FINAL REPORT

on

STUDY OF JOINT THERMAL CONDUCTANCE IN VACUUM

to

GEORGE C. MARSHALL SPACE FLIGHT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

September 30, 1970

Contract No. NAS8-25451
Control No. DCN 1-0-50-09535 (IF) & S-1 (IF)

by

J. F. Lagedrost, H. R. Miller, and F. A. Creswick

BATTELLE MEMORIAL INSTITUTE
Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201

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INTRODUCTION

Thermal conductance of a bolted joint depends to a large extent on the true area of contact, which derives primarily from a combination of the type of material, hardness, surface roughness, surface waviness, and type of finish. Other factors, of course, include the apparent contact pressure and the presence of interstitial materials between the mating surfaces. True contact area is generally composed of microscopic contact points between surface asperities. Since it is virtually impossible to machine mating surfaces to the degree of accuracy required for the waviness amplitude at the interface plane to be small compared with the height of the surface asperities, the asperity contact is generally limited to those localized areas where the mating high points of the surfaces acutally meet.

When heat conduction across bolted joints is used as a means for cooling space-vehicle components, ordinary machined surfaces in contact normally present an undesirably high thermal resistance at the interface, particularly in a vacuum environment. In practice, this resistance can be reduced slightly by a number of techniques, such as the addition of conductive grease or soft metal foil to the joint. However, apparently none of the various methods that have been employed so far present a completely satisfactory solution to the problem. Consequently, it is desirable that alternative methods offering potential for further improvement be pursued.

One alternative method that offers promise is the use of bright leveling copper plating.

Leveling copper electroplates are used chiefly as undercoats for nickel and chromium over steel, zinc and aluminum die castings, and plastics. Corrosion resistance of steel and zinc alloys is substantially improved by the use of leveling and ductile copper, which fills and smoothens surface irregularities. Consequently, this type of copper plating is now being used extensively as an industrial process for finishing metal surfaces. A number of major automotive companies are plating bright leveling acid copper in place of the conventional cyanide copper in order to minimize or eliminate the need for expensive buffing.

Enhanced thermal conductance as a result of using this plating method on mechanical joints can be anticipated for several reasons: (1) leveling the surface should increase the true area of contact, (2) the low yield strength and ductility of the copper plating should further increase contact area by localized plastic deformation under load, and (3) the high thermal conductivity of copper should help to minimize the thermal barrier at the joint interface.

Accordingly, the objective of this study was to determine experimentally the feasibility of using bright leveling copper plating to improve the thermal conductance of mechanical joints in a vacuum.

APPROACH

The approach to this evaluation was to measure thermal conductance across prepared surfaces of mating ends of one-inch-diameter Type 6061 aluminum rods in contact under various conditions of load and surface preparation. The measurements were made in a steady-state, longitudinal heat flow, thermal-conductivity measurement apparatus.

The plan included thermal-conductance measurements across at least six pairs of prepared surfaces--three in an as-machined condition, and three similarly prepared pairs with the bright leveling copper plate added. Each of the three was machined in a routine fashion to a different micro-surface roughness. The measurements were made under vacuum, near room temperature, and at several contact pressures.

Mating ends of the aluminum rods were lathe-turned to three levels of roughness, nominally 8, 63, and 125 μin. CLA. The thermal conductance across joints of essentially matched pairs of these surfaces was measured at various pressures prior to their being copper plated, and also after plating.

Contact pressures were maintained at reasonably low levels (in the range of 20 to 60 psi apparent, i.e., based on the apparent 1-in.-diameter contacting area) to permit evaluation of the joint conductances without significantly flattening or distorting local surface asperities.

The measurements were checked for repeatability in some cases by removing the load on the specimens, rotating one member of the pair a small amount, re-applying the load, and re-running the experiment.

As the program progressed, preliminary results indicated that factors other than the surface microfinish apparently were limiting joint conductance. Prominent among these was gross flatness. Although it was recognized that lathe-turned ends of the contacting rods would not be truly flat, an objective of this study was to achieve flatness, as well as smoothness, with the plating process. The plating did achieve smoothness, but not flatness. Therefore, conductance measurements were made on one pair of specimens, the nominal 63-μin. CLA starting surface, after its copper-plated surfaces had been lapped. Results of this measurement, considered in conjunction with other data, provided at least a qualitative evaluation of flatness effects within the scope of this study.

RESULTS AND CONCLUSIONS

(1) Large variations in thermal conductance were observed to result from re-positioning as-machined specimens in the experimental apparatus. In some cases, this variation was as high as a 3:1 ratio between maximum and minimum values.

