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SLIDING FRICTION OF COPPER

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THE SLIDING FRITION BETWEEN COPPER SPECIMENS WERE MEASURED UNDER ATMOSPHERIC CONDITIONS UNDER LOADS OF 0.1 TO 20 GRAMS. ALL OBSERVATIONS INDICATE THAT PLASTIC DEFORMATION EXISTS DURING THE SLIDING PROCESS. WHEN ADHESION IS NEGLIGIBLE, BASED ON THE PLASTIC DEFORMATION MECHANISM, ONE MAY DEDUCE THAT (1) THE FRICTION COEFFICIENT DEPENDS LARGELY ON THE PROPERTIES OF THE SOFTER MATERIAL OF TWO SPECIMENS, AND (2) UPON REPEATED SLIDING, A SLIGHT DROP IN FRICTION MAY BE OBSERVED. BOTH OF THESE PREDICTIONS HAVE BEEN VERFIED EXPERIMENTALLY.

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FOREWORD

This report was prepared by the Fluid and Lubricant Materials Branch, Nonmetallic Materials Division, A. F. Materials Laboratory with Dr. Tung Liu as Project Engineer. The work reported herein was initiated under Project 7342 "Fundamental Research on Macromolecular Materials and Lubrication Phenomena", Task 734204, "Fundamental Investigations of Frictions, Lubrication, Wear, and Fluid Mechanics". The report covers a period of work from 1 July 1962 to 30 June 1963.

ABSTRACT

The sliding friction between copper specimens were measured under atmospheric conditions under loads of 0.1 to 20 grams. With very clean surfaces, the coefficient of friction was 1.0-1.1 for the entire load range. With less clean surfaces, the coefficient of friction obtained was about 0.4. Since the degree of cleanliness cannot be controlled quantitatively, the friction - load curve of sliding copper pairs in air exhibits a bifurcation characteristic. The higher friction value may be satisfactorily explained by adhesion theory. No sign of adhesion, however, was detectable when the friction coefficient was 0.4. All observations to date indicate that plastic deformation exists during the sliding process. Using published data on the total expended work in plastic deformation, the coefficient of friction between copper pairs was estimated to be about 0.2. When adhesion is negligible, based on the plastic deformation mechanism, one may deduce that (1) the friction coefficient depends largely on the properties of the softer material of the two specimens, and (2) upon repeated sliding, a slight drop in friction may be observed. Both of these predictions have been verified experimentally.

This report has been reviewed and is approved.

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INTRODUCTION

The sliding friction between solids, particularly metallic solids, has been successfully explained qualitatively by adhesion theory, due largely to the extensive work of Bowden, Taber, and co-workers (2) as well as others. This theory in its originally primative form stated that the actual area of contact (A) between solids is equal to the load (W) divided by the flow pressure (p_m) of the weaker of the two solids in contact. At these regions of contact, the two solids form a number of junctions as if they were welded together. Friction (F) represents the force required to shear these junctions apart. Mathematically, the theory is expressed as:

$$A = \frac{W}{p_m} \tag{1}$$

$$F = As \tag{2}$$

$$\mu = \frac{F}{W} = \frac{As}{Ap_m} = \frac{s}{p_m} \tag{3}$$

where (s) is the shear stress. Thus, the coefficient of friction may be represented by the ratio of shear stress to flow stress of the material, and becomes its intrinsic property.

This representation, however, assumes the independence of yield pressure and shear stress which is inaccurate as pointed out by the authors. It also predicts, contrary to experimental results, that μ cannot be much more than unity. McFarlane and Taber (13) experimentally observed the growth of junctions prior to macroscopic sliding between the solids. Taber (16) later revised the theory by considering the junction growths under combined compressive and shear stress and arrived at the result:

$$\mu = \frac{1}{3\sqrt{\frac{1}{k^2} - 1}} \tag{4}$$

where (k) is the ratio of shear stress of the junction to that of the bulk of the material. This expression predicts an extremely high coefficient of friction when the two solids are identical both in composition and in orientation. Mismatched lattice invariably lead to the formation of a junction with lower shear stress.

Gwathmey et al (8) reported that the static friction coefficient between single crystals of copper (face centered cubic lattice) under vacuum exceeded 100 when two matched (100) surfaces were in contact. Replacing one with another (111) surface, the coefficient of friction dropped to 23. Takagi and Tsuya (17) extended the study to the directional effects on the friction between two (100) surfaces. They reported that when the direction was matched, the average μ was 114. When the rider was rotated 45° (the (100) surface has four fold symmetry and the 45° rotation represented the maximum mismatch) the coefficient of friction dropped down to half of the above value (average $\mu = 56$). Very high coefficients of friction between polycrystaline copper were also reported (1).

From the evidence cited above, together with those including other materials, it is quite evident that this refined adhesion theory explains rather satisfactorily the very high friction between clean metals in vacuum. However, the theory also predicts that the adhesion between clean metals in air should be appreciable unless other mechanisms responsible for the sliding friction become significant (the corresponding (k) values for $\mu = 1$ and 0.5 are 0.95 and 0.82 respectively). In particular when $\mu \simeq 1$, one percent change in (k) should alter the coefficient of friction by 10 per cent. Inasmuch as the composition of the surface cannot be closely controlled, the sliding friction data obtained under apparently similar circumstances may easily be expected to vary by a factor of two. Particularly when different experimental techniques are involved.

Whitehead (20) measured the sliding friction between copper specimens at a very slow speed of 0.01 cm/sec. over a load range of 0.01 to 10,000 grams. The experiments were carried out under an ordinary atmosphere and the data were apparently reported as the static friction coefficient (calculated from the maxima of frictional force). With electrolytically polished copper, a constant coefficient of friction (Amonton's second law) of 0.45 and 1.8 were observed for load ranges of <1 gm and >40 grams. For the loads in between, the coefficient of friction was found to increase with load. He explained that the friction coefficient of 1.8 was due to adhesion while at lower loads the latter was prevented because of the surface oxide film. This explanation was substantiated by Wilson's (21) measurement of contact resistance as a function of load using the identical apparatus. Whitehead also studied the effect of surface finish on the friction of copper and obtained friction coefficient - load curves having similar characteristic but with shifting load ranges at which Amonton's law failed (or the range where μ varied with load). At very high loads, of the coefficients of friction obtained, all but one data point lay very close to 1.8. No attempt was made by the author to explain the friction at very low loads other than attributing it to be due to the oxide film.

Walton (19), with carefully designed experimental procedure investigated the adhesion between copper specimens during the sliding process. He found that adhesion was not detectable whenever μ was less than 0.5. With a load of 100 grams, the sliding friction force was found to vary over a wide range. Taking the instantaneous values of μ, a linear relationship between μ and adhesion was obtained. Plotting the friction force versus adhesion, an intercept of 50 grams was obtained. This portion of the friction force evidently did not come from adhesion mechanism.

Evidence thus far indicates that the coefficient of friction of copper at low loads is due to a mechanism other than adhesion. Thus, in certain ranges of load, the friction should become very sensitive to the nature of the surface film. An experimental program was therefore carried out to study the friction of copper emphasizing the load range where Amontons' law was not obeyed.

EXPERIMENTAL

Figure 1 shows the experimental apparatus, the detail description of which will be published elsewhere (12). The specimens used consisted of a four inch disk and a 1/8" diameter spherical rider, which were used throughout this work. A close up of the specimens is shown in Figure 2. The disk specimen was mounted on a shaft driven through a hydraulic transmission capable of varying the speed from 0.1 to 500 rpm. The rider arm pivoted on two sets of jewel bearings and was connected to the drive shaft through a traverse mechanism. Upon engaging the traverse mechanism the rider arm can travel radially with respect to the disk specimen. At any desired location, the traverse mechanism may be disengaged leaving the rider at a fixed spot. A cam is provided such that the rider is automatically lifted up when it is close to the center or the edge of the disk to prevent any impact between the specimens. A linkage mounted with two parallel leaf springs on the rider arm support is connected between the core of a LVDT (linear variable differential transformer) and the rider holder, which provide the means for measuring friction force. The output of the LVDT was fed through an amplifier to a strip chart recorder. Using a set of springs, the output per unit force was calibrated versus an analytical balance. The overall accuracy is of the order of ±2% for frictional forces larger than 1 gram.

At the beginning of each run, the rider arm was carefully balanced and moved to the center of the disk specimen (not touching) and a dead weight load applied. (In this work the range of loads was 0.1 to 20 grams.) After the rotating speed has been adjusted, the arm traverse mechanism was engaged. The rider then scribes a spiral path on the virgin surface of the disk specimen as a stylus on a phonograph. Upon reaching the desired position, the rider was left to rub repeatedly on the same track of the disk by disengaging the traverse mechanism.

All the experimental work described in this paper was carried out under atmospheric conditions. During the experiments, the temperature, and relative humidity was frequently checked and found to be well in the ranges 75-85°F and 30-50% respectively. No attempt was made to control these variables. The apparatus itself, however, is capable of handling temperatures in excess of 1400°F, vacuum to 10^{-7} Torr. range, as well as controlled atmospheres.

The copper specimen used were made of 99.9% commercially pure copper. Other materials used were M-10 tool steel (hardness: RC50), commercially pure aluminum, fused quartz, and white sapphire.

