REDUCTION OF COLD WELDING BY GEOMETRIC PARAMETERS

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ABSTRACT

Cold-welding and fretting are especially relevant regarding opening and closing of engineering mechanisms, either placed in vacuum or embarked on spacecrafts, because they condition the life of the mechanism and its proper functioning. Fretting may cause wear of materials and coatings which could lead to cold welding. To avoid this risk, the question has to be answered, whether to select smaller radius (risking higher wear leading to big contact area) or select a bigger radius (higher contact area at the beginning).

This paper presents the results of a study comparing these both solutions under fretting contact using a steel-steel-contact which is known to cold weld. Different contact situations (geometry/contact pressure) were compared under “realistic” contact situations. Finally, a short introduction to the new “Cold-Weld-data base” will be given: it offers a collection of all cold welding data obtained so far and can be accessed via WEB.

1. INTRODUCTION

On spacecrafts, a variety of engineering mechanisms exhibit ball-to-flat surface contacts which are periodically closed for several (thousands of) times. Impact or fretting may 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".
Impact may lead to plastic deformation of the substrate, as contacts are often modelled only as static. This may lead to breaking of surface layers. Fretting wear may be caused by vibrations occurring during launch or during movement of e.g. antennas in space. Wear due to fretting was found to be much higher than due to impact and adhesion forces may increase by factor of ten compared to impact conditions !

In order to set-up experience in these effects, two special devices - called “impact facility” and “fretting facility” – were developed at AIT (formerly ARC Austrian Research Centers) 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. During a fretting test, the contact is closed softly and while being closed, fretting is applied to the contact. The adhesion force, i.e. the force required to re-open the contact, is measured at each opening.

Several studies have been performed in the past years, investigating the “materials influence”, i.e. different material combinations were tested, showing e.g. that stainless austenitic steels show higher adhesion than e.g. chromium steels, or that use of dissimilar materials show reduced adhesion. Several coatings were, investigated for their ability to prohibit cold welding. In most cases the coatings were broken under fretting, thereby setting free the metallic substrate. At this point, both metallic substrate come into contact, and adhesion between both contact partners start. Finally, the adhesion forces may exceed the available separation forces and the mechanism might be blocked by cold welding.

On the other hand, it would be expected that the separation force does not only depend on material only, but also on geometry (contact area). Adhesion forces are sometimes assessed on following basis: ultimate yield strength times contact area. Whereby, the contact area of ball-to-flat-contacts is calculated using Hertz theory. Following that, the adhesion forces in a ball-on-flat contact should decrease when using a smaller contact area. In development of mechanisms, mostly a load force is given. Following this “fixed parameter” in a ball-on-flat contact, for a smaller radius Hertzian theory predicts a smaller contact area than for a bigger radius. But the smaller radius also leads to a higher contact pressures. This on the other hand is expected to cause higher wear, if fretting occurs.

Hence the question arises, whether to select smaller radius (risking higher wear leading to big contact area) or select a bigger radius (higher contact area even at beginning).

[1] ARC Austrian Research Centers changed its name into AIT Austrian Institute of Technology by June2009

2. DESCRIPTION OF TEST METHOD

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 AIT (it is described in detail in an in-house specification of AIT [1]): 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 [1], [2]. Based on parameter studies [3], [4], 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 [1]. 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. (See Fig.1.)

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” [5], 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 AIT-in-house-specification [1], can be used to address the necessary opening forces for actuators in mechanisms. (Both, impact and fretting test are done at 60% EL.)