(2) A general improvement in joint conductance was observed to result from the application of the copper plating; however, because of the large variation in results, a conclusive demonstration that the copper plating alone provides improvement was not obtained. The observed conductance values for the plated specimens were in all cases greater than the average of values for the as-machined specimens, but in some individual measurements, as-machined specimens showed a higher conductance than the specimens after plating.

(3) It is concluded that other surface variables are as important as material and surface finish in affecting joint conductance; therefore, a leveling copper plating applied to an as-machined surface will not by itself assure low thermal resistance.

RECOMMENDATIONS

We recommend that, in future efforts to develop a practical means for processing mechanical joints so as to achieve both high and predictable thermal conductance, both mechanical surface-finishing variables and plating processes be considered. The potential benefits of bright leveling copper plating should be re-examined in a more extensive subsequent study in which other surface variables are controlled to a greater degree.

PROCEDURE

Specimen Preparation and Characterization

Test specimens were machined from 1-in.-diameter Type 6061 aluminum bar stock to a length of 5 in. Single ends of the specimens were lathe-turned to nominal roughness levels of 8, 63, and 125 microinches (μin.) CLA. A number of samples of each surface roughness were prepared, and 3 mating pairs were selected, one for each roughness level, on the basis of similar surface finish and flatness. Surface characterisitics were measured by a Talysurf* machine.

After thermal-conductance measurements had been carried out on these as-machined pairs, each specimen was then plated individually and Talysurf measurements were repeated. The excellent leveling characteristics of the acid copper are shown in the photograph of Figure 1, in which the 63-μin. surface roughness of the as-machined specimen on the left is reduced to less than 1 μin. by copper plating.

The joint thermal conductance of one matched pair, 8A and 8E, was measured after plating without further surface changes. As shown in Table 1, leveling acid copper plating of the 8-μin. specimens did not significantly alter surface flatness, but did greatly reduce the roughness. Another matched pair, 125C and 125G, was polished after plating to increase flatness, then replated, but uniform flatness could not be achieved by such polishing because edges were often preferentially polished. A third pair, 63F and 63H, was lapped after copper plating

