COLD MOLECULAR WELDING STUDY

GPO PRICE $ ______

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Hard copy (HC) $3.00

Microfiche (MF) .65

ff 653 July 65

FINAL REPORT
June 15, 1966 - June 14, 1967

Contract No. NAS9-3623
MRI Project No. FS-132-E

FACILITY FORM 602

N67-31501
(ACCESSION NUMBER)

15
(PAGES)

[redacted]
(NASA CR OR TMX OR AD NUMBER)
CR-65661

(THRU)

1
(CODE)

15
(CATEGORY)

For

NASA Manned Spacecraft Center
Advanced Spacecraft Technology Division
Houston, Texas 77058

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by

C. Eugene Moeller
Michael Noland

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PREFACE

This report covers the activities conducted on MRI fundamental study program FS-132-E, and fulfills the requirements of a no-cost extension on NASA Contract NAS9-3623, MRI Project 2817-E.

The work was conducted in the Materials Section of the Engineering Division under the technical supervision of Mr. Vern Hopkins. Mr. Gene Moeller was the project leader. The experimental work was conducted by Mr. A. J. Bossert. Mr. Michael Noland assisted in analyzing the data and coauthored the report with Mr. Moeller.

Approved for:

MIDWEST RESEARCH INSTITUTE

Harold L Stout

Harold L. Stout, Director
Engineering Division

5 July 1967

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I. INTRODUCTION

Cold molecular welding is the adhesion or cohesion of two materials at temperatures significantly below their melting points. Careful consideration of possible cold welding phenomenon is important in the design of equipment for operation in the space environment. This report presents the results of a program conducted to obtain a better understanding of experimental techniques for the evaluation of cold welding and to investigate the effects of certain test parameters not studied in the cold molecular welding study in ultrahigh vacuum recently conducted under NASA Contract No. NAS9-3623.

In the program discussed herein, the cold molecular welding characteristics of beryllium-copper pellets on 321 stainless steel wear plates were studied. The program consisted of four investigations:

1. The reproducibility of test results under identical experimental conditions;

2. A comparison between sliding tests in ultrahigh vacuum, dry air, and ambient air;

3. The effect of alternate sliding and resting of the metal couples for sliding durations between stops of one revolution and one-twelfth revolution; and

4. The effect of time at rest on the static coefficient of friction.

II. BACKGROUND

The cold molecular welding tendency of 45 metal combinations was studied under static and dynamic conditions in an ultrahigh vacuum environment on NASA Contract No. NAS9-3623.[1] Nine metals were investigated: 2014-T6 aluminum, Ti-6Al-4V titanium alloy, beryllium copper, electrolytic grade copper cobalt, 321 stainless steel, René 41 (nickel-base superalloy), E52100 steel, and coin silver. The coefficient of friction was measured in a test apparatus which consisted of pellets mounted in a rigid holder and resting or being rotated on a horizontal wear plate. The static coefficient of friction was measured at breakaway after contact for 300 hr.

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[1] "Cold Molecular Welding Study in Ultrahigh Vacuum", Final Report, Contract No. NAS9-3623, 8 October 1964 - 17 December 1965.

at a temperature of 200°C. The dynamic coefficient of friction was measured at a rotational velocity of 0.4 in/sec. Each metal was tested against itself and against each of the other metals.

For most of the metal combinations tested in this previous program, the maximum dynamic coefficient of friction was greater than the static breakaway value. With the exception of cobalt, very little correlation was found between the tendency of the metals to cold weld (as indicated by the coefficients of friction) and their physical properties. The data were taken from single tests with each metal combination; hence, it was desirable to conduct duplicate tests to determine the reproducibility of the data. In addition, the number of influential parameters which could be investigated under NASA Contract No. NAS9-3623 was limited, and so it was apparent that valuable information could be gained by a study of the effects of other variables. Therefore, the program presented in this report was initiated.

III. EXPERIMENTAL RESULTS

Measurements of the coefficient of friction on static breakaway and dynamic rotation of beryllium-copper pellets on a stainless steel wear plate were made using the experimental arrangement employed under NASA Contract No. NAS9-3623. The chemical composition and method of preparation of the specimens were the same as that described in Reference 1.