The spherical specimens obtained commercially had average surface finishes < 3 micro inches and were used without further polishing. The disk specimens were wet sanded with 600 grit finish (2-4 micro inches). Some specimens were further finished with a metallurgical polisher to a surface roughness less than one micro inch. Prior to the measurement, the specimen was washed with ether, isopropyl alcohol, and distilled water. The final washing with water also indicated whether the degreasing was complete. Whenever water droplets were found to hang on the specimen, the solvent washing process was repeated.

Many of the metallic specimens were cleaned electrolytically prior to the friction measurement as suggested by Dr. Campbell (3). Using 20% K_3PO_4 solution, the cathodic reduction was carried out for one minute at a current density of 1 ma/cm^2 and 10 seconds at 10 ma/cm^2. A 10 cm x 10 cm sheet copper was used as the anode. The specimen was rinsed with distilled water and dried with warm air immediately after removal from the electrolytic bath and placed on the experimental apparatus.

RESULTS

The effect of sliding speed was first determined by a series of runs of copper on copper with 10 grams of load. The friction coefficient was measured at five different rotating speeds, 5, 10, 20, 50, and 100 rpm, and with a fixed sliding diameter of 3 ± 0.25 in. The corresponding linear speed range is bout 0.8 to 16 in/sec. The results are shown in Figure 3. It can readily be seen that μ gradually increased with speed. At a speed of 20 rpm or less, its effect on friction coefficient is negligible. All other runs were therefore made at a single speed of 20 rpm in order to eliminate one variable. The linear sliding speed during the initial spiral path increased from 0.5 to about 3 in/sec. Which is also the average speed during repeated sliding.

Results from the thoroughly cleaned copper specimen are presented in

Figure 4 which shows that the coefficient of friction is about 1.0 to 1.1 for the entire load range measured (0.1-20 grams). The results agreed well with our earlier value of 1.1 using another apparatus over the load range 120-6000 grams (11). This value also agrees with the average results obtained by Walton (19) with a 100 gram load. Throughout this work, data are reported as dynamic friction as it was found that static friction values obtained from sliding techniques is sensitive to the surface preparation procedure as well as the damping action of the apparatus and instrument. Whitehead (20) apparently reported static coefficient friction values of 1.5-1.8. The discrepancy can in part be explained as the difference between the static and dynamic friction forces.

A typical portion of recorded frictional force is shown in Figure 5. It can be seen that friction force showed a variation of ±30%. On occasions, especially at low loads, much lower coefficients of friction of about 0.4 were observed initially, and in most of these cases, friction coefficients of 1.0 to 1.1 were again observed after repeated rubbing. This is obviously due to some surface contamination as may be seen from the following results.

If the cathodic reduction procedure was omitted, that is, the final cleaning was made with solvent washing and checked with water wetting, the results obtained were considerably different. On the virgin surface of the disk (the initial spiral path) the coefficient of friction is in the neighborhood of 0.4. Upon repeated rubbing for loads of five grams or higher, the coefficient of friction eventually rose up to about 1.0. At lower loads the friction coefficient usually remained constant. In general, the higher the load, the less time was needed for the friction to rise. The data are summarized in Table 1 and illustrated in Figure 6. A typical recording is shown in Figure 7 which shows that friction coefficient had jumped from about

0.4.to over 1.0 within a very short time.

Examining the results of a large number of runs, the instantaneous friction coefficient appeared to be either 0.4 or 1.0. Increased speed tends to hasten the rise in friction. However, the two values of friction coefficient were not changed. Smoother surface finish has effects similar to that of increased speed, it only facilitates the rise in friction. The wear tracks were examined under a microscope. Considerable differences were noticed between the track from which the coefficient of friction of 1.0 has been observed and for one with the lower friction values. The former showed a large amount of metal transfer and a much wider track as well as severe wear on the rider. If the sliding was terminated while the friction remained about 0.4, the track showed merely groves in the direction of sliding with no evidence of metal transfer. Individual groves are of the order of 2×10^{-4} in wide. The wear on the rider was also barely noticeable.

Another series of experiments were carried out with a fixed track using gradually increased load from 0.1 to 20 grams. Starting with 0.1 gram load, the loads were increased to 0.2, 0.5, 1.0, 2.0, 5.0, and 10.0 grams with twenty minutes of running time at each loads. The sliding system was then allowed to run under 20 gram load for 60 minutes after which the load was reduced stepwise in the same manner until 0.1 grams was reached. The results are shown in Table 2. It was noticed that the rider may be replaced with a new rider during any stage without noticeable change in the results. Data from a typical run is shown in Figure 8 where the coefficient of friction is plotted versus load. Results also shows that the friction coefficient of two different values may be obtained under apparently identical conditions. This phenomenon was first reported by Ling and Weiner (10) as "bifurcation".

The fact that values of μ of the upper branch fell down somewhat at low load is apparently due to the presence of impurities.

Friction measurements were also made with M-10 tool steel specimens in order to show the peculiarity of the copper-copper systems. Typical friction traces with and without cathodic reduction cleaning process are shown in Figure 9. The effect of surface film is quite apparent. However, the results did not show the two distinct levels of friction exhibited by the copper-copper system.

Riders made of M-10 tool steel, fused quartz, and white sapphire were also used for friction measurements on copper disks. The results are summarized in Table 3. Riders of these three materials together with copper were also run with commercially pure aluminum disks. The results are shown in Table 4. All metal specimens were cleaned with the cathodic reduction process while the quartz and sapphire riders were cleaned by solvents only.

DISCUSSION

For thoroughly cleaned copper specimens, Amontons' law was obeyed with μ = 1.0-1.1 for the entire load range (0.1 to 20 grams). Adhesion between surfaces was very evident. For slightly contaminated surfaces Amontons' law again was obeyed initially, however, the coefficient of friction was only 0.4. Our earlier results (11) using not carefully cleaned samples showed that on occasions, this $\mu = 0.4$ was observed with loads in excess of 500 grams. In all these cases, no sign of adhesion was observed which agrees with others as Walton (19) demonstrated that adhesion between copper was not detectable for $\mu < 0.5$. The range in which Whitehead observed (20) μ increased with load is, therefore, identical to the specific experimental environments.

Ling and Weiner (10) first reported the bifurcation of the μ-load curve of lead pairs. They found that the shape of the upper branch could be explained by adhesion, but not that of the lower one. They also found a bifurcation of adhesion with a negligibly small lower branch. Russell, Burton, and Ku (15) studied the friction between oxidized copper in dry helium atmosphere and also observed the bifurcation phenomenon. They, likewise, concluded that two mechanisms of friction must exist under apparently identical conditions. In the case of copper-copper system, it is also found necessary to consider some mechanism other than adhesion to explain the lower value of μ.

Greenwood and Tabor (7) showed that the coefficient of friction of the order of unity such as that observed between very clean copper specimens in air, must be due to weak adhesion as caused by the surface oxide. In the same paper they also pointed out that a certain amount of work could be expended in plastically deforming the specimens even though they were separated by a lubricating film.

Feng (5) illustrated severe plastic deformation at the sliding interface. Moore and Tegart (14) showed that with a hard rider sliding repeatedly on a copper surface, the oxide, and other impurities were found well below the surface. Such could only happen if the region near the contact area underwent considerable plastic deformation.

For estimating the energy required for plastic deformation (ploughing term as frequently used) Bowden and Tabor (2) used microscopic model and concluded that the ploughing term is usually negligible. Walton (19) refined the calculation using microscopic model asperities, and showed that for small spherical asperities and using the hardness of the oxide for the calculation, a coefficient of friction of the order of 0.5 could indeed be accounted for. However, his results showed that μ is very sensitive to the thickness and the structure of the oxide film and the asperity dimension. This suggests that the coefficient of friction would be very sensitive to the rider material. Results shown in Table 3 and 4 indicate otherwise.

A different approach originally suggested by Dr. Ling (9) is considered in the estimation of the energy involved in plastic deformation. Since copper has a face centered cubic structure, it is more logical to assume that the asperities are of the shape of rectangular corners (Figure 10a). When two such asperities are in contact the cone is deformed to the shape of Figure 10b. The displaced volume:

$$v_i = \frac{1}{6} h_i^3 \tag{5}$$

with an area of contact

$$A_i = \frac{\sqrt{3}}{2} h_i^2 \tag{6}$$

The total volume of the asperity which undergoes plastic deformation may be estimated as:

$$V_i = \frac{1}{6}(3h_i)^3 \text{ or } \frac{9}{2} h_i^2 \tag{7}$$

The corresponding work done by the frictional force F is:

$$F \cdot \ell = 2 E_w \Sigma V_i \tag{8}$$

where E_w is the total expended energy in plastic deformation per unit volume and ℓ is the distance traveled. The factor of 2 is introduced for identical materials at slow speeds. The area of contact is related to the load W and the flow stress p_m by the relation:

$$\Sigma A_i = \frac{W}{p_m} \tag{9}$$

The coefficient of friction is, therefore,

$$\mu = \frac{F}{W}$$
$$= \frac{2 E_w \Sigma V_i}{p_m \ell \Sigma A_i} \qquad (10)$$

to simplify the problem, let us assume V_i's and A_i's are constant and $\ell \sim \frac{1}{2} h_i$ equation (10) is then reduced to:

$$\mu = \frac{21 E_w}{p_m} \qquad (11)$$

Comparing with equation (3)$\left(\mu = \frac{s}{p_m}\right)$, it is clear that this mechanism will lead to similar qualitative results predicted by the crude adhesion theory. Consequently, it is easily ignored since it is usually much smaller compared to adhesion, whenever the latter is present.