*Talysurf 4, Engis Equipment Company, Morton Grove, Illinois

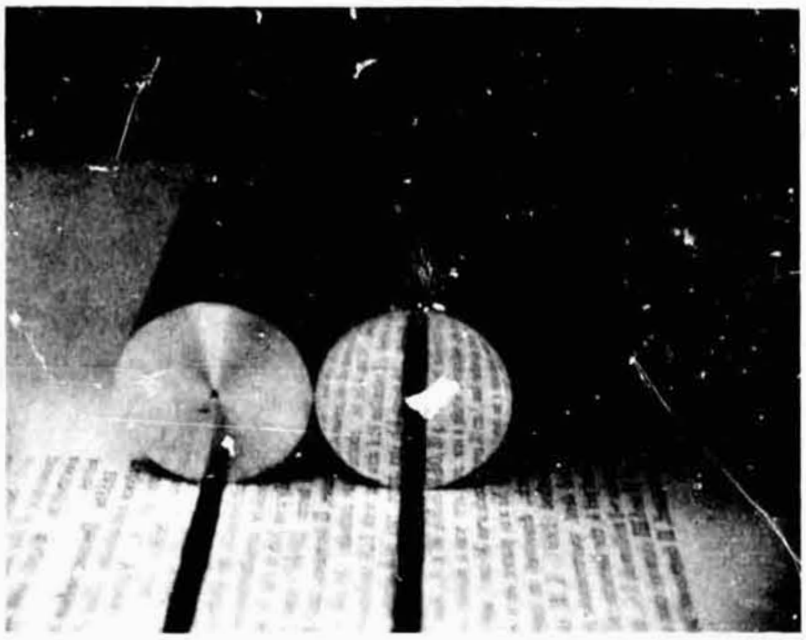


FIGURE 1. PHOTOGRAPH OF SPECIMENS BEFORE (LEFT-63H) AND AFTER (RIGHT 63F) PLATING WITH 3 MILS OF LEVELING ACID COPPER

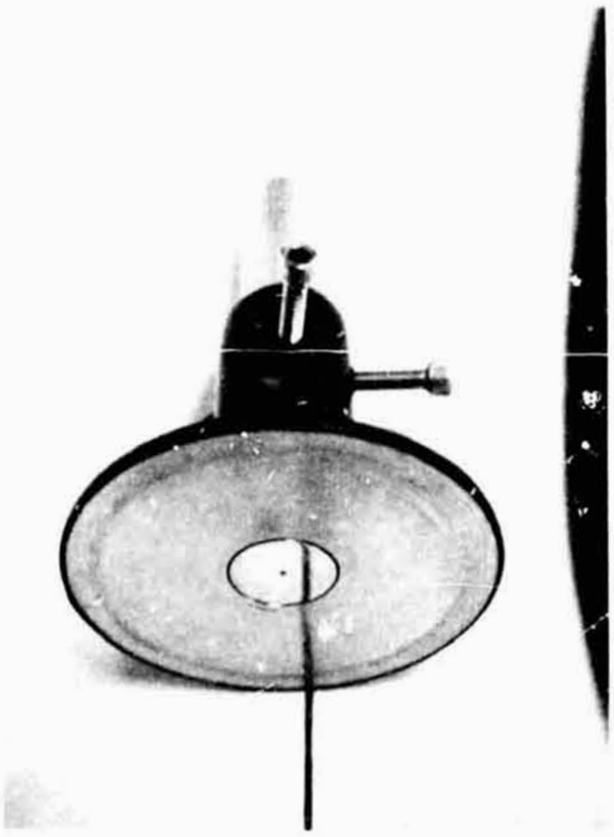


FIGURE 3. VIEW OF ASSEMBLED FIXTURE EMPLOYED FOR OBTAINING UNIFORM COPPER DISTRIBUTION

TABLE 1. CHARACTERIZATION OF ALUMINUM ALLOY 6061 SURFACES FOR JOINT THERMAL CONDUCTANCE STUDIES

Specimen No.	Plating Thickness, inch	Surface Roughness Measurements, μin.[a]						Flatness, μin.[b]			
		After Machining RMS	After Machining CLA	After Plating RMS	After Plating CLA	After Polishing CLA	After Lapping CLA	After Machining	After Plating	After Polishing	After Lapping
8A	0.0015	8	10	0.5	1	-	-	120	90 and 140[c]	-	-
8E	0.0015	8	10	0.5	1	-	-	170	140 and 250[c]	-	-
63F	0.003	63	78	0.7	1	5	2	60	450	90	<6[c]
63H	0.003	63	78	0.7	1	7	3	60	150 and 200	-	<10[c]
125C	0.005	125	150	1.5	35	18	-	60	130	900[c]	-
125G	0.006	125	150	1.0	-	5	-	140	200 and 400	100 and 400 (c)	-

(a) RMS: root mean square; CLA: Center Line Average.

(b) Distance from highest peak to trough of waves for one or two different radii. Ten μin. are equivalent to 0.00001 inch.

(c) Joint thermal-conductance measured on this surface.

in order to achieve a high degree of flatness. Talysurf recordings after machining, plating, polishing, and lapping are illustrated in Figure 2 for Specimen 63F. Talysurf data listed in Table 1 and shown in Figure 2 for the lapped surfaces were confirmed using optical-flat measurement equipment.*

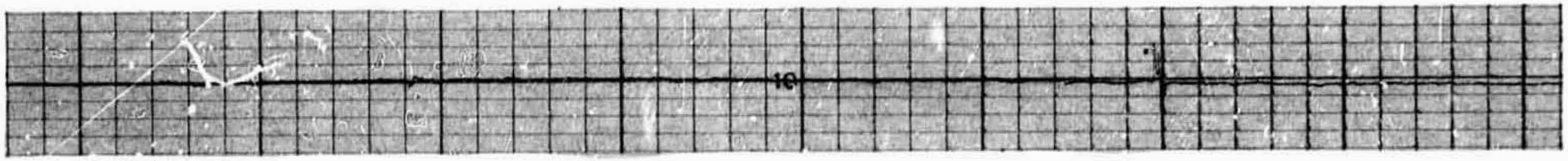
Fixture Design and Plating Procedure

Two basic types of fixtures, a tubular Lucite shield and a stainless steel disk-shaped robber, were designed to improve copper-thickness uniformity on the ends of the aluminum rods. A Kocour thickness tester was used for measuring thickness. The stainless steel disk was chosen because it eliminated copper build-up on the circumference of rods when the rods were slightly recessed into the fixture. There was metal buildup on rods plated in the Lucite shield. A photograph of the disk and rod assembly is shown in Figure 3.

