INFLUENCE OF IMPACT PARAMETER AND COATINGS ON COLD WELDING DUE TO IMPACT UNDER HIGH VACUUM

A. Merstallinger, E. Semerad, B. D. Dunn *
Austrian Research Centre Seibersdorf, A-2444 Seibersdorf/Austria
phone: 0043 2254 780 - 3328, fax: -3366, andreas.merstallinger@arcs.ac.at
* Materials and Processes Division, ESTEC, Noordwijk/The Netherlands

ABSTRACT

A variety of engineering mechanisms exhibit ball-to-flat surface contacts which are periodically closed for several (thousands of) times. The 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-welding.
A specially designed laboratory apparatus - called the "impact facility", has been fabricated at the Austrian Research Centre (ARC) and used to investigate the influence of the two main parameters likely to cause "cold-welding" . These are: 1 the impact energy, and 2) the static load, which determine whether the surfaces under test will "cold-weld" together. The adhesion force, i.e. the force required to re-open the "cold-welded" contact, was measured after each contact cycle. Experiments with stainless steel (type 17-7 PH) in contact with itself under vacuum will be presented. It was found that the adhesion force increased directly with an increase in static load. Under impact conditions, with energies greater than the Hertzian limit, no significant relationship was found between impact energy and adhesion force. Further "cold-welding" experiments were conducted on various pairs of metals. These have enhanced our knowledge of the behaviour of coatings, such as TiC or MoS_2-film on stainless steel. Additional results will compare the ability of MoS_2 to lower the adhesion force between materials when it is present either as a surface film, or present within the microstructure of the composite materials Ag15MoS_2 and Vespel SP3. A final model will be demonstrated in order to show how results from the ARC equipment can be compared to those laboratory results generated by a different test equipment that was independently fabricated by the company CSEM.

1. INTRODUCTION

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 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.
As discussed in previous papers, e.g. [1], contact situations may be classified in three different types: static, impact and fretting. The amount of destruction of surface layers increases in order mentioned above. This is followed by increasing adhesion forces. Fig. 1 shows a comparison of adhesion forces due to the three different contact types in a Ti(IMI834)-SS440C pairing [1]. In fretting conditions the maximum adhesion force was found to be 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).

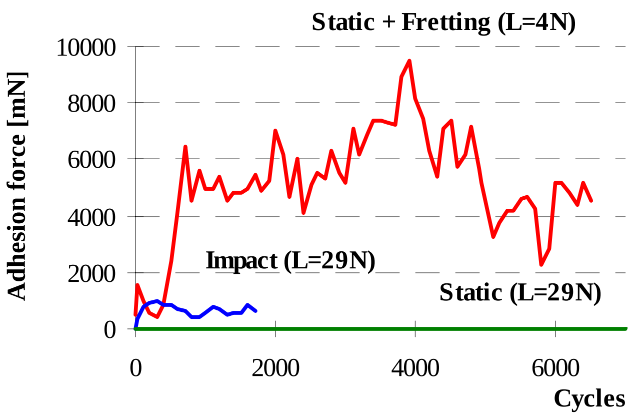

Fig.1 Comparison of adhesion in static (load 29N), impact (load 29N) and fretting (load 4 N) condition under vacuum. Immediate adhesion in fretting, increase in impact. (Max. adhesion in static 0.1 N after > 25,000 cycles, in impact 0.96 N, in fretting 9.5 N.)

Consequently contaminant layers (oxides) are removed 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. A failure due to blocking under impact condition was reported with an adhesion force in the range of 0.3 N. This could be confirmed by impact testing [2]. Surveying, several impact tests including also a study recently presented [1], an adhesion force in the range of 1 N can be expected for static loads in the range of the elastic limit and impact energies causing yield.
Results obtained by the authors are compared to studies on adhesion after cyclic impact under vacuum done by Maillat [3], [4] and a recent study by CSEM [5].