In order to estimate the coefficient of friction from the above equation, data on the total expended energy during plastic deformation must be available. This kind of data, however, is not readily available except for some deformation by impact (18). However, the total work (E_w) may be estimated from the ideal work (E_w') by a multiplying factor, say about two. Thus,

$$\mu \simeq \frac{42 E_w'}{p_m} \qquad (12)$$

To evaluate E_w' it is necessary to calculate the true strain

$$\bar{\varepsilon} = \ln \frac{V_i}{V_i - v_i} = 0.04$$

Calculation of E_w from measured compressive stress-strain curve of copper have been done by Clarebrough <u>et al</u> (4) for much higher strain. These authors also showed that E_w's for torsion and compression, on a true strain basis, agreed well within experimental errors. Gordon (6) obtained the data of E_w' on the tension of copper down to 0.103. These data are shown in Figure 9. With extrapolation, the value of E_w' was found to be 0.9 cal/cc. Using p_m = 88 kg/mm^2, we have:

$$\mu = \frac{42 \times 0.9 \times 4.185 \times 10^7}{88 \times 10^5 \times 980.6}$$

$$= 0.18$$

In case one asperity is very hard, the deformation may be confined to one asperity with twice the displaced volume. With higher strain, the coefficient of friction is calculated to be 0.20.

The above calculation is rather crude as the increase in contact area was not considered. The effect of combined stress was also neglected. However, the order of magnitude is correct, indicating that energy expended in plastic deformation is probably the cause of friction force in the absence of adhesion. It should be emphasized that neither the asperity size nor the properties of surface film is involved, thus, predicting a roughly constant coefficient of friction of copper with different surface finish and oxide film thickness provided it is not too thick. Two deductions may be drawn directly:

(1) In the absence of adhesion, energy expended in plastic deformation becomes the principal source of friction force. As mentioned above, in copper-copper system, if the rider is replaced with a very hard material to restrict the deformation to the copper specimen only, the corresponding change of μ is only about ten percent. (Although

a cubic crystal was used as the model, similar relationships will hold for asperities derived from other crystal systems.) The sliding friction coefficient depends mostly on the nature of the softer of the two specimens. Using riders made of harder materials (M-10 tool steel, fused quartz, and white sapphire) on copper, the results are shown in Table 3 where $\mu = 0.33 \pm 0.08$. Using an aluminum substrate Table 4 shows that μ became 0.65 ± 0.07.

(2) In the plastic deformation of metals, certain amount of the energy is stored. The amount, however, is only a small fraction of the total expended energy, the ratio of stored energy (E_s) to the idea work (E_w') is shown in Figure 11 as a function of true strain. At the strain of 0.04, it can be seen that the ratio E_s/E_w' is less than 20%. Since E_w' is always less than E_w (total expended energy), E_s/E_w should be even smaller. This means that the total expended energy for plastic deformation is not changed substantially by cold work. In a sliding system, if it remains the principal mechanism, the friction coefficient may be expected to drop slightly upon repeated sliding on the same track due to the stored energy. Experimental observation of this effect may be hindered by the initiation of other mechanisms which cause friction to rise. Table 5 shows the friction coefficient of M-10 tool steel, quartz and white sapphire on copper, both at the virgin surface and after one hour of continuous rubbing (approximately 1200 paths). The μ's of both M-10 and sapphire remained fairly constant. While with fused quartz, the friction coefficients were more than doubled indicating other mechanisms, possibly adhesion, has started.

CONCLUSIONS

(1) The sliding friction coefficient of copper on copper under atmospheric conditions exhibits a bifurcation phenomenon, ie., two values could be obtained with apparently identical conditions. Both branches were constant over the load range (0.1 to 20 grams) used.

(2) When the specimens were thoroughly cleaned electrolytically a coefficient of friction above 1.0 is usually obtained. The appearance of wear tracks indicated that adhesion was the principal mechanism.

(3) The initial friction coefficient between solvents cleaned copper specimens is about 0.4. At this stage of the sliding process, no evidence of adhesion was observable from the wear track but plastic deformation was evident. Apparently the trace of impurity inhibited adhesion.

(4) Plastic deformation should be considered as a significant mechanism in sliding friction when adhesion is weak. Crude calculations based on the total expended energy showed that the coefficient of friction between copper specimens should be about 0.2. This value is lower than the experimental data, but it is of the right order of magnitude and could conceivable be improved by more refined calculation.

(5) Based on plastic deformation mechanism, sliding friction coefficient is insensitive to the rider material provided it is harder than the substrate. Experimental results using both copper and aluminum substrates showed that such is the case.

(6) Upon repeated rubbing, if plastic deformation remains the principal mechanism, the friction coefficient may drop slightly with time. However, it may rise due to other mechanisms. This is substantiated by the experimental results with copper substrate.

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NOMENCLATURE

A	True area of contact.
Ai	Area of contact of the i^{th} pair of asperities.
E_s	Stored energy in plastic deformation (per unit volume of material).
E_w	Total expended work in plastic deformation (per unit volume of material).
E_w'	Total ideal expended work in plastic deformation (per unit volume of materials.)
F	Friction force.
h_i	Edge length of the displaced cone of the i^{th} pair of asperities.
k	ratio of shear stress of junction to that of the material.
	Distance traveled in the deformation of asperities.
p_m	Flow Stress.
s	Shear Stress.
Vi	Volume of plastically deformed material of the i^{th} pair of asperities.
vi	Displaced volume due to plastics deformation of the i^{th} pair of asperities.
w	Load
	True Strain.
	Coefficient of friction.

TABLE 4

SUMMARY OF SLIDING FRICTION DATA OF COPPER CLEANED WITH SOLVENTS ONLY

LOAD (gms)	INITIAL	2 Min.	5 Min.	10 Min.	20 Min.	60 Min.
0.1	0.45	-----	-----	-----	-----	0.44
	0.34	-----	-----	-----	-----	0.39
0.2	0.43	-----	-----	-----	-----	0.45
	0.39	-----	-----	-----	-----	0.42
0.5	0.41	-----	-----	-----	-----	0.36
	0.35	-----	-----	-----	-----	0.39
1.0	0.34	-----	-----	-----	-----	0.42
	0.36	-----	-----	-----	-----	0.47
2.0	0.37	-----	-----	-----	-----	0.37
	0.43	-----	-----	-----	-----	0.48
5.0	0.40	0.41	X	X	X	1.06
	0.38	0.40	0.38	0.39	X	X
*	0.45	X	X	X	1.02	0.96
10.0	0.44	X	X	1.07	1.00	0.98
	0.44	X	0.95	0.90	-----	-----
*	0.39	X	0.94	1.00	-----	-----
20.0	0.39	X	X	1.02	0.98	0.96
	0.38	1.06	1.12	1.05	-----	-----
*	0.45	0.98	1.02	1.02	-----	-----

X Denotes fluctuation between 0.35 and 1.20, no steady readings could be obtained.

* Denotes the disk specimens were polished to < 1 μ-in., others were sanded to 2-4 μ-in.

TABLE 2

SLIDING FRICTION OF COPPER CLEANED WITH SOLVENTS ONLY WITH STEPWISE VARIABLE LOAD

LOAD(gm.)	FRICTION COEFFICIENT A	B	C	D*
0.1	.45	.39	.34	.31
0.2	.43	.39	.39	.39
0.5	.41	.35	.36	.37
1.0	.39	.36	.34	.36
2.0	.43	.37	.37	.53
5.0	1.09	1.04	1.12	.45
10.0	1.15	.94	1.06	.90
20.0	1.15	1.04	1.03	1.01
10.0	1.04	.94	.98	.99
5.0	.90	.92	.90	.99
2.0	1.13	.77	1.16	1.05
1.0	1.05	.77	.84	.92
0.5	1.04	.90	.78	.86
0.2	.78	.70	.84	.77
0.1	.31	.39	.29	.39

* In Series D, a new rider was used after each load change. One rider was used in each of the other series.