Nonproprietary solutions** for activating 6061 aluminum alloy for plating were unsatisfactory due to poor adhesion and resulting blistering. Satisfactory adhesion was achieved and blistering was eliminated by substituting proprietary alkaline and acid etching solutions for the nonetching alkaline soak cleaner and two acid etching solutions. Double zincating was employed in both procedures to insure a thin adherent zinc deposit before copper striking in a cyanide copper bath. The procedure used to prepare specimens listed in Table 1 is detailed in Appendix A

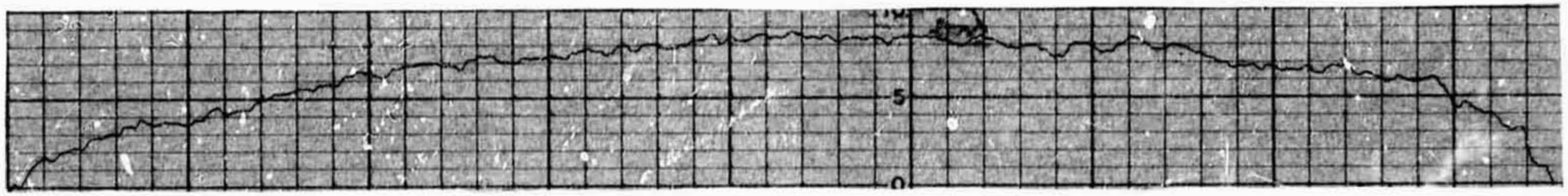
* Do All Mono-light instrument made by Do All Company of Des Plaines, Illinois.

**For wrought alloy 61S, page 231, 1970 Metal Finishing Guidebook Directory.



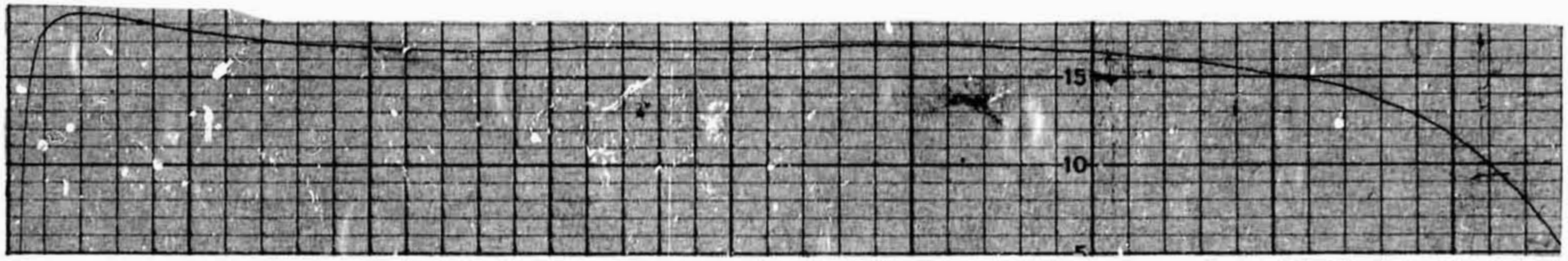
(d)

One Radius After Lapping: CLA=2 μin.; Vertical Small Division=20 μin.; Horizontal Small Division=0.01 in.



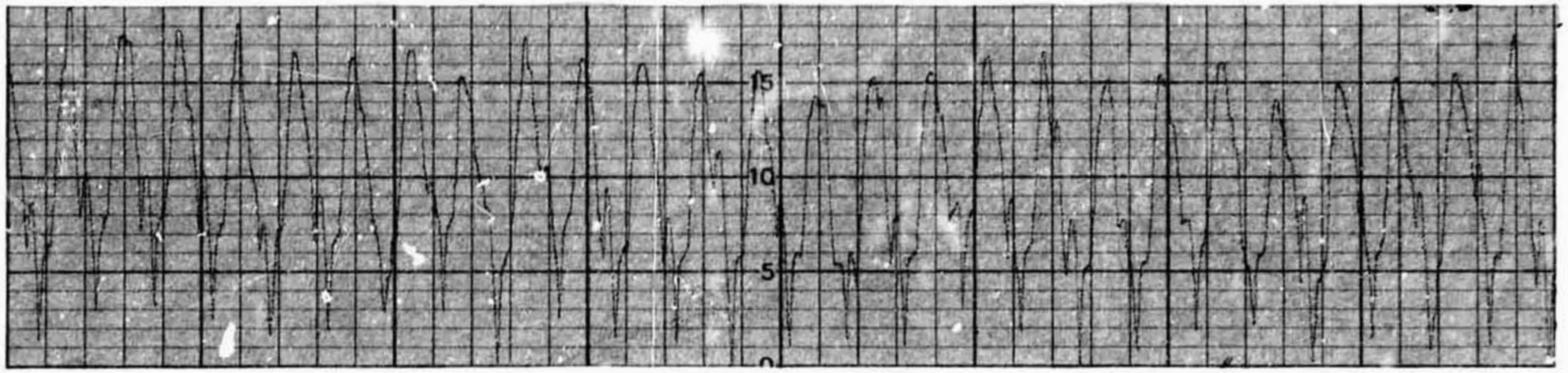
(c)

One Radius After Polishing: CLA=5 μin.; Vertical Small Division=10 μin.; Horizontal Small Division=0.10 in.