2. EXPERIMENTAL

Testing philosophy and parameters at ARCS

To enable comparison of cold welding tendency between different material pairings, the following testing philosophy was set-up at ARC (it is described in detail in an in-house specification of ARC [6]): the maximum adhesion forces are compared upon the parameters static load and impact energy with respect to elastic regime. Both are calculated acc. to Hertz' theory. Using the yield strength of the softer material, the "von MISES-criterion" defines an elastic limit (EL) for the contact pressure and a critical impact energy causing first yield (W_Y) [6], [7]. Acc. to ARC-standard the static load is selected to achieve a contact pressure of 40, 60 and 100%EL. This is done within one test to reduce testing effort. (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.) Impact energy is herein chosen to enable comparison to CSEM-results.
At ARCS special facilities [6] were set-up for this purpose based on loading by electromagnets. This enables to select static load and impact energy independently. An additional set-up also enables introduction of fretting [1]. PC-control and data acquisition enable to record adhesion force at each lift-off and to achieve resolutions down to 1 mN.
The main parameters varied, were the static load and the impact energy. Table 1 (Annex) shows the pairings, as well as the parameters. Besides the static load given in [N], also the related contact pressure in [%EL], and the pin radius are given. Secondly, the impact energy (W) is given in relation (W/W_Y) to the critical impact energy (W_Y). The impact velocity is calculated using the mass of the pushrod. The material properties used for calculation are given in table 2. If no coatings were applied, the specimen were freshly ground to Ra<0.1µm before testing [6]. The contact is closed and opened for 10 seconds, each. At ARC the base pressure of vacuum was less than 5.10^{-8} mbar, i.e. surfaces are not recovered during opening. Tests were run for more than 5,000 cycles per load level, preceded by >5,000 cycles running in-phase. Adhesion was recorded at each opening.

Testing philosophy and parameters at CSEM

Philosophy of CSEM, to define the impact, was to measure the maximum force occurring during impact. CSEM-impact parameter refers to the relation between the contact pressure caused by the actual impact force and the yield strength of the softer material (Y_S) and is given in [%Y_S].
Herein, a vacuum tribometer was adopted. The selected impact energy was obtained by adjusting the dead weight and controlling the impact speed. By this way, the static load results from the dead weight and can neither be independent selected nor changed during test without breaking vacuum. The contact was closed for and opened for 10 seconds, too. Vacuum level was only approx. 10^{-7} mbar. Data acquisition was done manually, i.e. only about 30 data points out of 10.000 cycles were recorded with a resolution of 50 mN.
To enable comparison to ARCS-parameters and results, the authors set up a simplified numerical model of the adopted tribometer and calculated the impact energies for the tests done at CSEM. (Hence, in the table 1 in the annex, the CSEM-parameter "CSEM-Press." is added to the impact energy values.) To set up comparability of test results, impact parameters were chosen to fit to CSEM-tests.

3. RESULTS

Comparability of testing between ARCS and CSEM

Setting up the model showed, that the values 100%Y_S, 200%Y_S and 300%Y_S refer to impact energies of 1, 12-49 and 200 times the critical impact energy. (Compare table 1, columns "CSEM-Press." and W/W_Y.) At 200% the impact energy shows a direct correlation to the hardness of materials.

Influence of impact energy and static load

Influence of impact energy and static load were evaluated from results on SS17-7 PH versus itself (without coating). Fig. 2 shows a plot of the maximum adhesion obtained at the static load levels 40, 60 and 100%EL at a test with impact at 49 W/W_Y (CSEM: 200%), white bar, and at 200 W/W_Y (CSEM: 300%), black bar. The adhesion force increases with static load level.

No correlation of impact energy (49 W_Y or 200 W_Y) to adhesion is detectable: at 40 and 60%EL the adhesion force at low impact energy is lower than that for higher impact energy, and at 100% EL it is higher (Fig. 2.). This independence is underlined by the fact that the measured contact areas are similar: 0.18 and 0.22 mm^2. (Both impact energies exceed the critical energy causing yield.)

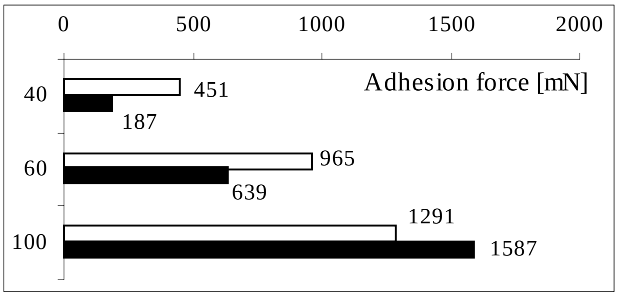

Fig.2 Adhesion force as function of static load (in %EL) and impact energy (49 W_Y , 200 W_Y <). Adhesion increases with static load. No influence of impact energy is visible.

Influence of coatings

Two coatings (only on the disc) were investigated for their ability to reduce adhesion, TiC and MoS_2. Fig. 3 shows that TiC reduces adhesion forces to about 25-30% with respect to un-coated pairing. In case of MoS_2, only some few cycles showed adhesion. However, adhesion of 103 mN (~0.1 N) is very low. From these results, already a general advantage of soft lubricant layers may be concluded from their higher ability of re-distribution at each impact.

MoS_2 coatings versus MoS_2 composites

The study included also two composites materials containing 15v% MoS_2 each (see table 2): Vespel SP3 (Polyimide) and a silver alloy "AgMoS_2". Vespel shows negligible adhesion. The silver alloy shows some small adhesion 117 mN. 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 no metal is present but, on the other hand, silver has very low shear strength, i.e. bonds are easily broken.