TABLE 3

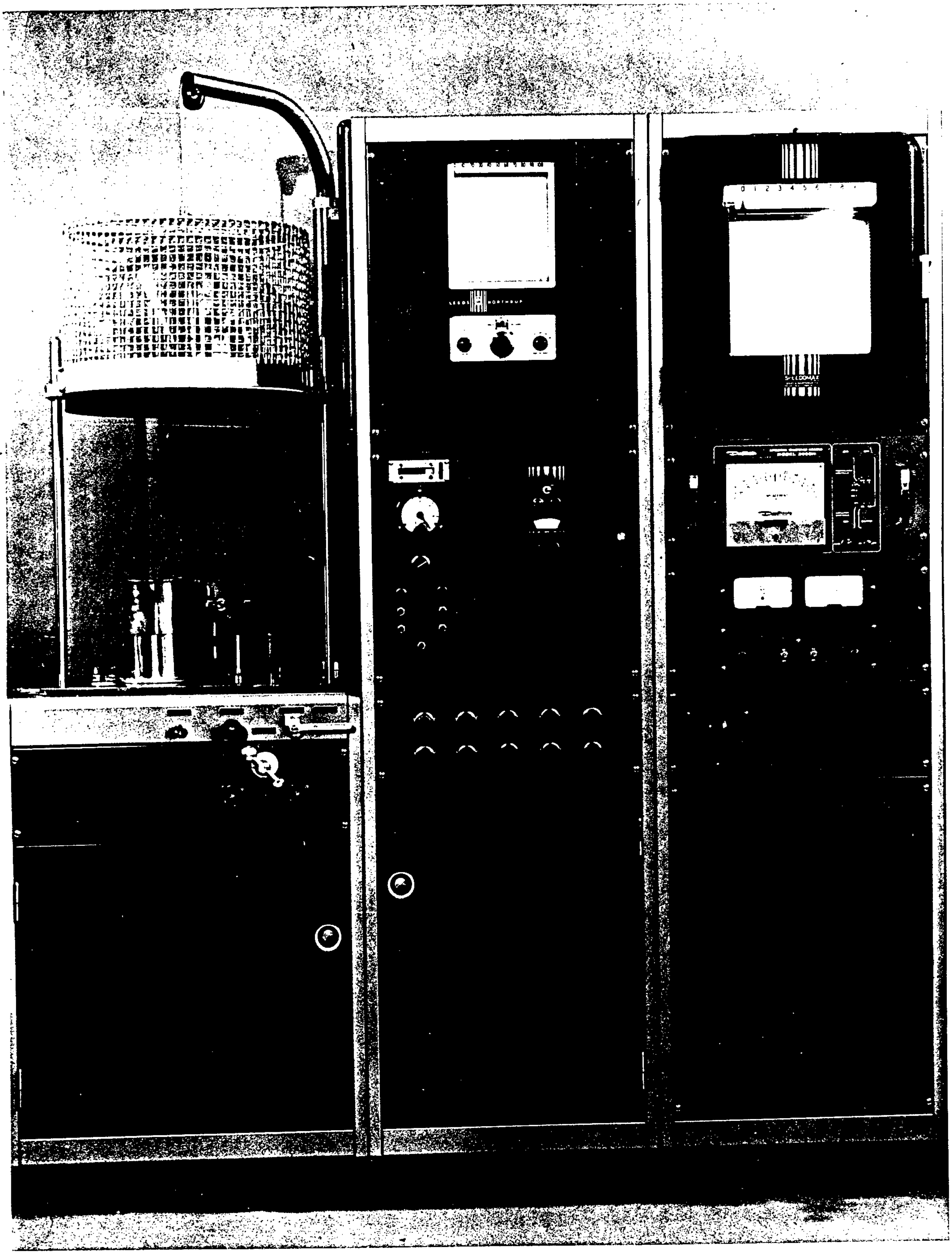
SLIDING FRICTION OF VARIOUS RIDERS ON COPPER

RIDER	LOAD (gm)	FRICTION COEFFICIENT Initial	After 60 min.
M-10 Tool Steel	5	0.32	0.38
	10	0.41	0.37
	20	0.36	0.42
Fused Quartz	5	0.32	0.86
	10	0.39	0.77
	20	0.34	0.75
White Sapphire	5	0.26	0.24
	10	0.30	0.25
	20	0.28	0.40

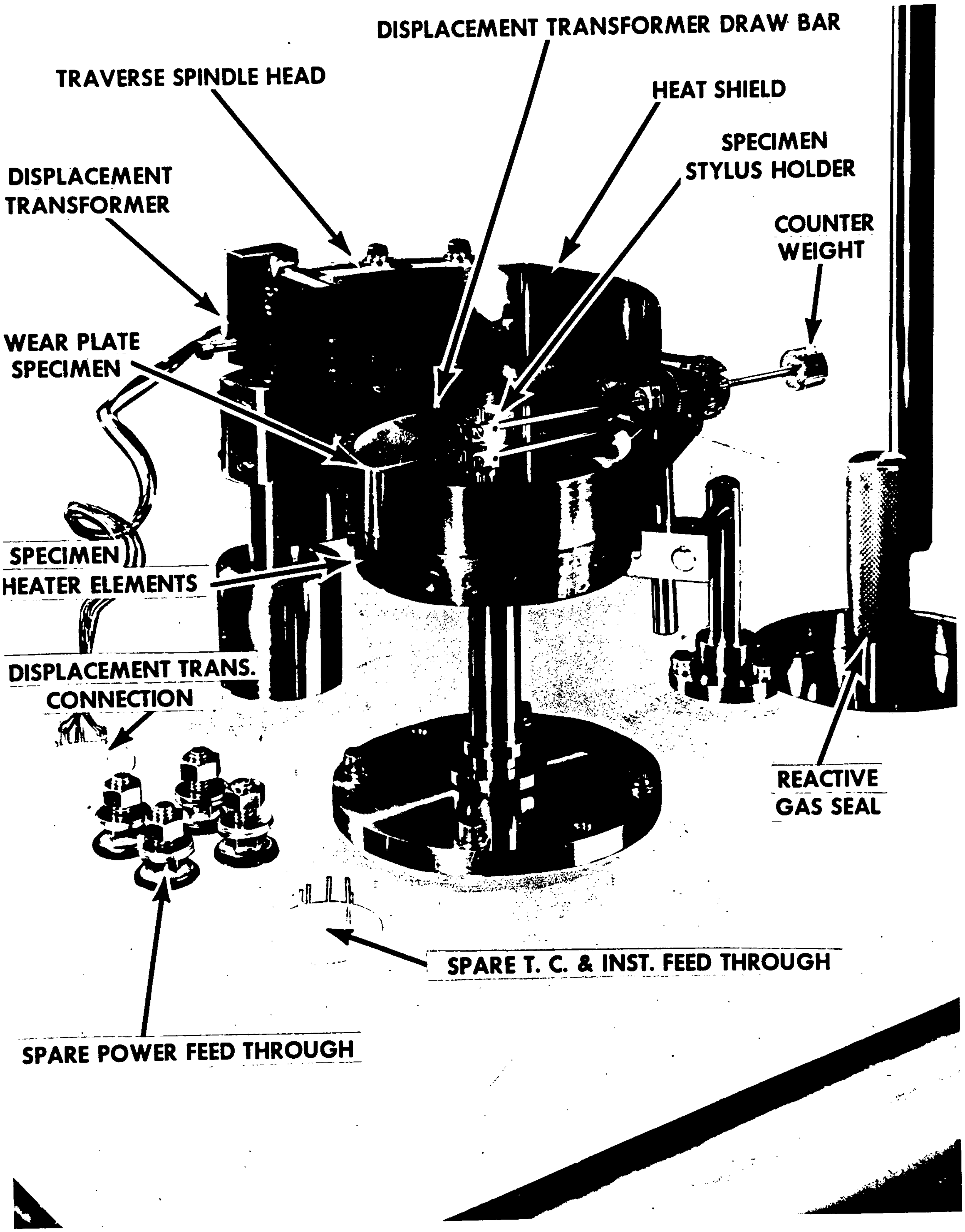
TABLE 4

SLIDING FRICTION ON ALUMINUM SUBSTRATE

RIDER	LOAD (gm)	FRICTION COEFFICIENT
M-10 Tool Steel	0.2	0.58
	10.0	0.64
Fused Quartz	0.2	0.61
	10.0	0.67
White Sapphire	0.2	0.63
	10.0	0.67
Copper	00.2	0.73
	10.0	0.69



TM-ML-HCM-C3-71


DISPLACEMENT TRANSFORMER DRAW BAR
TRAVERSE SPINDLE HEAD
HEAT SHIELD
SPECIMEN
STYLUS HOLDER
DISPLACEMENT
TRANSFORMER
COUNTER
WEIGHT
WEAR PLATE
SPECIMEN
SPECIMEN
HEATER ELEMENTS
DISPLACEMENT TRANS.
CONNECTION
REACTIVE
GAS SEAL
SPARE T. C. & INST. FEED THROUGH
SPARE POWER FEED THROUGH

