESTL are to investigate further.

3. ESTL TEST RIG

Initial plans for the test rig have been modified following the LDEF deintegration results. The aim of the rig is now to investigate long term static adhesion effects under a range of high contact stress levels for a number of different materials.

3.1 Test Rig Description

A layout diagram of the ESTL test facility is shown in Figure 1. The facility essentially comprises a 60 cm diameter vacuum chamber with a platform to carry the test specimens. Pressures are maintained at high vacuum levels by an ion pump, and a gate valve allows the chamber to be isolated from an externally mounted branched extension. The extension acts as a "vacuum lock", allowing a linear motion device and its mounting flange to be rotated and aligned to operate any of the test samples. A transducer in the pushrod monitors the applied loads, and a small Vespel tip-piece will allow relative radial motion between the tip and the actuated pushrod. Pressures in the "vacuum lock" will be quickly brought down as required, by a close-coupled turbopump.

Figure 2 shows the test sample and its actuation lever system in more detail, while Figure 3 shows a plan view of the system. The mechanism employs a lever system, with an extension pushrod (1) screw fitted at the inner radius. The actuation arm pivots on Bendix frictionless flexural bearings (2), which are mounted in a spigoted clevis shaped housing (3).

The preload is applied by the compression spring (4). The fixed sample (6) spigots into a hole at the outer radius of the mounting platform (5), and is clamped in position by a bolt. The arm-mounted sample holder (7) will have two machined flats to fit inside a slot cut into the actuation arm (8). A headed-pin (9) will fit through a pair of slots in the limbs of the arm, and through a hole in the sample. The arm and headed-pin will have dry lubricant applied. The headed-pins will be restrained from falling out by a spring pin and a washer fitted to their far end.

In order that high levels of contact stress can be attained, despite using a low capacity high sensitivity force transducer, the contact area will be defined by three small headed pins (10) or alternatively three balls inserted into the arm-mounted sample holder. These will be matched for height such that the sample will sit flat and remain stable.

Figure 3 shows the plan view of the facility, the spacing shown will allow thirty stations in total.

Materials used within the facility will be aluminium alloy, for the main structural members, and stainless steel, for small pins, springs, belleville washers, bolts etc.

The mounting platform will be underslung from the chamber lid by a number of aluminium alloy support columns, and thermally isolated by PTFE washers.

3.2 Test Rig Characteristics

The lever-arm ratio for the actuation arm is 2:1, and the load transducer is rated at 500 N maximum load.

The actuation arm must first overcome the applied preload, before separating the two sample faces. Assuming that adhesion loads less than the applied preload are to be expected then the maximum preload for the adhesion system is therefore 500 N, due to the lever arm ratio.

The slots in the actuation arm permit an initial measurement of the load generated by parasitic effects (e.g. the pivot torque) plus the applied preload. The load generated by the sample static adhesion is not seen until the clearance has been taken up in the slot. The output from each sample actuation will therefore be a trace of load versus displacement, on which the static adhesion effect will be clearly visible. The use of flexural pivots means that little or no change in hinge torque is to be expected over the duration of the testing.

3.3 Test Philosophy

The literature review has revealed that the adhesion forces generated between mating surfaces are significantly affected by a number of different variables, listed in Table 1:-

TABLE 1

Some of the Factors affecting
Generated Static Adhesion Forces

Load
Vacuum
Materials
Temperature
Surface Finish
Time of Contact
Area of Contact
Contact Geometry
Pre-Conditioning
Surface Cleanliness

As previously stated however the initial aim of this work will be to investigate the effect of stress levels on the tendency of different material combinations to generate static adhesion forces.

The results quoted by Kellogg (10) suggest that the rate of diffusion is quick to slow down. It is proposed therefore in initial proving tests to compare the performance over a short time period (possibly one year) of as many material combinations as the facility will allow. On completion further long term test-work is being considered comparing perhaps only the two best combinations which have the greatest practical significance, whilst varying other parameters to investigate any improvements which may be feasible.

3.4 Test Conditions

The first variable under consideration will be the contact stress. With thirty test stations available it is currently planned to test ten different material combinations under three stress levels. The stress levels will be chosen as a ratio relative to the material yield stress, for the weakest material in the combination. The ratios are currently planned to be 0.5, 1.0 and 1.2. This will test the materials in two contact stress regimes, i.e. elastic/plastic and elastic, as well as at the transition point.