(b)

One Radius After Plating: CLA=1 μin.; Vertical Small Division=50 μin.; Horizontal Small Division=0.01 in.



(a)

A Section Of One Radius After Machining: CLA=78 μin.; Vertical Small Division=20 μin.; Horizontal Small Division =0.002 in.

FIGURE 2. TALYSURF RECORDINGS FOR SPECIMEN 63F AFTER MACHINING (a), AFTER PLATING (b), AFTER POLISHING (c), AND AFTER LAPPING (d).

Suggested sources for plating of space hardware using the recommended procedure are also included in Appendix A.

Satisfactory copper thickness distribution was obtained on two of six specimens, 8A and 8E, plated with 0.0015 inch, as indicated in Table 1. Poor copper distribution on the other four specimens is attributed primarily to a misalignment of the bar in the center of the hole in the stainless steel disk. Such nonuniformity might have been eliminated if a conductive gasket between the bar and the stainless steel ring had been used in place of a nonconducting gasket. A tendency for insufficient copper thickness near the circumference of the guide hole in the center of each aluminum specimen was exaggerated when the thickness of the copper was increased from 0.0015 to 0.003 or 0.005 inch. Thus, a thickness limit of about 0.0015 inch seems appropriate to avoid large variations in thickness uniformity. If thickness is limited to 0.0015 inch, surface roughness should not exceed about 20 μ inches, rms. The edge effects that complicated the preparation of the 1-inch-diameter specimens would be less troublesome in larger pieces of equipment.

Thermal Conductance Measurements

The thermal-conductance measurement apparatus used in this study is illustrated in Figure 4. In this apparatus, heat is transferred axially along a rod specimen from a source of a sink. Conductivity is then calculated using the standard relationship,