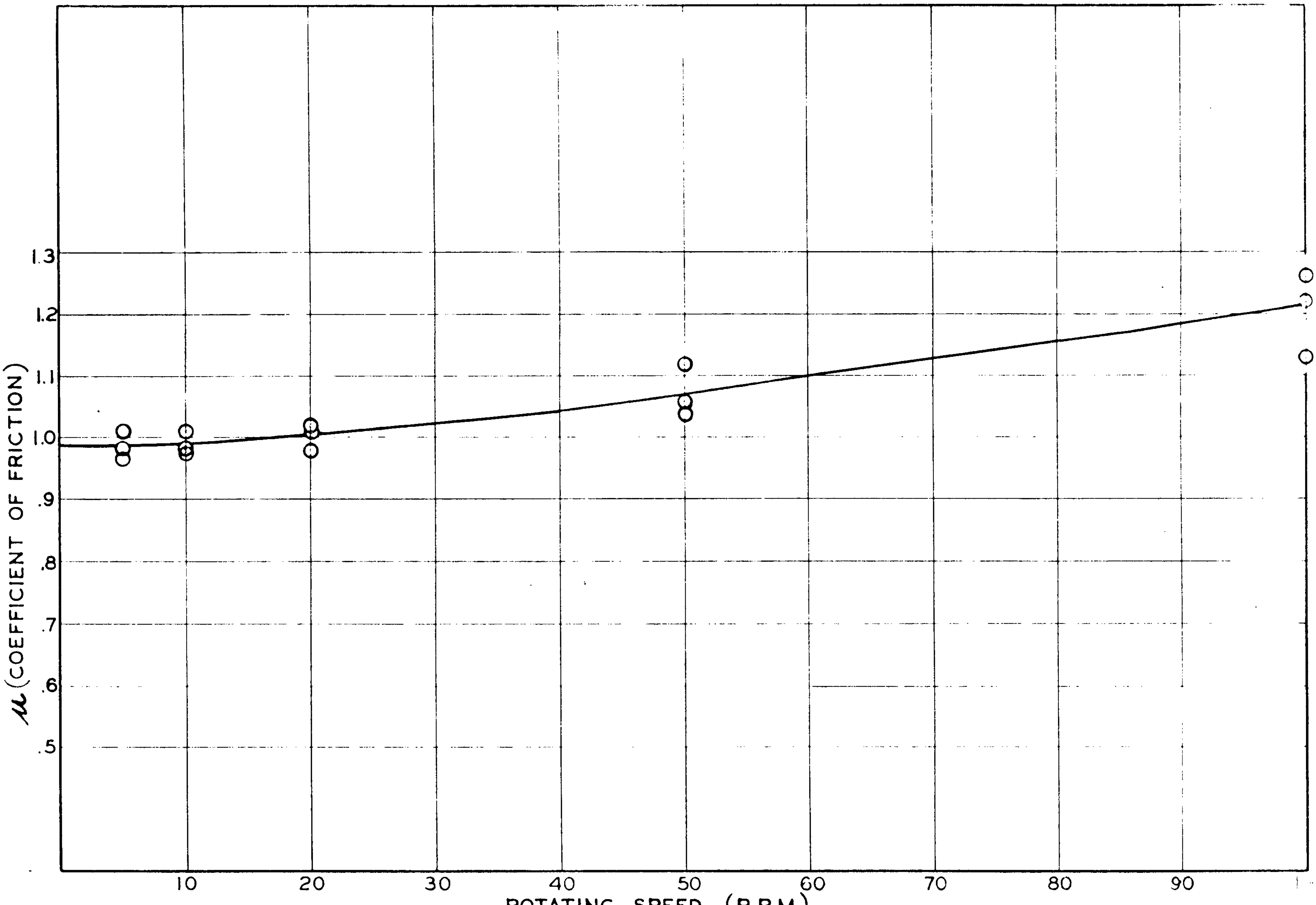


FIG. 3 EFFECT OF SPEED ON THE SLIDING FRICTION OF COPPER

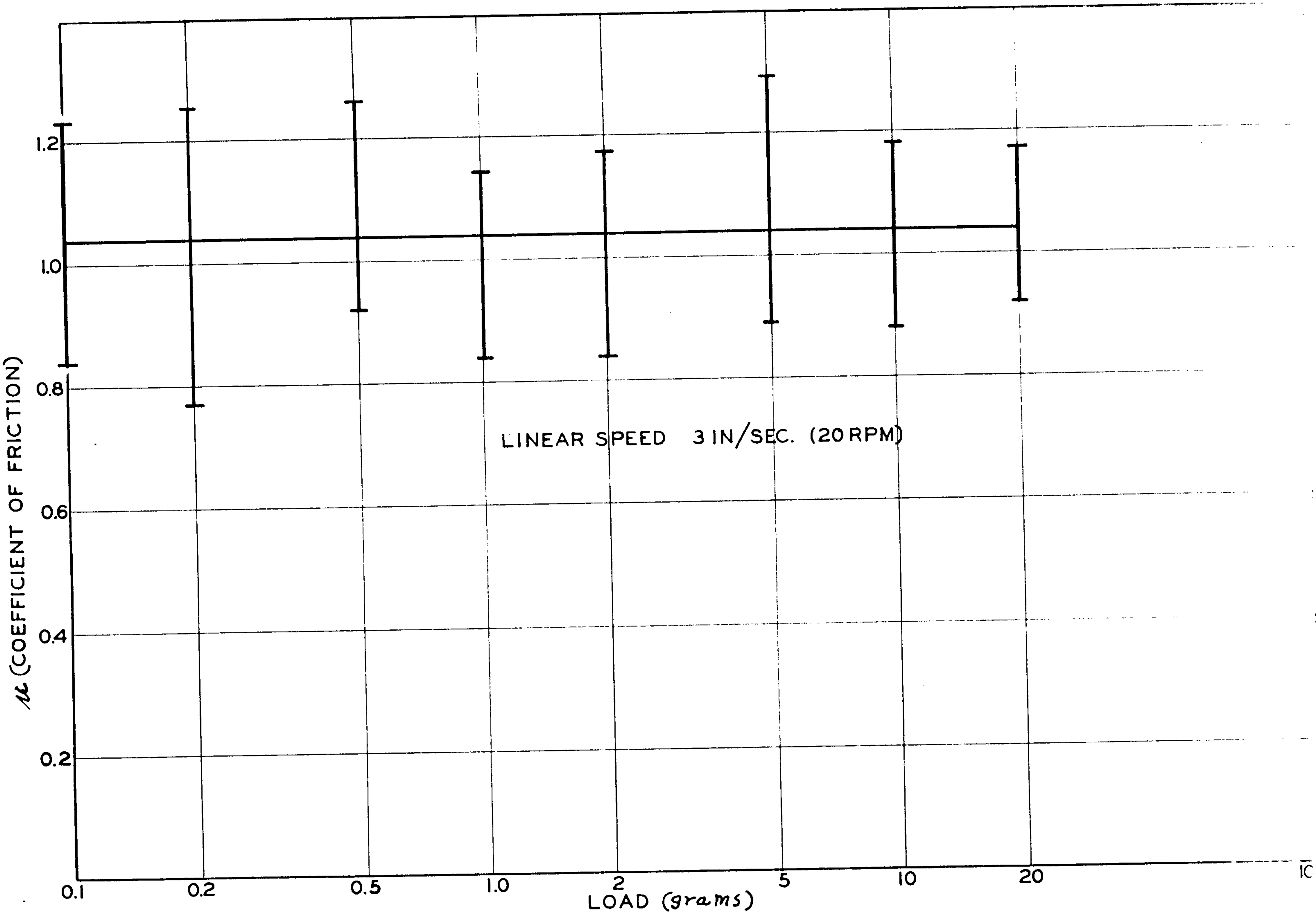
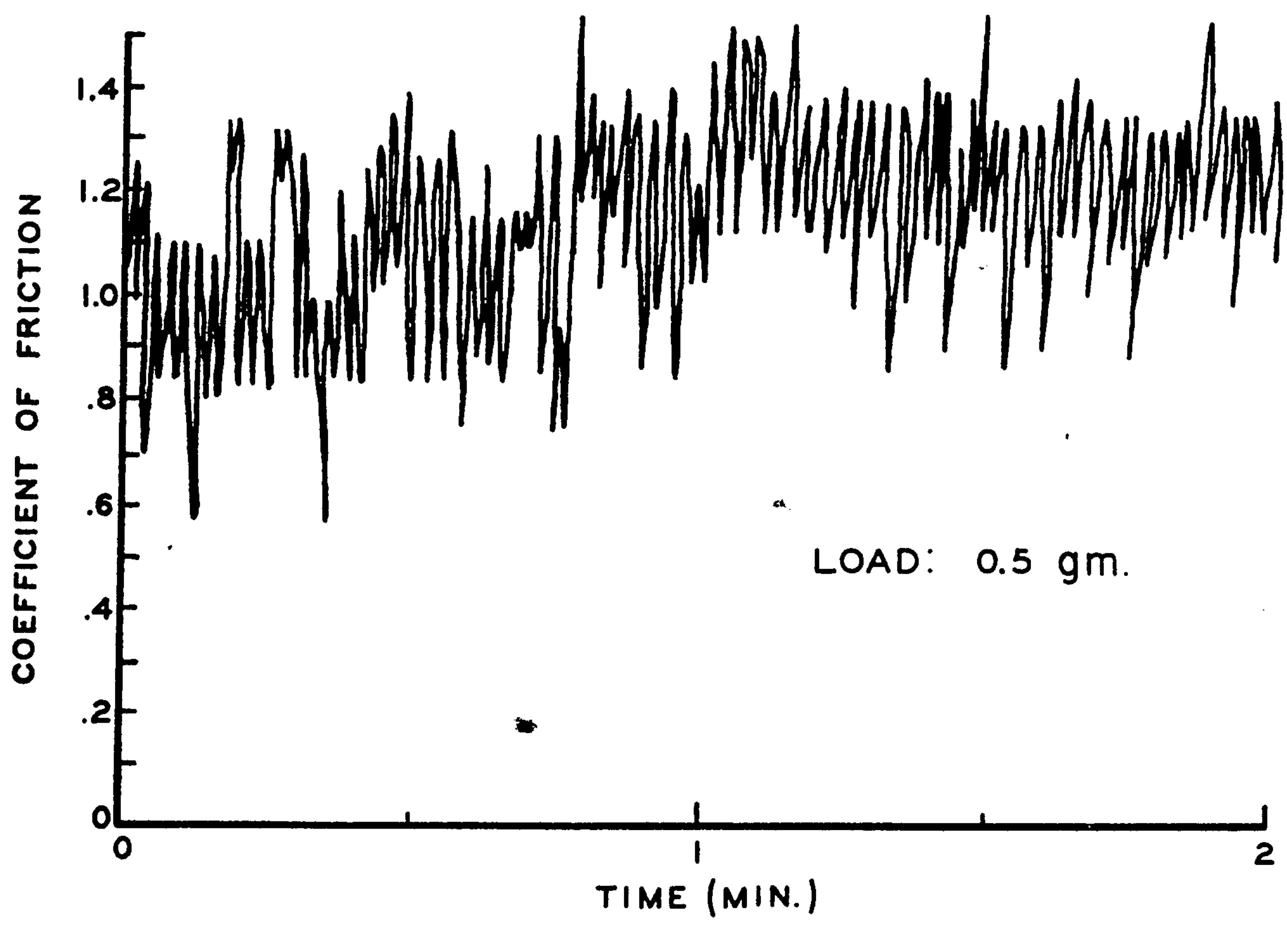