A. Reproducibility Tests

Repeated tests were conducted with beryllium-copper pellets on a 321 stainless steel wear plate to determine the reproducibility of the data. Six tests were conducted at a pressure of 10^{-9} torr with 1,000 psi contact pressure and a wear plate temperature of 200°C. The relative sliding velocity during the dynamic portions of the tests was 0.4 in/sec. The results are presented in Table I. The breakaway friction was measured after 16 hr. of static contact. The data obtained for the beryllium-copper/321 stainless steel pair in the previous program are presented for comparison.

B. Tests in Atmosphere

The effect of moisture content in the environment upon cold molecular welding tendencies was investigated by conducting tests in dry air ($<$ 10 percent relative humidity) and ambient air (40-60 percent relative humidity). Data from these tests are presented in Table II.

TABLE I

COLD WELDING REPRODUCIBILITY TESTS - 10^{-9} TORR

Three Beryllium-Copper Pellets on SS321 Plate
1,000 psi Contact Pressure
Plate Temperature 200°C
Velocity 0.4 in/sec

Test	Break-away Friction	Sliding Friction first 30°	Sliding Friction 0 to 0.5 hr.	Sliding Friction 0.5 to 5 hr.	Sliding Friction 5 to 24 hr.
R1	0.5	0.5 - 0.6	0.9 - 3.1	0.6 - 2.0	0.4 - 2.8
R2	1.5	0.5 - 0.6	0.4 - > 4.9 (32 min.)	-	-
R3	0.5	0.5 - 0.6	0.4 - 0.9	0.4 - 1.0	0.4 - 0.7
R4	0.5	0.6 - 0.7	> 4.9 (10 min.)	-	-
R5	3.1	0.4 - 0.5	0.6 - 2.7	0.4 - 2.3	0.4 - 2.8
R6	0.7	0.4 - 0.9	> 4.9 (15 min.)	-	-
*	0.7	-	0.2 - 0.8	0.3 - 1.0	Test Interrupted By Loss of Contact Between Test Surfaces

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* Data from initial studies.

TABLE II

COLD WELDING TESTS IN ATMOSPHERE - 760 TORR

Three Beryllium-Copper Pellets on SS321 Plate
1,000 psi Contact Pressure
Plate Temperature 200°C
Velocity 0.4 in/sec
Tests A1 - A3 - Air with Relative Humidity 40 - 60 percent
Tests DA1 - DA3 - Air with Relative Humidity < 10 percent

Test	Break-away Friction	Sliding Friction first 30°	Sliding Friction 0 to 0.5 hr.	Sliding Friction 0.5 to 5 hr.	Sliding Friction 5 to 24 hr.	Comments
A1	0.8	0.6 - 0.8	0.6 - 1.3	0.6 - 1.3	0.6 - 1.3	Pellets worn away at 17 hr.
A2	0.9	0.6 - 0.9	0.6 - 1.1	0.6 - 1.1	-	Pellets worn away at 4.5 hr.
A3	0.7	0.6 - 0.7	0.4 - 0.9	0.4 - 0.6	-	Pellets worn away at 6 hr.
DA1	0.6	0.6 - 0.8	0.4 - 0.8	-	-	Pellets worn away at 0.5 hr.
DA2	0.7	0.7 - 0.8	0.5 - 1.2	-	-	Pellets worn away at 0.6 hr.
DA3	1.0	0.8 - 1.0	0.5 - 1.4	0.2 - 1.00	-	Pellets worn away at 4.5 hr.

C. Intermittent Sliding Tests

The effect of alternate sliding and resting of the metal couples was studied to evaluate a wear sequence not investigated in the previous study. The tests were conducted by placing the pellets in contact with the wear plate for 24 hr. before initial static breakaway friction was measured. Sliding friction was measured during either one or one-twelfth revolution depending upon the particular test. This was followed by another 24-hr. period of rest and the sequence was repeated. Six tests were conducted with one revolution between resting periods and four with dynamic periods of one-twelfth revolution. All intermittent sliding tests were conducted at a pressure of 10^{-9} torr, 1,000 psi contact pressure, 200°C wear plate temperature, and a 0.4 in/sec sliding velocity during the sliding period. The data are presented in Table III.