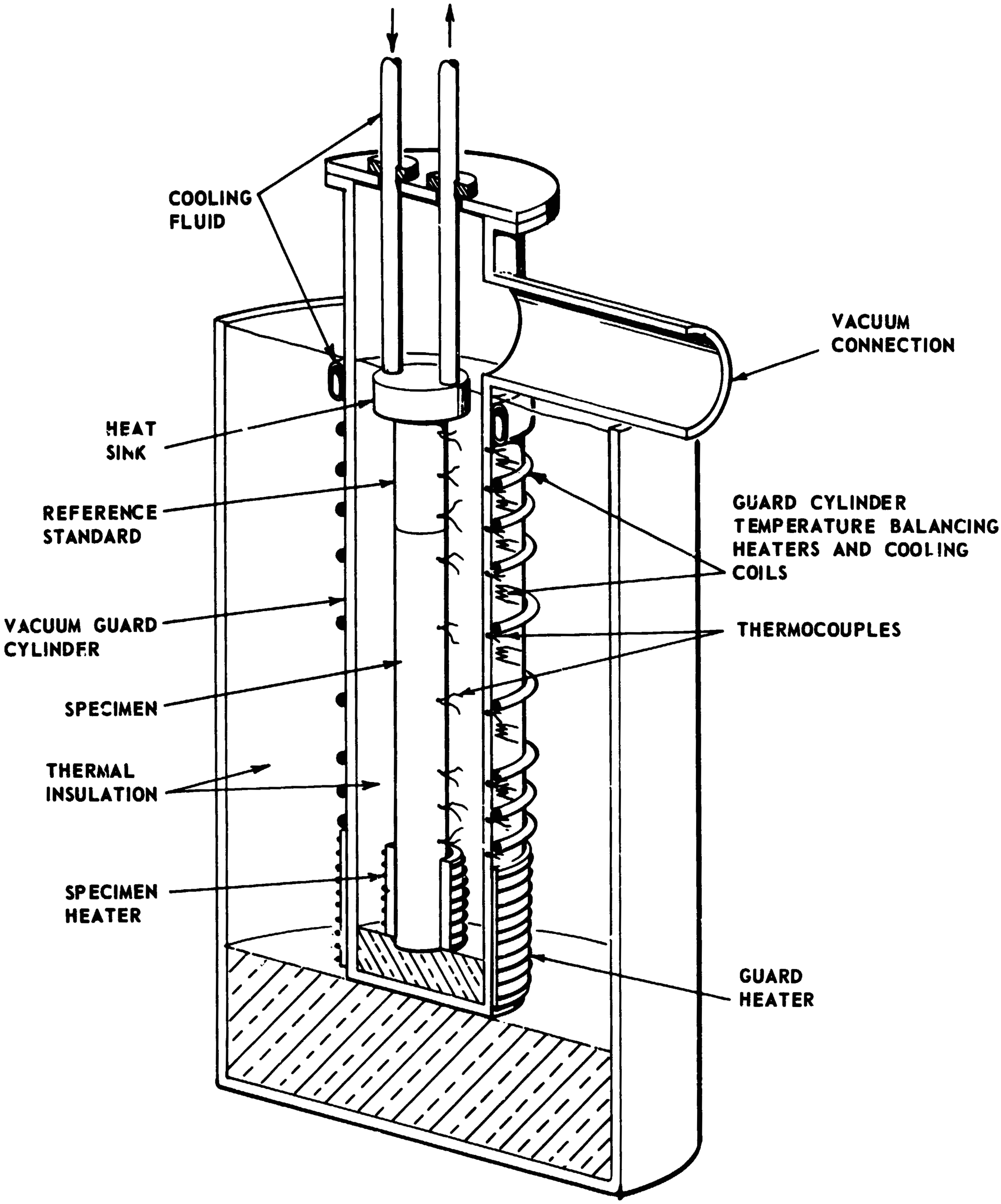


FIGURE 4.

THERMAL-CONDUCTIVITY APPARATUS FOR METALS

$$q = k\,A\,\frac{dT}{dx} \quad , \qquad (1)$$

where

q = heat flow rate

k = thermal conductivity

A = specimen cross section area

$\frac{dT}{dx}$ = specimen temperature gradient in longitudinal direction .

Longitudinal heat flow is maintained with the aid of thermal insulation and a guard cylinder which is fitted with heaters and cooling coils. Temperatures in the guard cylinder are matched with those in the specimen or meter at a given vertical location through use of the guard heaters and cooling coils; this effectively minimizes radial heat losses. The system is normally run under vacuum to eliminate convective heat transfer as well as protect the specimen.

Thermal conductance across the lightly loaded joint of the two rods used in this study was defined as

$$c = \frac{q}{\Delta T} \quad , \qquad (2)$$

where q is the heat flow longitudinally through the aluminum rods, as computed using Equation (1), and ΔT is the temperature difference across the joined surfaces, as determined from extrapolation of thermocouple data.

All measurements of this study were made at moderately low temperatures; the normal average contact-surface temperature was near 80 C. The system was run under vacuum of nominally 1×10^{-4} mm Hg.

Loading was accomplished by applying external dead weight to the vertical column; translation was possible through sliding vacuum seals.

Concentricity of the pair was assured by a 0.03-in.-diameter pin inserted in a central hole in each specimen. Nonaxial loading was prevented by the use of a ball joint to support the lower specimen.

Thermal-contact conductance of each of the three basic as-machined surfaces was measured at each of four pressures. In addition, repeat conductance measurements were made on the 125-and the 8-μin. CLA (extremes) surfaces to check on uniformity. The repeat measurements were executed identically to the originals, after slight rotational displacement of the mating pair.

DISCUSSION OF RESULTS

Thermal-Conductance Data

The results of the thermal-conductance measurements are given in Table 2 and plotted in Figures 5, 6, and 7. Results illustrate the extreme sensitivity of location to conductance across the as-machined surfaces, and also, the lack of correlation with surface finish. Obviously, factors other than or in addition to microfinish have a substantial effect.