FIG.4 FRICTION COEFFICIENT BETWEEN CLEAN COPPER SPECIMENS SLIDING IN AIR.

FIG. 5 TYPICAL RECORDING OF SLIDING FRICTION OF CLEAN COPPER



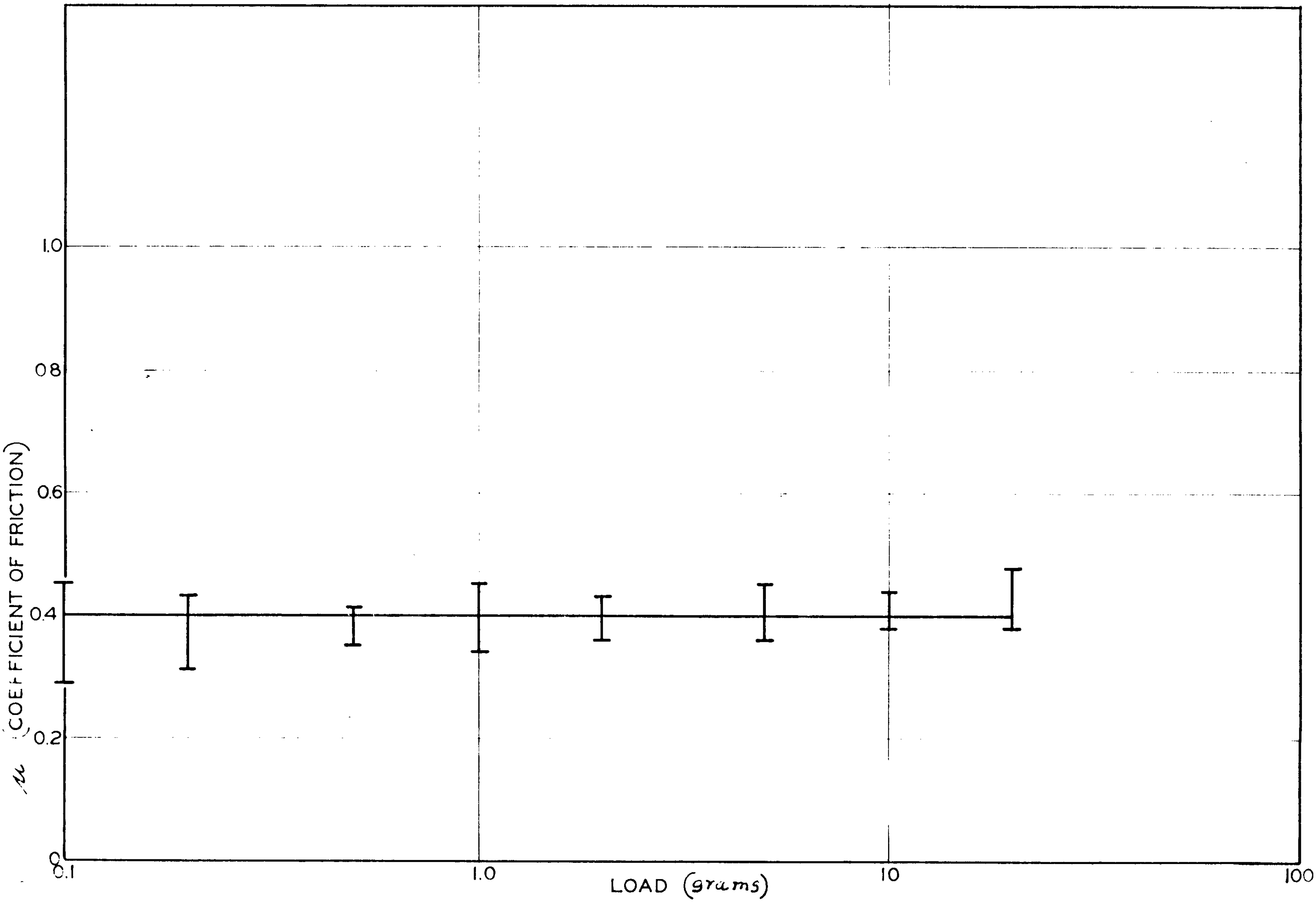
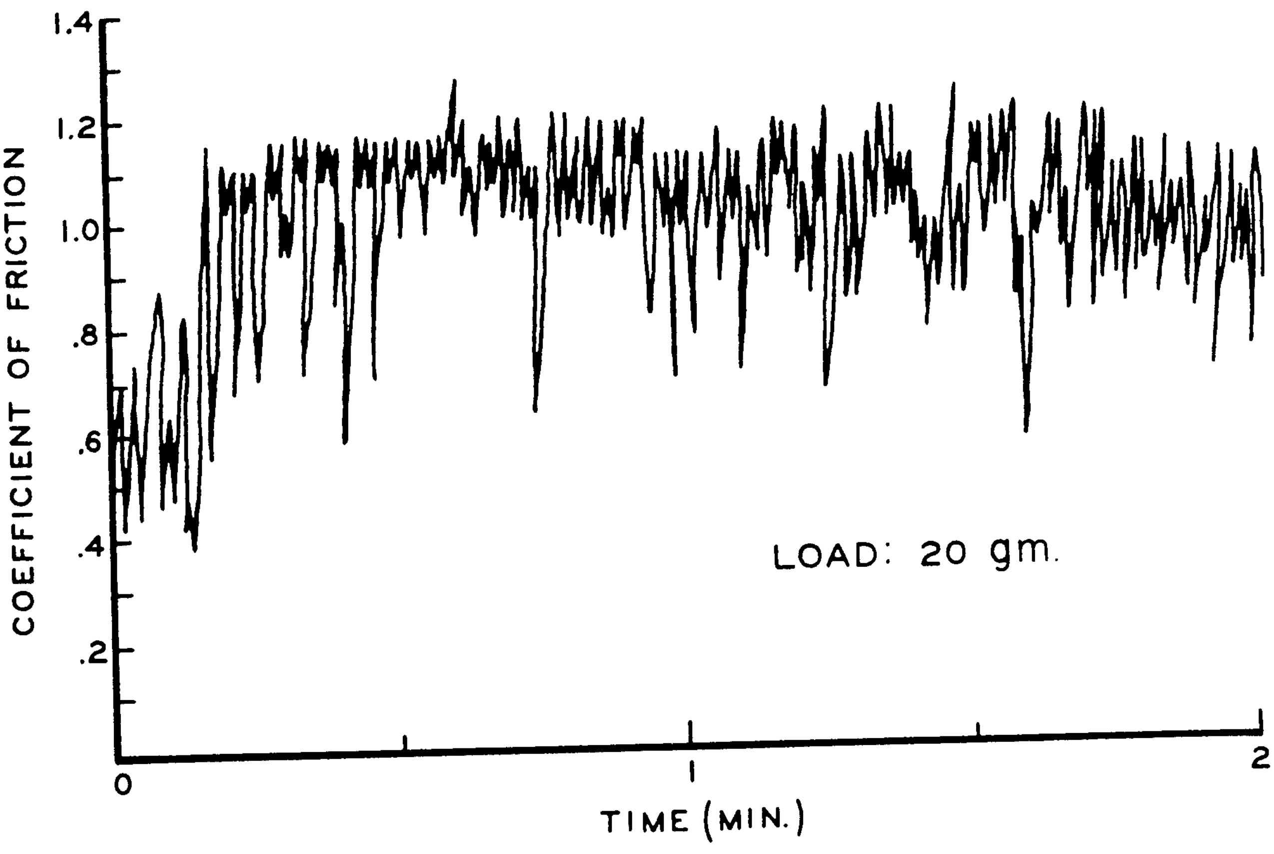


FIG. 6 INITAL SLIDING FRICTION COEFFICIENT OF COPPER CLEANED WITH SOLVENT ONLY.