D. Effect of Static Contact Time

The effect of time at rest on the initial breakaway friction and the subsequent sliding friction was investigated by tests at a pressure of 10^{-9} torr. The beryllium-copper pellets were statically held on the 321 stainless steel wear plate at 200°C with a contact pressure of 1,000 psi for times ranging from 25 hr. to 1600 hr. The breakaway friction was determined at the initiation of sliding and the sliding friction was measured for the next 24 hr. or until a condition of excessive friction occurred. The data are given in Table IV.

IV. DISCUSSION OF RESULTS

The values of breakaway friction in the reproducibility tests exhibit good agreement in four cases but have larger values in the other two tests. Sliding friction during the first 30° of rotation shows close agreement between the tests in all cases. During this period of rotation the pellets are in contact with a clean, previously unworn wear plate. After the first revolution, however, the pellets move on a surface over which they have passed before. Subsequent sliding friction is unpredictable and reproducibility is then lost. The data of Table I indicate that if the coefficient of sliding friction does not exceed the limitations of the test apparatus (4.9) during the first 0.5 hr., a stable condition is achieved which prevails for the remainder of the 24-hr. test. However, the stable value of sliding friction varies appreciably between tests.

TABLE III

COLD WELDING INTERMITTENT SLIDING TESTS - 10^{-9} TORR

Three Beryllium-Copper Pellets on SS321 Plate
1,000 psi Contact Pressure
Plate Temperature 200°C
Velocity 0.4 in/sec

One Revolution

Test	Break-away Friction	Sliding Friction 360°	Break-away Friction	Sliding Friction 360°	Break-away Friction	Sliding Friction 360°	Break-away Friction	Sliding Friction 360°
I1	0.5	0.5 - 1.0	1.1	0.9 - 1.2	0.9	0.8 - 1.0	0.9	0.8 - 1.0
I2	0.5	0.4 - 0.9	0.7	0.6 - 0.8	0.7	0.6 - 0.9	0.9	0.6 - 0.9
I3	0.3	0.4 - 1.2	> 4.9	-	-	-	-	-
I4	0.4	0.4 - 0.7	0.8	0.6 - 0.9	1.0	0.9 - 1.0	0.8	0.5 - 1.0
I5	1.4	0.4 - 1.4	4.2	0.7 - 3.5	4.3	3.0 - 4.9	1.2	1.0 - 4.8
I6	0.4	0.3 - 0.8	0.6	0.5 - 0.9	0.6	0.4 - 0.8	0.9	0.4 - 0.8

One-Twelfth Revolution

Test	Break-away Friction	Sliding Friction first 30°	Break-away Friction	Comments
S1	0.5	0.5 - 0.8	-	Evidence of scrubbing on contact
S2	0.7	0.7 - 0.9	0.9	Evidence of scrubbing on contact
S3	0.9	0.8 - 0.9	1.6	Evidence of scrubbing on contact
S4	0.4	0.4 - 0.5	0.5	Evidence of scrubbing on contact

TABLE IV

COLD WELDING--EFFECT OF CONTACT TIME - 10^{-9} TORR

Three Beryllium-Copper Pellets on SS321 Plate
1,000 psi Contact Pressure
Plate Temperature 200°C
Velocity 0.4 in/sec

Test	Contact Time (Hours)	Break-away Friction	Sliding Friction First 30°	Sliding Friction 0 to 0.5 hr.	Sliding Friction 0.5 to 5 hr.	Sliding Friction 5 to 24 hr.	Comments
T1	25	0.6	0.5	0.7 - 2.6	0.6 - 2.1	0.2 - 1.7	Some pits in plate, BeCu on plate
T2	50	0.5	0.6	0.8 - 1.8	0.6 - 1.3	0.6 - 1.4	Plate scarred, two-way transfer of metals
T3	100	0.8	0.6	0.2 - 1.4	0.2 - 0.9	0.2 - 2.4	Chattering very noticeable for entire run
T4	200	1.2	1.0 - 1.5	0.7 - 2.6	0.5 - 2.4	0.4 - 1.1	Some pits in plate, 1 pellet 90% of accumulated debris
T5	400	0.8	0.7	0.7 - 2.4	0.4 - 1.5	0.3 - 0.6	Many deep pits with BeCu on plate
T6	800	0.6	0.7 - 0.8	0.8 - 2.0	1.1 - 2.1	0.6 - 1.3	Many deep scars with BeCu on plate
T7	1600	0.7	0.5 - 0.6	> 4.9	One revolution	-	One deep scar, some BeCu on plate