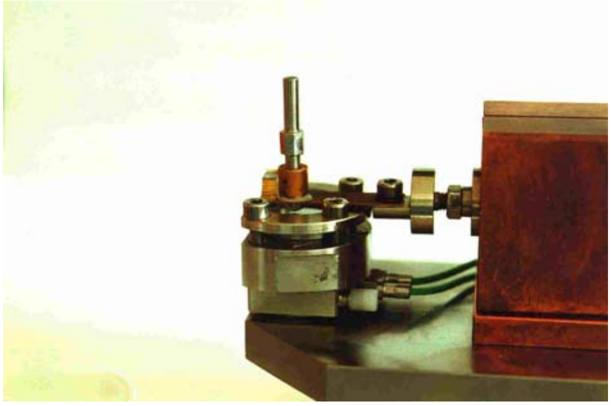

Fig.1 Fretting device: Detail showing the fixation of pin (upper rod) and disc (mounted directly on a force transducer). Right side: piezo actuator for generation of fretting movement.

3. 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”.

Basic studies [4] by AIT have shown that under impact conditions, an increase of the static load lead to an increase of the adhesion force. Fig. 2 shows the adhesion forces found for stainless steel SS17-7ph in contact to itself (ball on flat contact, without any coating). The three bars refer to the measured adhesion under static loads related to contact pressures of 40, 60 and 100% of the elastic limit. It can be seen that the adhesion forces increases with the contact pressure, when impact occurs (no fretting).

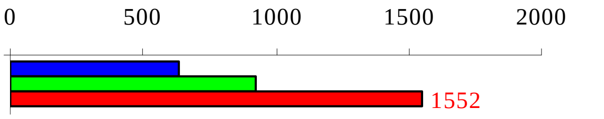

Fig.2 Adhesion forces of steel SS17-7ph versus itself (uncoated) under impact, adhesion increases with static load, i.e. contact pressures 40-60-100%EL

On the other hand, studies investigating adhesion under fretting have shown strongly severe wear. Fig.3 shows images from impact (left) and fretting (right). Impact leads only to some plastic deformations, leading to adhesion forces not higher than 2 Newtons. Fretting, however, causes severe surface damages leading to adhesion forces of several sometimes more the 10 Newtons. Fig.4 shows a comparison of some typical space material in contact to themselves.

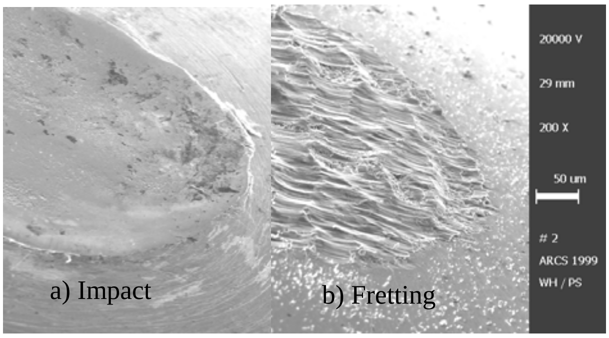

Fig. 3 Surface of a pin (SS17-7ph) after impact and fretting. Impact: only some plastic flow visible by piling up of edges. Fretting: strong destruction of surface, adhesive wear combined with high adhesion forces (Compare to Fig.3 for adhesion forces: "SS17-7".)

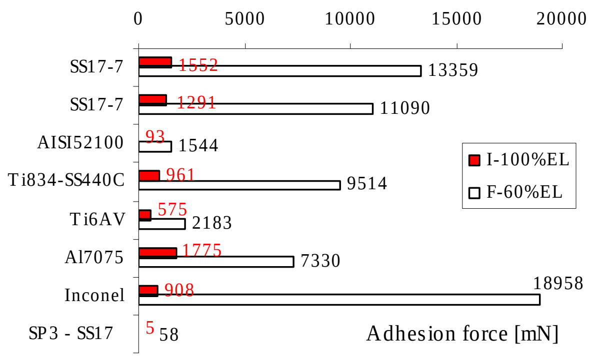

Fig.4 Comparison of adhesion force under impact (I) and fretting (F): Adhesion between metals under fretting are up to tenfold higher than under impact. Highest adhesion for Ti, Al-alloys, stainless steels containing Ni and Ni alloys (Inconel 7l8). No adhesion between polymer composite (VESPEL SP3: Polyimide with 15m% MoS_2) and steel (SS 17-7PH).[6]

Hence, 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. 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 a mechanism under impact condition was reported with an adhesion force in the range of 0.3 N [7]. In fretting conditions the adhesion forces may reach several tens of Newtons. Hence, adhesion forces are in a range that can lead to failure of mechanisms.