FIG. 7 TYPICAL RECORDING OF SLIDING FRICTION OF COPPER CLEANED WITH SOLVENTS ONLY



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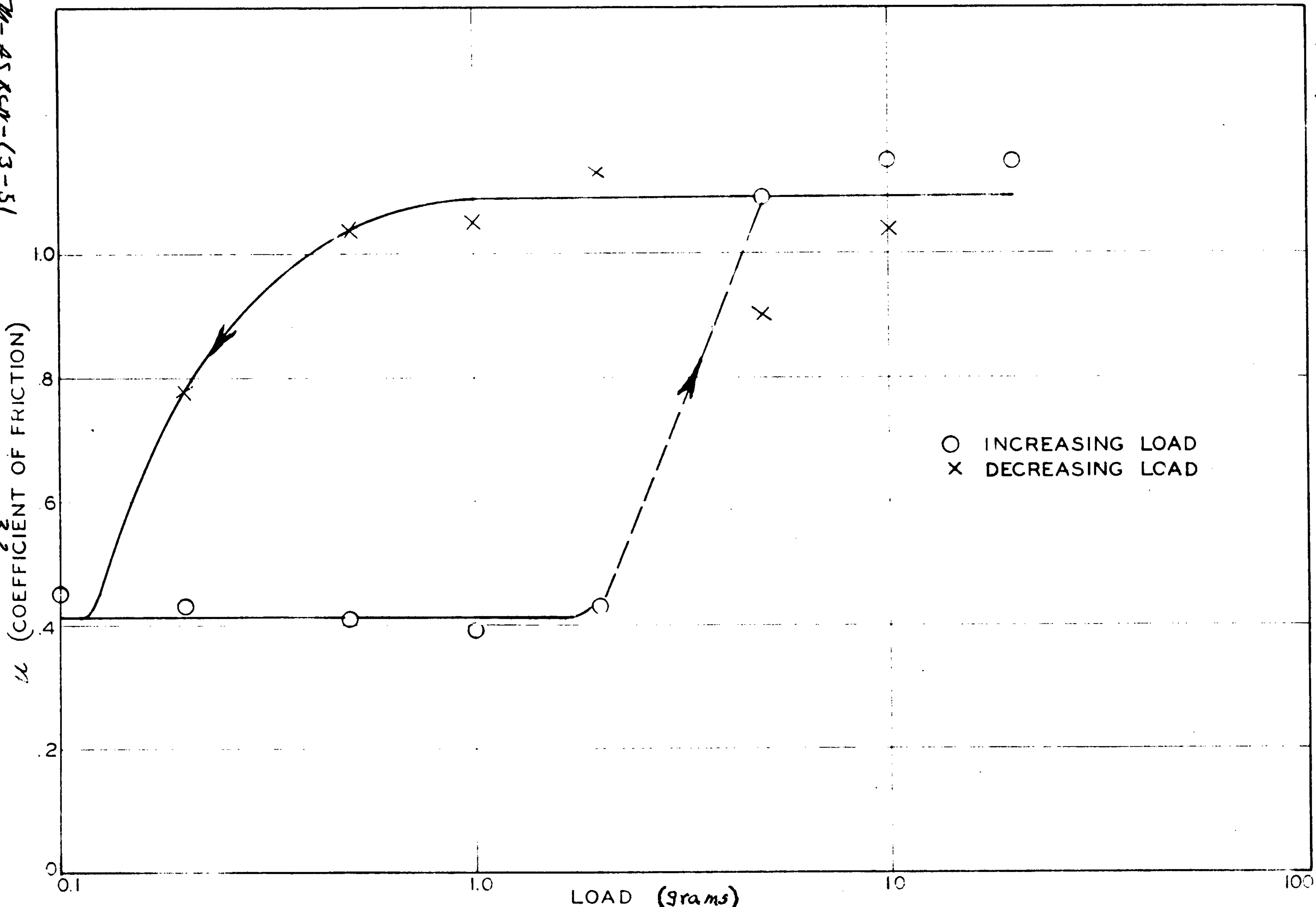
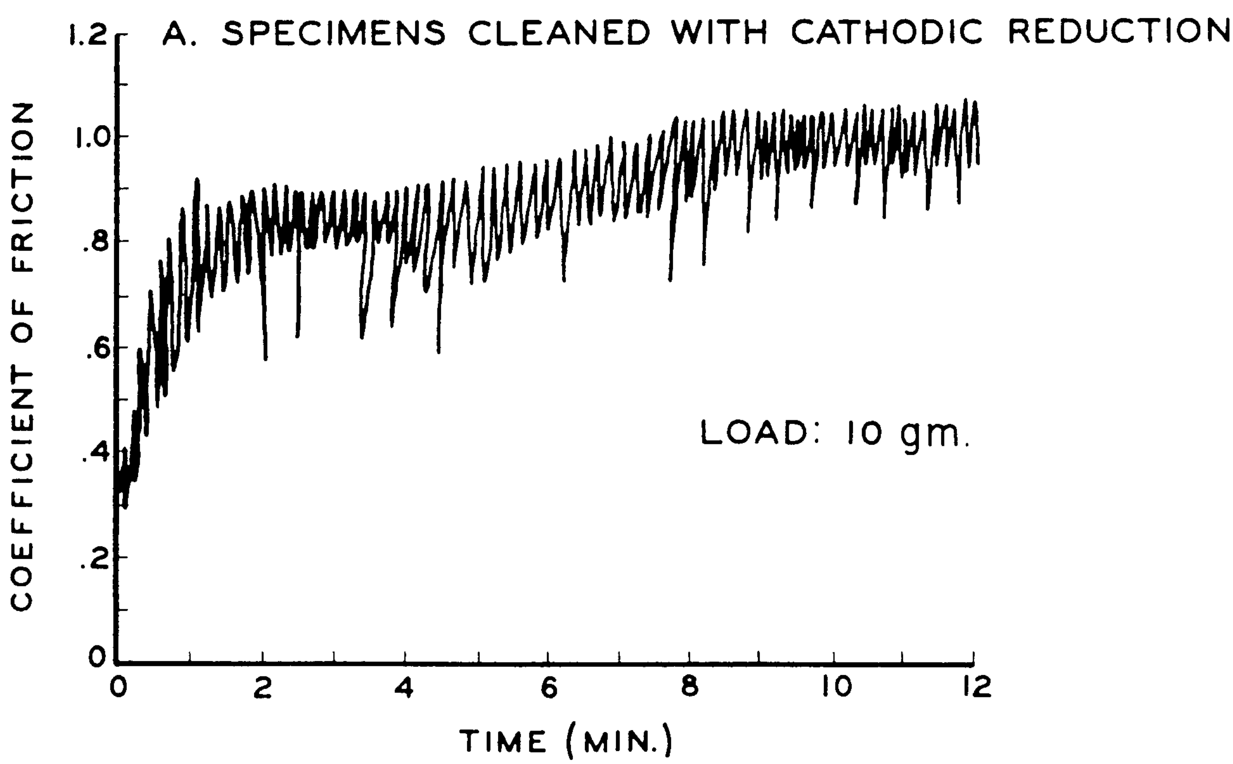
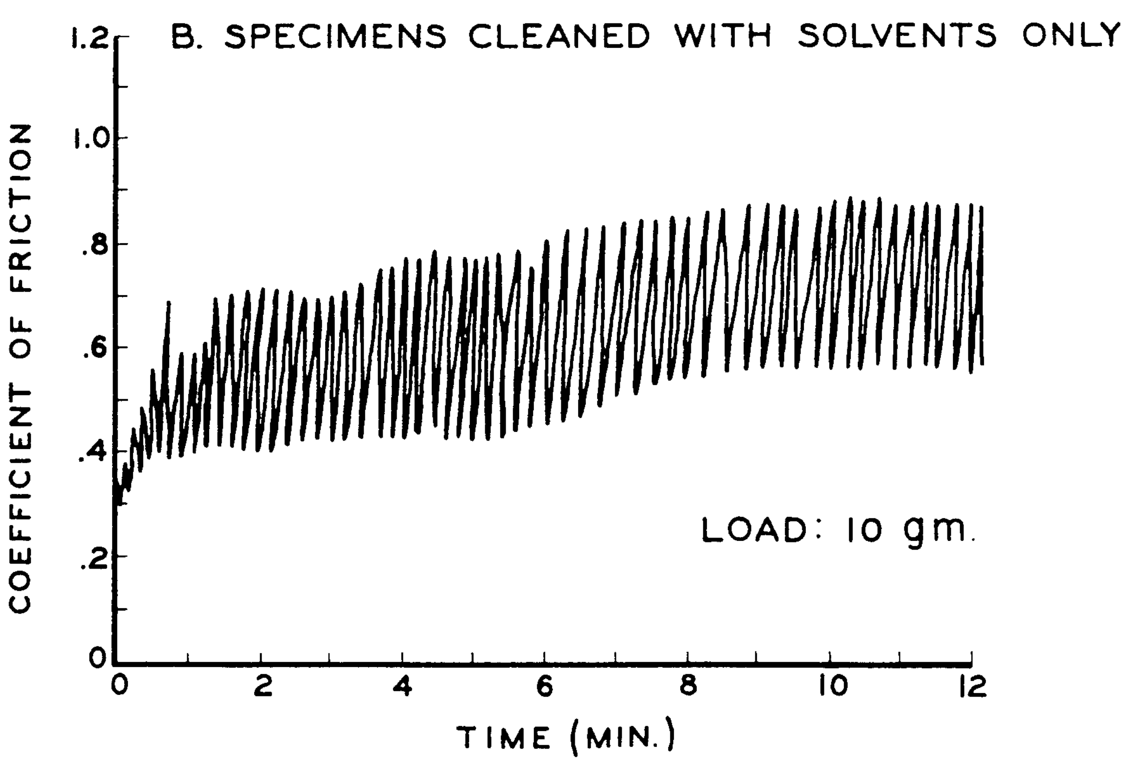


FIG. 8 [redacted] TYPICAL RESULT OF SLIDING FRICTION OF SOLVENT CLEANED SPECIMEN WITH CHANGING LOAD.