With all the samples in the same chamber, the conditions will be nominally identical. The surface roughness, as defined by Ra, for the initial tests will be set at 0.4 microns Ra.

During the extended period of load application, the chamber vacuum will be maintained at less than 10^{-6} torr. The temperature will be maintained at ESTL laboratory ambient (20°C +/- 2°C).

Vacuum levels are expected to reach 10^{-6} torr very quickly after evacuation, and after removal of the roughing pump the system pressure will reduce over the life of the test to a value somewhat lower, $\sim 10^{-8}$ torr. The very slow reduction in the interface vacuum levels, once molecular flow conditions have been achieved, broadly reflects the behaviour of such interfaces during long term deep space missions.

3.5 Material Combinations

A list of the materials under consideration for inclusion in this test programme are shown in Table 2. The decision as to the material combinations and the interface barrier, if any, to be used will be agreed with ESTEC at a later date.

The choice of interface geometry will be made on the basis of the most likely usage for the materials. Where the materials are usually destined for use in conforming contacts, like ball bearings, then the ball on flat technique will be chosen, e.g. 52100 and 440C. Where the materials are structural and would be expected to be used in non-conforming contacts like clamps, the flat on flat test samples will be employed, e.g. Anodised Al Alloy, Densimet.

TABLE 2

Materials under consideration for Testing.

Base Materials:-

440C
52100
Inconel
Densimet
TiC on 440C
Vespel SP-3
Anodised Al Alloy
Anodised Ti Alloy
Hard Chrome on Al
Hard Chrome on Ti Alloy
Hard Chrome on Stainless
Tungsten Carbide on Ti Alloy

Interface Diffusion Barrier Materials:-

MoS_2
Lead
PTFE
Braycote 601

4. CONCLUSIONS

1) The possibility of static adhesion occurring in an interface which is not disturbed seems remote judging by the results from the LDEF strip down. However it is still important to take precautions against the possibility of adhesion by choosing suitable material surfaces at the interface, and by possibly using an interface diffusion barrier.

2) The rig currently being designed at ESTL will provide further data for the designer with regard to long term storage effects in vacuum on engineering interfaces. The test programme will employ high contact stress levels and will measure the adhesion forces when separated in vacuum. The first investigation will be aimed at determining the contact stress level, if any, at which static adhesion can be expected for various material combinations.

3) Further tests over extended duration periods will be considered, as well as the possibility of investigating the sensitivity to other contributory factors, e.g. surface finish.

4) The most likely cause of seizure in clamped interfaces is due to the removal of the oxide layer and the adhering of nascent material. This condition is most likely to occur when fretting motion is present even for short periods.

5) The investigation of static adhesion following fretting motion, more commonly known as galling, in vacuum is the area of research still largely waiting to be addressed.