Table 2 also gives conductance values for the specimen pairs in the as-plated condition. As indicated, measurements were made on two of the sample pairs following rotational relocation. These showed far less sensitivity to the location effect than was evident for as-machined surfaces. Although not enough data are available to permit a comprehensive evaluation of orientation effects, it is apparent that considerably better consistency is achieved with the copper plating over that of the as-machined

TABLE 2. JOINT THERMAL CONDUCTANCE DATA

Specimen Pair	Nominal CLA, μin.	Surface Condition	Joint Conductance, watts per deg C			
			20 psi	27 psi	45 psi	56 psi
C-G	125	as-machined	1.49	1.64	1.78	1.79
		as-machined	0.52	0.50	0.71	0.85
		as-machined	0.94	1.05	1.35	1.54
		as-plated	1.28	1.47	1.88	2.04
		as-plated	- -	- -	- -	1.92
A-E	8	as-machined	0.49	0.61	0.84	0.92
		as-machined	1.04	1.20	1.56	1.75
		as-machined	- -	1.06	- -	1.75
		as-plated	0.86	1.05	1.35	1.56
		as-plated	- -	- -	- -	1.54
F-H	63	as-machined	0.36	0.45	0.50	0.57
		as-plated and lapped	0.62	0.85	1.75	1.96

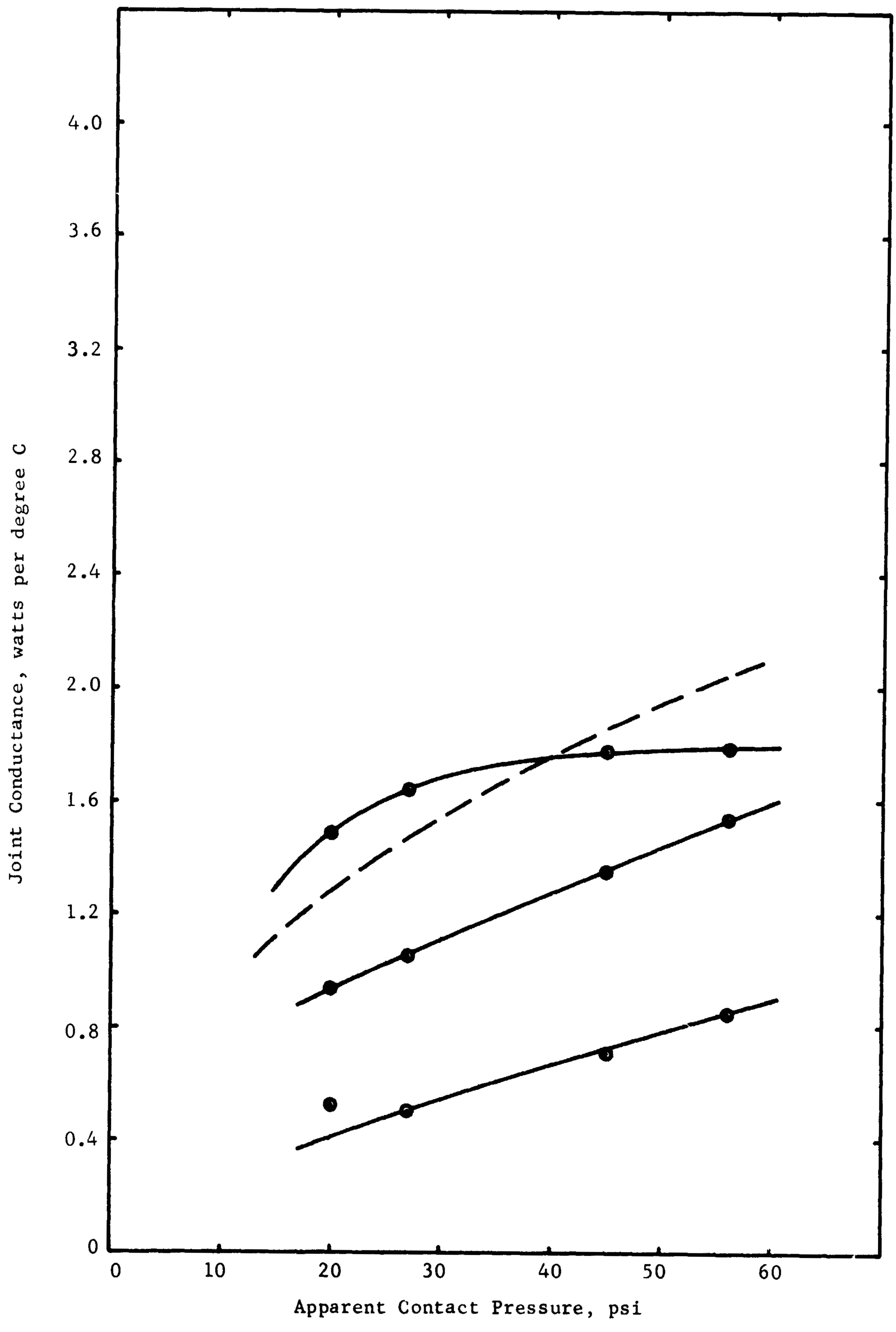


FIGURE 5. JOINT THERMAL CONDUCTANCE OF NOMINAL 125 μin. CLA SURFACES IN CONTACT AT VARIOUS ROTATIONAL POSITIONS (Dashed curve represents data after plating)