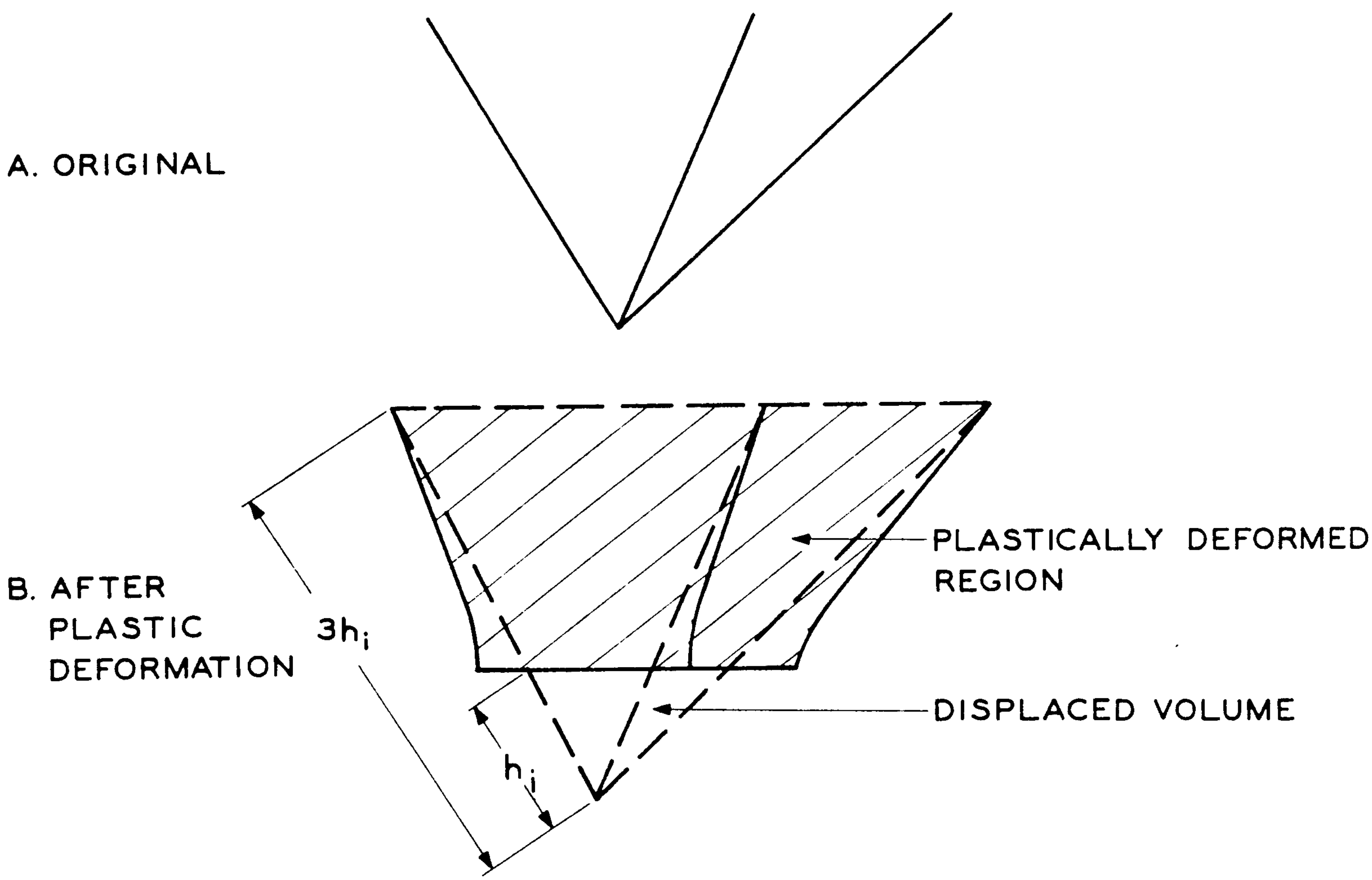
FIG. 9 SLIDING FRICTION BETWEEN M-10 TOOL STEEL SPECIMENS





M-ASRCN-13-[illegible]51

FIG. 10 MODEL ASPERITY



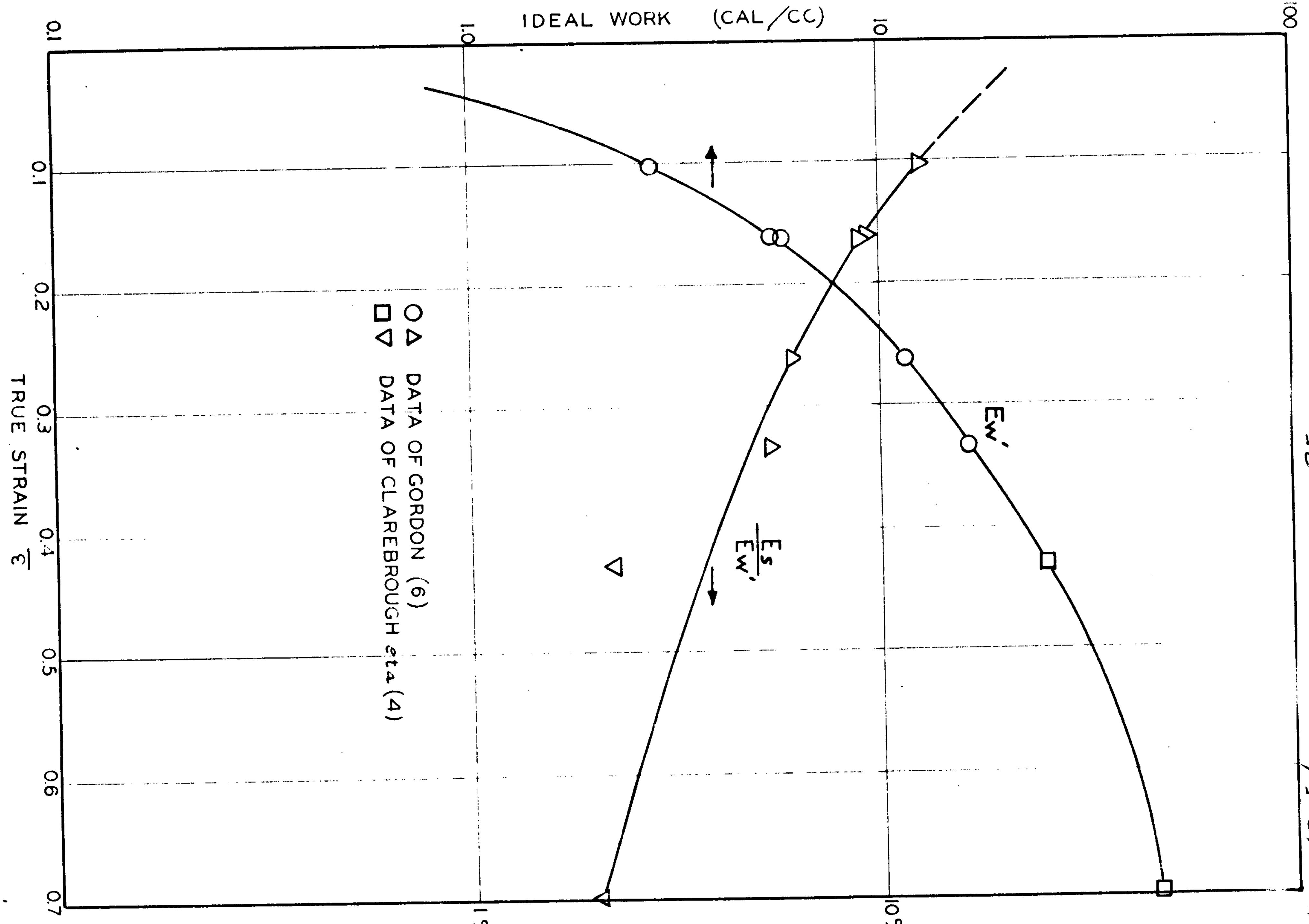


FIG.11 ENERGY DATA IN PLASTIC DEFORMATION OF COPPER