4. PHILOSOPHY OF STUDY

The objective of this study was to investigate, if contact pressure and contact area have influence on the adhesion force under fretting conditions.

Therefore, a set of 4 test parameters was selected with varying load and pin radius (i.e. curvature of spherical pin tip). Table 1 shows the test parameters. Three tests were done at load of 1 N with radii of 1, 2 and 15mm. This is related contact pressures of 118, 57 and 19% of the elastic limit. One test was done as similar contact pressure of 58%EL, but using a different combination of radius (10mm) and load 12N. (See fig.5 a,b.) For all tests the same material combination was selected: AISI316L in contact or itself without any coating. This is a stainless austenitic steel, which was already tested previously and shows high adhesion forces. Three parallel tests were done for each set of parameters. (For materials properties refer to table in annex. The calculations of contact pressures were done using standard Hertzian theory, see e.g. [2].)

Tests	Tip Radius mm	Load N	Contact pressure MPa	Contact pressure in % EL
F1x	1	1	1272	118
F2x	3	1	611	57
F3x	10	12	209	58
F5x	15	1	627	19

Table 1 Test parameters: three parallel tests per set

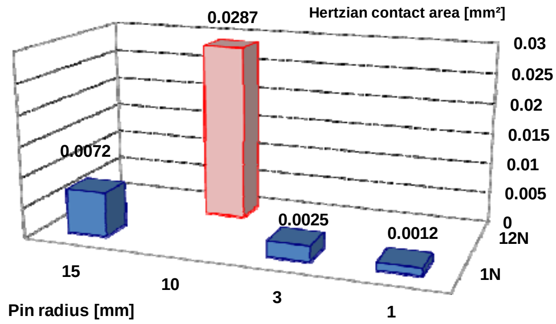

Fig5a Test parameters: contact areas calculated by Hertz.

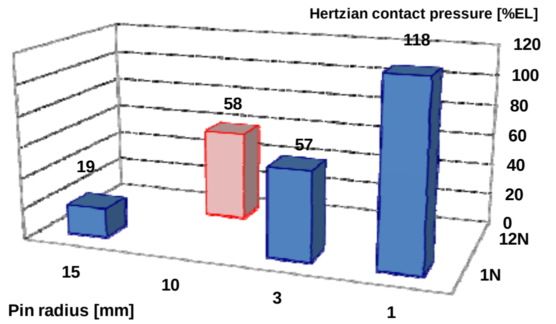

Fig.5b Test parameters: contact pressures calculated by Hertz.

5. MODELLING AND ENGINEERING

Theoretical estimation of adhesion forces (1)

Theoretically, adhesion forces could be calculated on following basis: ultimate yield strength times contact area. Whereby, the contact area of ball-to-flat-contacts is calculated using Hertz theory. Following that, the adhesion forces in a ball-on-flat contact should decrease when using a smaller contact area. The values for the stainless steel AISI316L versus itself are shown in Fig.6. It can be seen that, the (theoretical) adhesion force is directly related to the contact area (Fig.5a.).

Important drawbacks of model: surface and wear

The above mentioned approach ignores two important facts:
Cleanliness of surfaces: the surfaces of conventional metal are covered with reaction layers and they are rough. Hence, the above mentioned contact area is wrong: the "real" contact area is much smaller due to roughness and due to the fact that bigger part of the surface is not metallic clean and will not contribute to adhesion force. However, this advantageous reduction of adhesion force cannot (!) be predicted.

On the other hand, the contact area is changing due to fretting wear: it increases strongly. This amount is also not predictable.

Hence, the experimental tests are necessary to measure adhesion forces.