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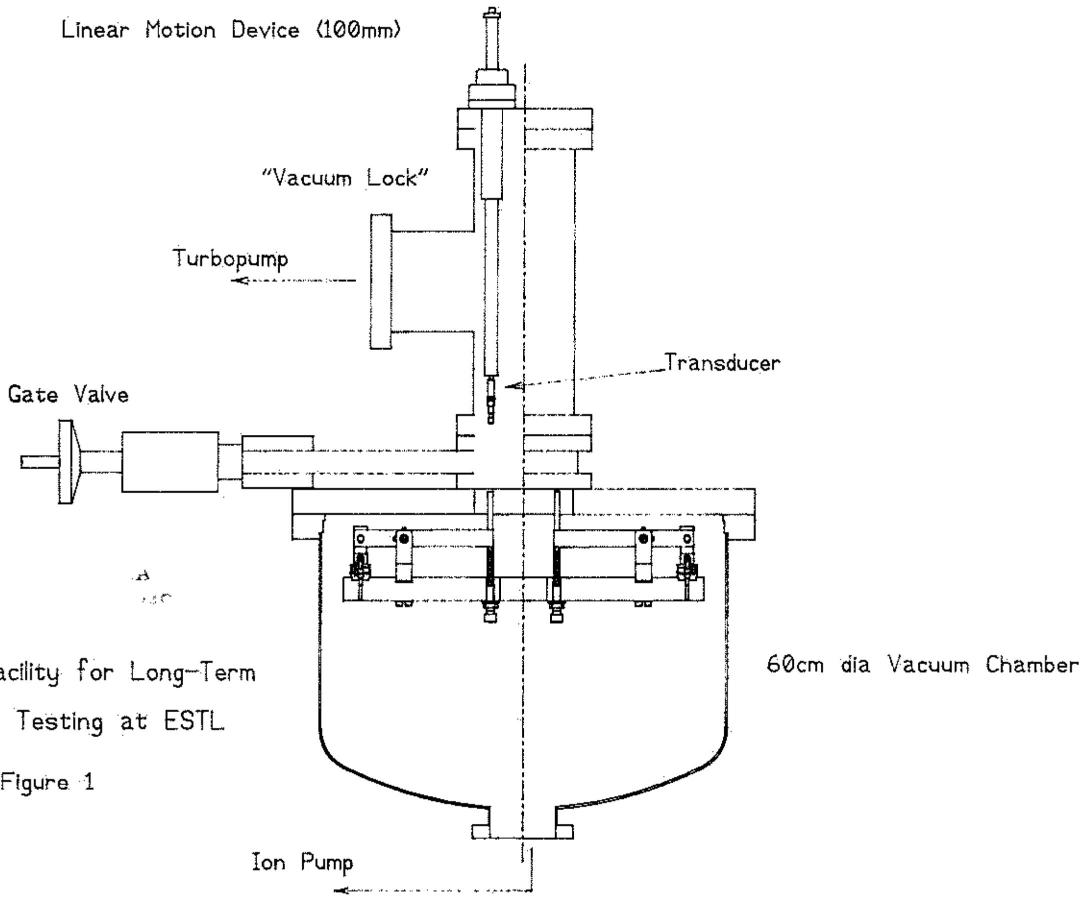
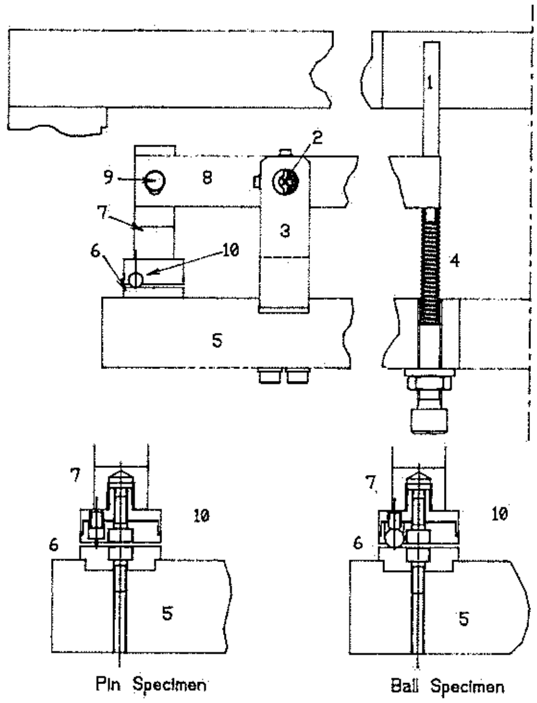
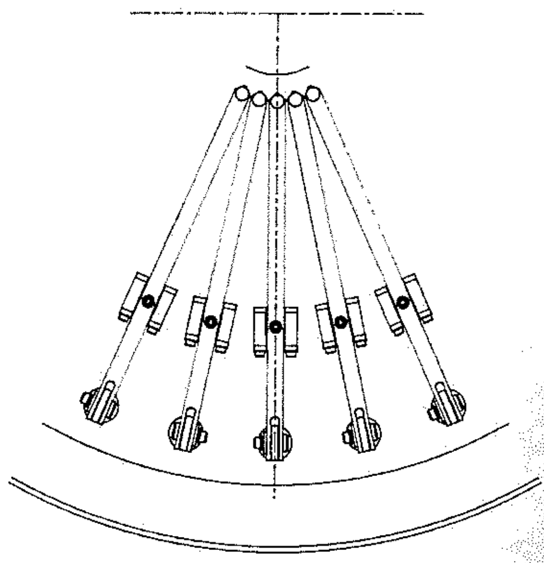


Layout of Facility for Long-Term Storage Testing at ESTL

Figure 1



Adhesion Measurement Mechanism (Pin and Ball Specimens)
Figure 2



Plan View of ESTL Test Facility
Figure 3