The tests conducted in air, ambient with a relative humidity ranging from 40 to 60 percent and dry air with a relative humidity of less than 10 percent, indicate that humidity has no apparent effect on either the static or sliding coefficient of friction. However, as noted in Table II, the wear rate of pellets in ambient air appears to be less than in dry air.

The data from the intermittent sliding tests (Table III) show fairly consistent results. In the I - series, the pellets were in static contact with the plate for 24 hr., rotated one complete revolution, held static for 24 hr., etc., for four complete cycles. The data indicate that the coefficient of initial breakaway friction is in the range of 0.4 to 1.4. After rubbing the pellets over the plate, the coefficients for subsequent breakaways were considerably higher, 0.6 to $>$ 4.9. The coefficients for the third and fourth breakaway were nearly the same as the second; hence, the frictional pattern appears to become established as soon as the pellets begin sliding over previously rubbed surfaces.

The data from the four intermittent tests with only one-twelfth revolution (30 degrees in the S - series (Table III) indicate that movement on "clean" surfaces and subsequent breakaway from the "clean" increases the breakaway friction from the range of 0.4 to 0.9 to a range of 0.5 to 1.6. This increase is probably due to the rupture of the oxide layers on the surfaces by the mechanical action and the increase of contact surface by the smearing of the asperities of the surfaces. This series of tests permitted the examination of the contact regions between the pellets and the wear plate before the regions were obliterated by the subsequent rubbing action which occurred in all other test series. A view of the initial contact surfaces where one of the three pellets remained on the wear plate for 24 hr. is shown in Fig. 1. All the contact surfaces for the four tests were studied and an average of 50 points of contact were estimated for each contact surface of the pellet with the plate. The photomacrograph shows the deposits and grooves left by the asperities of the pellet surface when the pellet was moved. The difference between the deposits and the grooves is not apparent in Fig. 1 but is easily distinguished in the original color photograph. It should be noted that each groove in the wear plate starts from a deposit of the pellet material on the wear plate. Furthermore, Fig. 1 indicates that relative motion took place between the pellets and the plate when the pellets were being lowered onto the plate before the 24 hr. of static contact (Fig. 2 indicates the probable positions of the pellet on the plate). Thus, some smearing of the asperities occurred before the period of static contact.

The data of Table IV indicate that the duration of static contact time has no significant influence on initial breakaway friction. The

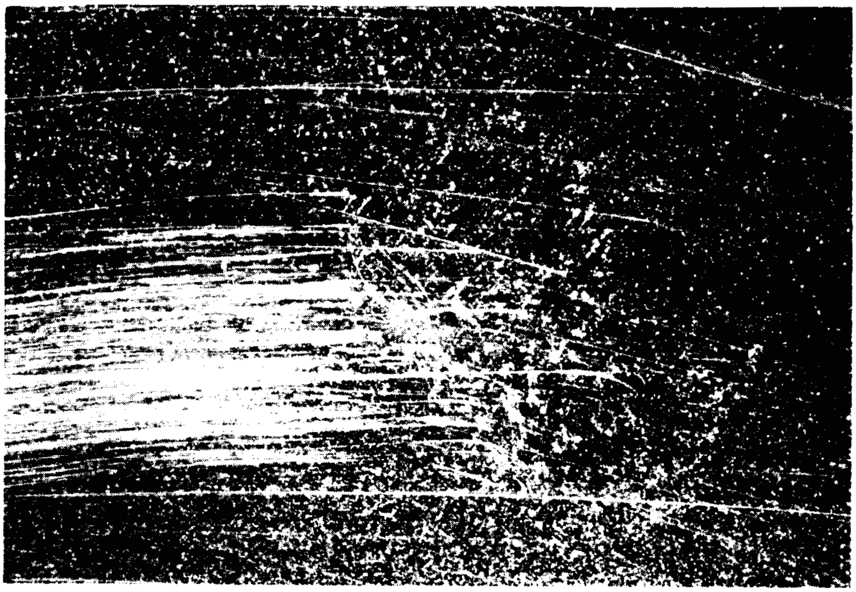


Fig. 1 - Photomacrograph of Wear Plate with Evidences of Movement of Pellet.