Steel versus Aluminium

From Fig. 4, adhesion between SS17-7 PH and Al AA 7075 (each versus itself) can be compared: adhesion of Al7075 versus Al7075 is slightly higher (1744 mN) than for SS17-7 PH vs. SS17-7 PH (1587 mN). From experience, aluminium should be much more prone to adhesion. This can be seen, if the bond strength of the contact is compared (i.e. the adhesion force divided by the contact area measured by SEM): Al-Al shows a bond strength of 0.65% with respect to its yield strength, and SS17-7 PH versus itself only 0.36%, which is approx. half the value of Al-Al.

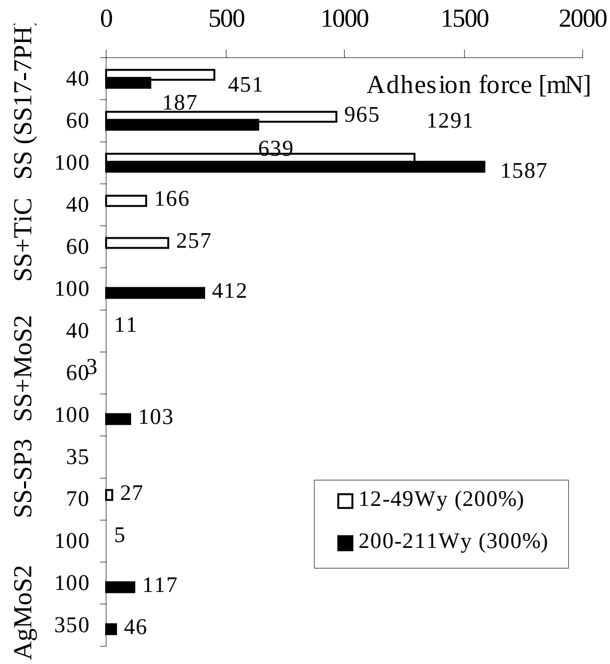

Fig.3 Adhesion force as function of static load (in %EL) and impact energy (SS = SS17-7PH). Coatings on discs (TiC and MoS_2) reduce adhesion. MoS_2 acts in both types: as coating and in composites.

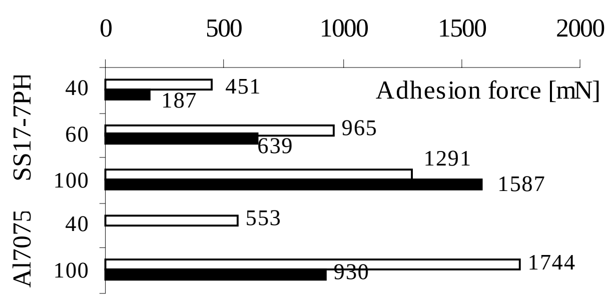

Fig.4 Adhesion force as function of static load (in %EL) and impact energy (49 W_Y , 200 W_Y <). Comparison of SS17-7PH and Al AA7075 (Al7075). In terms of bond strength, Al sticks to itself twice as strong as SS17-7PH.

Inter-laboratory comparison of adhesion force

The most right columns of table 1 show a comparison of the maximum adhesion forces for all tests obtained by ARC and CSEM. The main visible effects should be an increase of adhesion force with static load (see also fig. 2), and that aluminium versus itself must show some adhesion force. (Even under static conditions aluminium was found to show measurable adhesion forces, 120 mN

[8].) However, test results of only 0 and 300 mN are reported [3], [4], [5].

Besides that, running-in effects, found e.g. for SS17-7 PH versus SS17-7 PH+TiC or the SS17-7 PH versus Vespel are only detectable, if the adhesion force of all (!) cycles is acquired. This is also required for spiky behaviour of the adhesion force, i.e. adhesion forces increasing and vanishing within few cycles (found for hard coatings in case of break-through). Also in the case of the MoS_2–coating only few adhesion-"spikes" occurred, a mean value would be near zero.

4. CONCLUSION

The **first aim of this study** 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 two coatings (TiC and MoS_2 on SS17-7 PH) were investigated under impact conditions. The **second aim of this study** was to assess comparability (of parameters) and repeatability (of test results) between ARCS and CSEM.

Results on the steel-steel-pairing reveal a **direct relation between the static load and the adhesion force**. No unique and significant influence of the impact energy is detectable.

The experience that **Aluminium is more prone to adhesion** than harder metals like steel is shown: The relative bond strength of the Al-Al-pairing is calculated to be twice the value for steel-steel.

Generally, **coatings** reduce adhesion in case of impact. **Hard coatings** (TiC) may break and, therefore, adhesion is lower but still found. Adhesion forces up to 0.41 N were 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 (only 0.1 N). No running-in effects are visible.