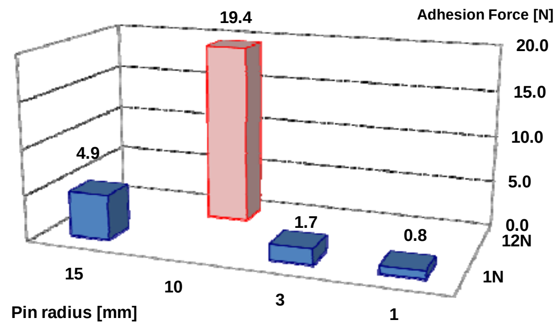

Fig.6 Adhesion forces: calculated using Yield strength times Hertzian contact area.

Engineering dilemma

In development of mechanisms, mostly a load force is given. Following this "fixed parameter" in a ball-on-flat contact, for a smaller radius Hertzian theory predicts a smaller contact area than for a bigger radius. But the smaller radius also leads to a higher contact pressures. This on the other hand is expected to cause higher wear, if fretting occurs.

Hence the question shall now be answered, whether to select smaller radius (risking higher wear leading to big contact area) or select a bigger radius (higher contact area even at beginning).

6. RESULTS OF TESTS

For each set of parameters three parallel tests were done. Averaged values for each set of parameter are shown in fig.7. Adhesion forces are generally high but expected for this material. The only significant difference is seen for the smallest contact area (pin radius 1mm at 1N). Here the adhesion force is slightly lower (6,2N).

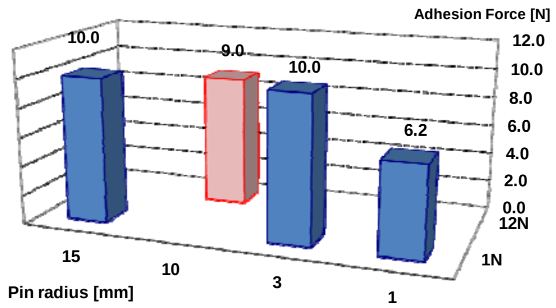

Fig.7 Adhesion forces: measured values (average value of three parallel test, uncertainty of test method 30%).

On the other hand, fretting wear leads to an increase of the contact area. Fig.8 shows that the contact area of the test with the higher load is remarkably higher than the other tests. Hence, wear is higher for higher loads, even if the contact pressure is comparable: ~58%EL similar for radius of 10mm and load of 12N to radius of 3mm and load of 1N.

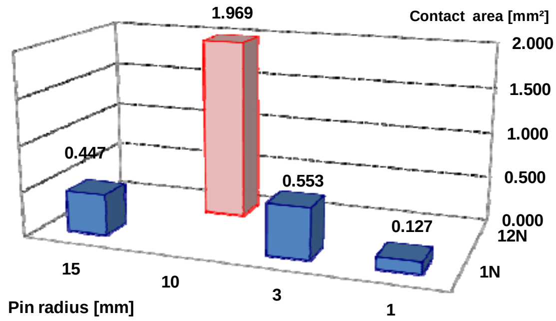

Fig.8 Contact area after fretting test: measured contact area after the test (average value of three parallel tests).

7. DISCUSSION

Estimation of Adhesion forces (2) using wear area

It may also be considered to estimate the adhesion force by yield strength times the wear contact area, e.g. using the measured wear contact area after a friction test. The results is shown in fig.9: the contact area measured after the fretting tests were multiplied with the yield strength.

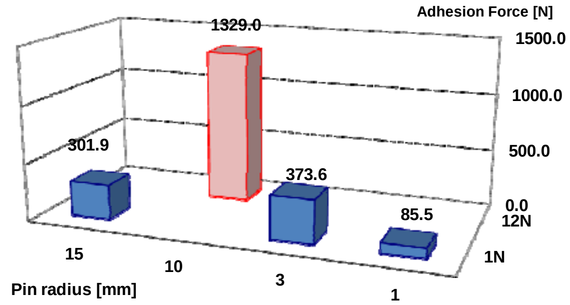

Fig.9 Adhesion forces: calculated using Yield strength times wear contact area, i.e. the contact area measured after the fretting test.