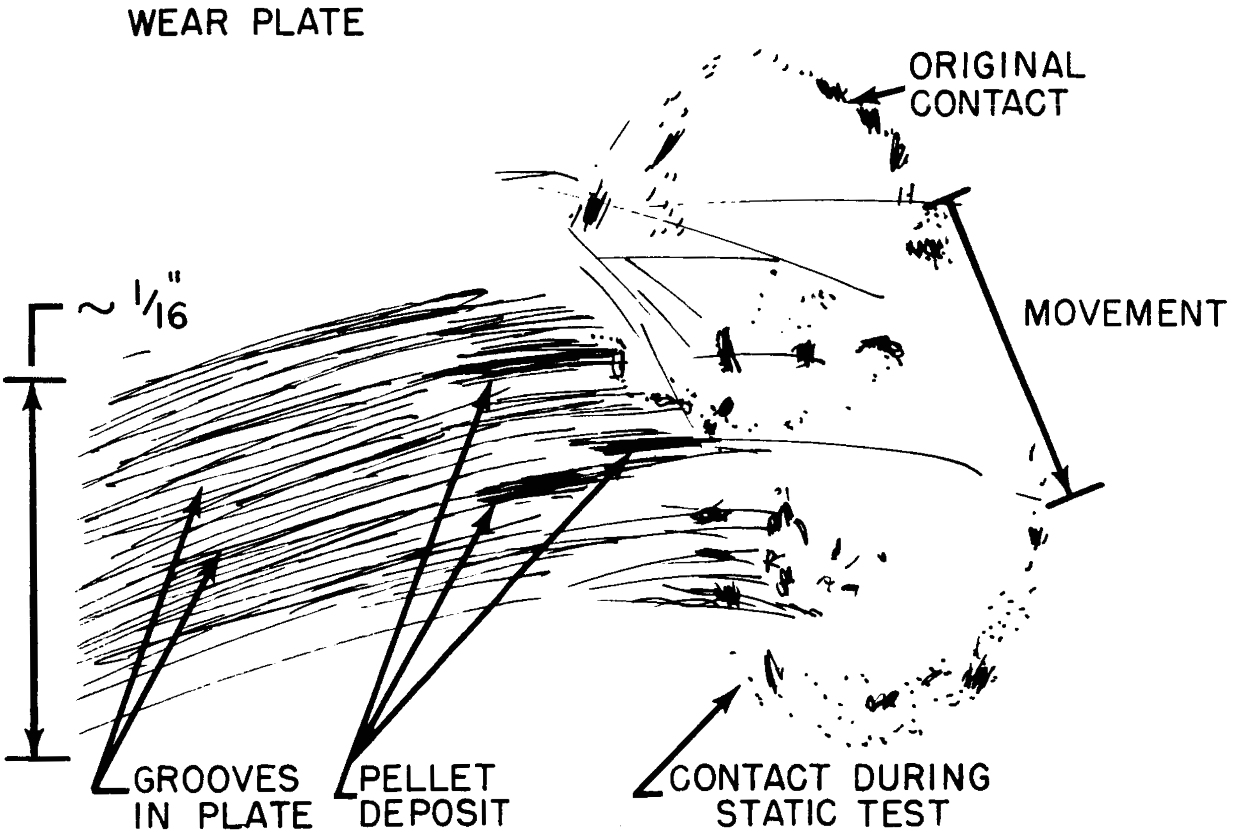


Fig. 2 - Description of Probable Motion of the Pellet Surface on the Wear Plate Surface.