Composites containing solid lubricants (polymer based, Vespel SP3, or metal (silver) based, both approx. 15v% MoS2) can be regarded as a second choice after solid lubricant coatings. However, low strength of the both matrix-materials could assist in having low adhesion.

The results were used to **update the in-house standard** [6] in that way, that the standard value of impact energy became 40 W_Y and the static load were fixed to 40, 60 and 100% of the elastic limit. These parameters shall be done within one test at durations of >5000 cycles running-in and >5000 for each load level.

Comparability to CSEM-test device was successfully set up. However, the relation between the impact force (measured by CSEM as base parameter) and the impact energy was found to be not unequivocal. This is assumed to be due to influence of the damping capacity of the contact bodies.

Repeatability (i.e. of results between different laboratories) cannot be stated, since the results differ strongly. Two main facts should be visible: increase of adhesion force due to static load (to be seen at the steel-steel-pairing) and that aluminium must show adhesion (even under static conditions [8]).

Hence, the ARCS-impact test device provides the necessary simulation capability and is able 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.

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ANNEX

Impact testing											
Parameter										Results	
Disc		Pin		(Static) Load		Impact				Max. Adhesion	
Material	Coating		Radius [mm]	[N]	Cont. Press. [%EL]	CSEM Press. [% Y_S]	ARC Energy W [J]	ARC Energy W/W_Y	Speed v [m/s]	ARC [mN]	CSEM [mN]
SS17-7 PH	-	SS17-7 PH	2	2.9	38	100%	7.0E-5	1	0.02	-	0
			2	3.3	40	200%	4.0E-3	49	0.13	451	0
			2	10.9	59	200%	4.0E-3	49	0.13	965	-
			2	53.0	100	200%	4.0E-3	49	0.13	1291	-
			2	3.3	40	300%	1.7E-2	200	0.26	187	-
			2	10.9	59	300%	1.7E-2	200	0.26	639	300
			2	53.0	100	300%	1.7E-2	200	0.26	1587	-
SS17-7 PH	TiC	SS17-7 PH	2	2.9	38	100%	4.7E-4	1	0.04	-	0
			2	2.9	38	200%	3.6E-3	44	0.12	166	300
			2	10.9	59	200%	3.6E-3	44	0.12	257	-
			2	53.0	100	300%	1.7E-2	200	0.26	412	-
SS17-7 PH	MoS_2	SS17-7 PH	2	2.9	38	100%	7.0E-5	1	0.02	-	0
			2	2.9	38	200%	3.6E-3	44	0.12	11	0
			2	10.9	59	200%	3.6E-3	44	0.12	3	-
			2	53.0	100	300%	1.7E-2	200	0.26	103	-
Al7075	-	Al7075	10.5	3.3	20	100%	4.0E-3	1	0.13	-	0
			3.65	3.3	41	200%	4.0E-3	35	0.13	553	0
			3.65	48.0	100	200%	4.0E-3	35	0.13	1744	-
			2	3.3	61	300%	4.0E-3	211	0.13	-	0
			3	33.0	100	300%	1.3E-2	200	0.23	930	-
Vespel SP3	-	SS17-7 PH	10.5	3.5	35	100%	6.0E-4	1	0.05	-	0
			3.65	3.5	70	200%	6.0E-4	12	0.05	27	0
			3.65	10.0	100	200%	6.0E-4	12	0.05	5	-
AG10Cu	-	Ag MoS_2	20	11.4	100		1.1E-3	200	0.07	117	-
			3	11.4	354		1.1E-3	60000	0.07	46	0

Table 1. Survey of test parameters and results: maximum adhesion force obtained by ARC and CSEM [3], [4], [5]. (Comparability of impact energy between ARCS and CSEM can be seen from the column "CSEM-press." where the value used by CSEM is given.) ("-" in column results means: no test performed.)

Material-Designation	Composition	Yield Strength [MPa]	Hardness Vickers [daN/mm²]	Young's Modulus [GPa]	Coating (only on disc)
Stainless Steel SS17-7 PH	17Cr 7Ni 1Al	2020	525	210	None, TiC, MoS_2
Al alloy AA7075	5.6Zn 2.5Mg 1.6Cu 0.3Cr	654	170	72	None
Vespel SP3	Polyimide – 15v% MoS_2	69	18	2.5	None
Ag10Cu	Ag 10Cu	620	150	82.7	None
$AgMoS_2$	Ag 15v% MoS_2	138	26	71	None

Table 2. Survey of materials used for test specimen. (The abbreviation "Al7075" is used for the Al alloy AA 7075.) The steel was hardened by CSEM acc. to a (non-standard) procedure [5].