Comparison of theoretical and experimental results

Adhesion was derived by three methods:

1. Theory: calculation by yield strength times Hertzian contact area (fig.6), this would lead to the conclusion that smaller radii are preferable. Neglecting any wear, Hertzian theory gives a smaller contact area.

2. Semi-Theory: yield strength times measured wear contact area, i.e. use of the wear contact area which is measured after a fretting test (Fig.9). The derived values for the adhesion force are similar to approach 1. The conclusion would be similar to the approach 1-Theory: use smaller radius. Even though the contact pressure is higher than the EL, the wear does lead to a smaller contact area when the tip radius is smaller. However, starting with contact pressure higher than EL is still no issue.

3. Experimental: measured adhesion forces are quite comparable for all parameter sets. They do not show significant influence of initial contact details (fig.7). Smaller contact radius seems to be advantageous, the adhesion force is slightly lower (average 6,2N compare to approx. 10N for all other tests).

It is clearly visible that both theoretical and semi-theoretical extrapolations do not fit to the experimental behaviour. The main reason is seen in the fact that the definition and determination of the "contact area" is insufficient: the theoretical approaches reveal a "nominal contact area", but the adhesion is related to what shall be referred to as "real contact area":
The real contact area, i.e. the area where metallic bonds actually exist, is much smaller than the nominal one predicted by theory. This is due to the surface roughness and the surface contamination. Both factors reduce the measured adhesion forces by orders of magnitude (compare fig.7 and fig.9). Using theoretical approaches, at a load of 12N the highest adhesion should be found (fig.6 and 9.). Even this overall

tendency is not found in experimental testing (see fig.7). Wear due to fretting is levelling out the contact pressure to values in a range of few MPas.
Hence, adhesion forces cannot be “modelled” since neither the “real contact area” nor fretting wear are predictable.

8. CONCLUSION

In development of mechanisms, mostly a load force is given. Following this “fixed parameter” in a ball-on-flat contact, for a smaller radius Hertzian theory predicts a smaller contact area than for a bigger radius. But the smaller radius also leads to a higher contact pressures. This on the other hand is expected to cause higher wear, if fretting occurs.

The **aim of this study** was to answer the question, whether to select smaller radius (risking higher wear leading to big contact area) or select a bigger radius (higher contact area even at beginning).

Three approaches were compared, two of them based on theoretical extrapolation of adhesion forces. The third was determination by experiments on basis of an AIT-in-house-standard formerly agreed with ESTEC.

It was shown, that both the **theoretical predictions were by far not comparable** to experimental data. The main reason is seen, that the adhesion is driven by the “real contact area” which cannot predicted, e.g. hertzian theory would predict a “nomial contact area” neglecting surface roughness and surface contamination. Especially, the latter has the main contribution and keeps unpredictable.

Regarding the **question big/small radius, no significant tendency** was determined from experimental data. Due to wear, in all parameter sets a similar contact pressure arises (typically a few MPas).

Hence, the AIT devices can offer the appropriate experimental capability to make a step forward in cold-welding effects from „common experience“ to measurable numbers, useful for designers of spacecraft applications.

In order to assist engineers with experimental data, a **new internet data base** was set up by AIT. It collects all data generated from all studies performed for ESTEC. It can be accessed free of charge after registration: http://service.arcs.ac.at/coldwelddata. (See annex)

REFERENCES

[1] 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).

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

[3] 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.

[4] 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.)

[5] 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.

[6] Merstallinger A.; Semerad E.; Dunn B.D.; “Influence of coatings and allyoing on cold welding due to impact and fretting”, 10th Europ. Space Mechanisms & Tribology Symposium, San Sebastian, Proceedings ESA SP-524, 2003.

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

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