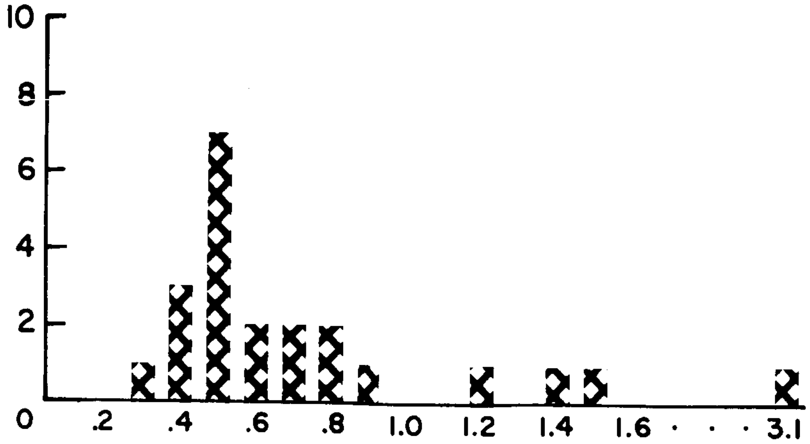
sliding friction during the first 30 degrees of motion is also unaffected by contact time. In the test with 1600-hr. static contact time excessive sliding friction (greater than 4.9) was observed by the end of the first revolution. Excessive sliding friction was also observed within the first 0.5 hr. of sliding in three of the reproducibility tests presented in Table I. The test conditions of the reproducibility tests were the same as those of Table IV except the former involved a 16-hr. contact time. This would indicate that the early development of excessive sliding friction may be due to the random nature of the cold welding tendencies rather than the 1600-hr. contact time.

Since the duration of static contact time has no significant influence on the friction of initial breakaway and the first 30 degrees of motion, the seven tests for studying the effects of contact time can be considered as additional reproducibility tests. Furthermore, the initial data of the 10 intermittent sliding tests could be considered as additional reproducibility tests because they were conducted with the same parameters as the six original reproducibility tests. Hence, 23 tests can be considered as having identical conditions during breakaway and the first 30 degrees of motion. The data from these tests are given in Fig. 3 as the number of occurrences versus the respective coefficients of friction. Figure 3 shows that 0.5 is the most probable value for the breakaway coefficient of friction and the range of 0.4 to 0.6 is the most probable value for the coefficient during the first 30 degrees of sliding. The coefficients of the original tests of beryllium-copper pellets on SS 321 plate were 0.7 and 0.2 - 0.8, respectively. Thus, the original data are in good agreement with the most probable values of the reproducibility tests.

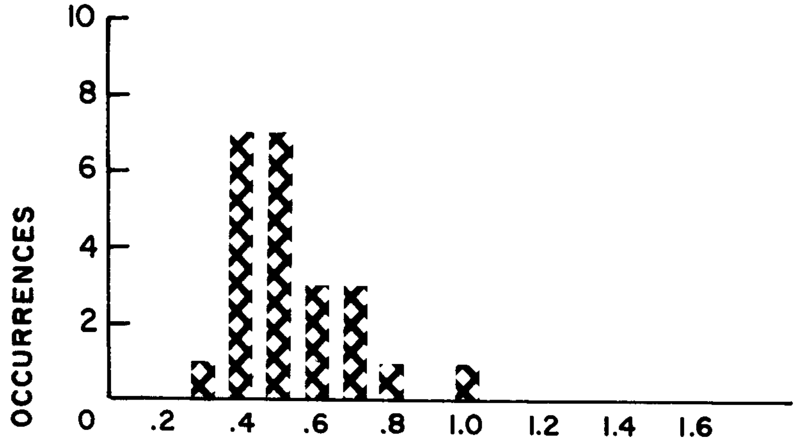
Visual examination of the wear patterns developed in the tests allow several observations concerning the nature of the wear:

1. Loose wear debris was always present after tests in air but never present after tests in vacuum.

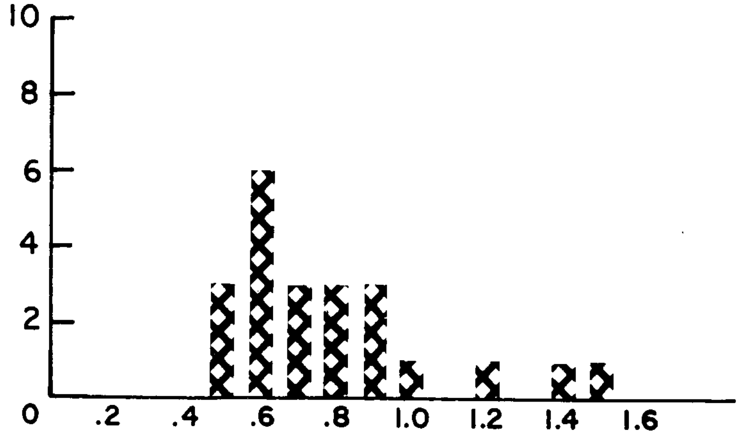
2. Visual estimates of the actual contact areas of the pellets and the wear plate surfaces (typically shown in Fig. 1) indicate a contact area of 1 to 2 percent of the projected area of the pellets; this localized contact area is distributed over an average of approximately 50 points per pellet. A calculation based on the load and the yield strength of the beryllium-copper pellets, indicates that a contact area of approximately 1 percent of the projected area should support the load. A calculation, based on the breakaway torque and the shear strength of the beryllium-copper, corresponds to shearing approximately 1 percent of the projected



(a) BREAKAWAY COEFFICIENT OF FRICTION



(b) MINIMUM COEFFICIENT OF SLIDING FRICTION - 1 ST 30 DEGREES



(c) MAXIMUM COEFFICIENT OF SLIDING FRICTION - 1ST 30 DEGREES

Fig. 3 - Histogram of Occurrences of Coefficients of Friction

area of the pellets. These results appear to agree with the theory developed by Bowden and Tabor for the adhesion of metal surfaces.[2]

3. Relative motion between the specimens at the time of initial contact appears to cause rupture of the oxide layers on the specimens; this permits metal-to-metal contact and promotes welding.

4. Breakaway of the pellets and their subsequent motion over new areas of the wear plate tear small, irregular fragments (0.001 to 0.003 in. diameter) from the pellets. These fragments of pellet material are firmly deposited onto the wear plate.

5. Subsequent passage of the pellets over these deposits apparently causes a buildup of pellet material on the wear plate; this buildup takes the form of islands with lengths about five times their height and width.

6. Eventually, after 10 to 30 passages of pellets over an island, the latter is torn away by failure of the wear plate material. Sometimes, a piece of wear plate is torn out immediately; at other times, the wear plate seems to fracture and split, then weld to itself.

7. Further motion of the pellets over the wear plate results in increasingly greater variations in the friction measurements; the transfer of material back and forth between the pellets and the wear plate occurs in a random manner.

V. CONCLUSIONS

A number of conclusions are indicated by the results of this program:

1. Reproducibility of the data is good under conditions in which the pellets slide on a virgin wear plate surface. However, there is considerable variation in results obtained from identical tests in which the pellets slide on a worn wear plate. A lesser degree of scatter is also evident for the values of breakaway friction.

2. Moisture content in an air atmosphere does not appear to significantly influence either breakaway or sliding friction. However, the data indicate that the wear rate is lower in ambient air than in dry air.

2/ Bowden, F. P., and D. Tabor, "The Friction and Lubrication of Solids, Part II", p. 52, Oxford (1964).

3. In cases involving intermittent sliding, the initial value of breakaway friction is generally the smallest. Values of breakaway friction for subsequent initiations of motion are larger.

4. The duration of static contact time has no apparent influence on the initial breakaway friction.

5. In total, 23 tests had identical parameters during initial breakaway and the first 30 degrees of motion when the effects of static contact time were found to be negligible. From the data of the 23 tests, the most probably value of initial breakaway friction was 0.5 and that of sliding friction during the first 30 degrees of rotation 0.4 to 0.6; the total range of values were 0.3 to 3.1 and 0.3 to 1.5, respectively.

VI. RECOMMENDATIONS

The studies of the beryllium-copper pellets on a SS 321 wear plate brought forth numerous results pertaining to this one combination. These data dictate that several other metal combinations should be similarly studied. These combinations should consist of metals having significantly different hardness and shear strengths than the two metals which were studied. The selection of the materials should be based on their importance as engineering materials in space vehicles.