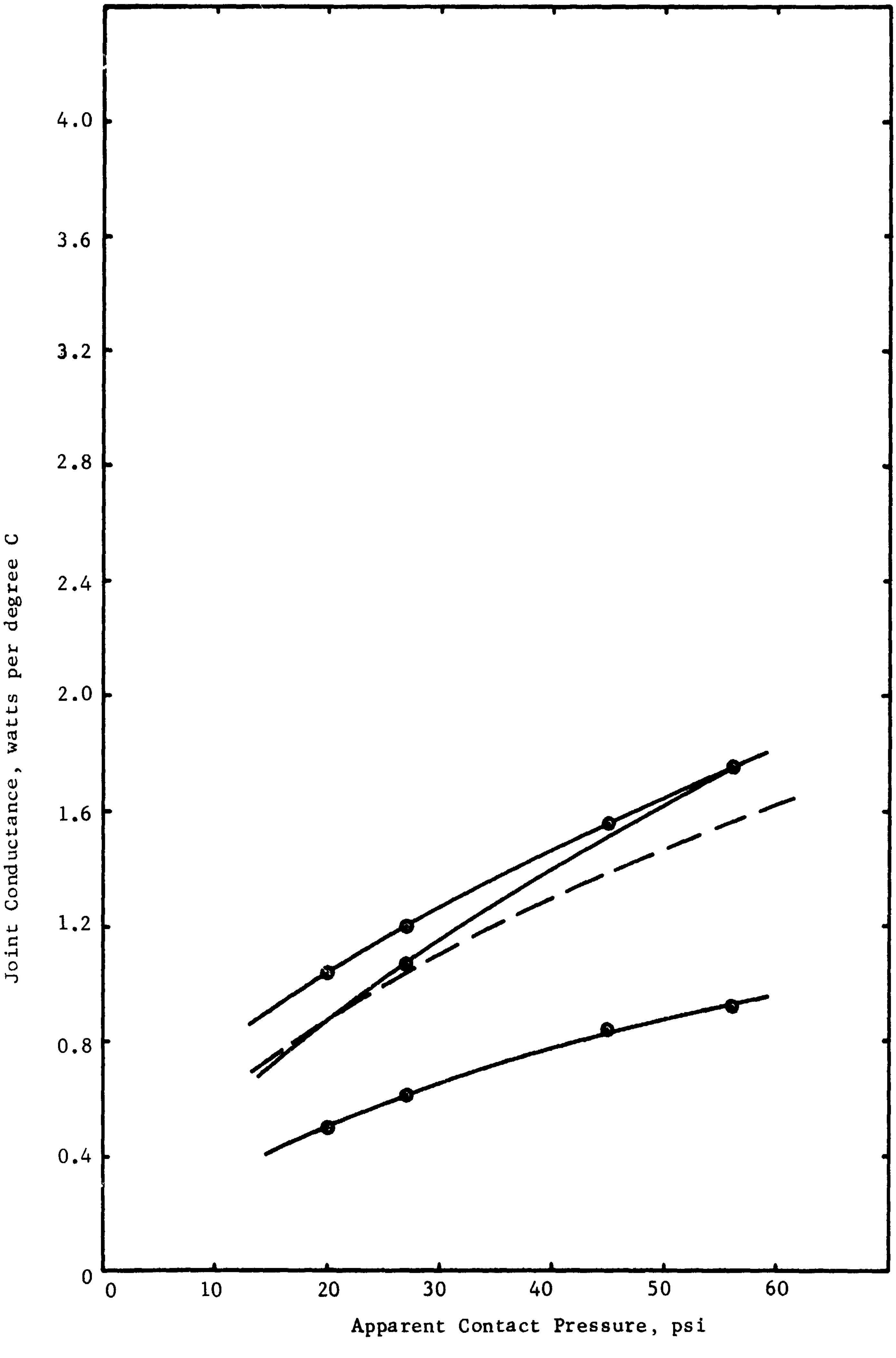


FIGURE 6. JOINT THERMAL CONDUCTANCE OF NOMINAL 8 μin. CLA SURFACES IN CONTACT AT VARIOUS ROTATIONAL POSITIONS (Dashed curve represents data after plating.)

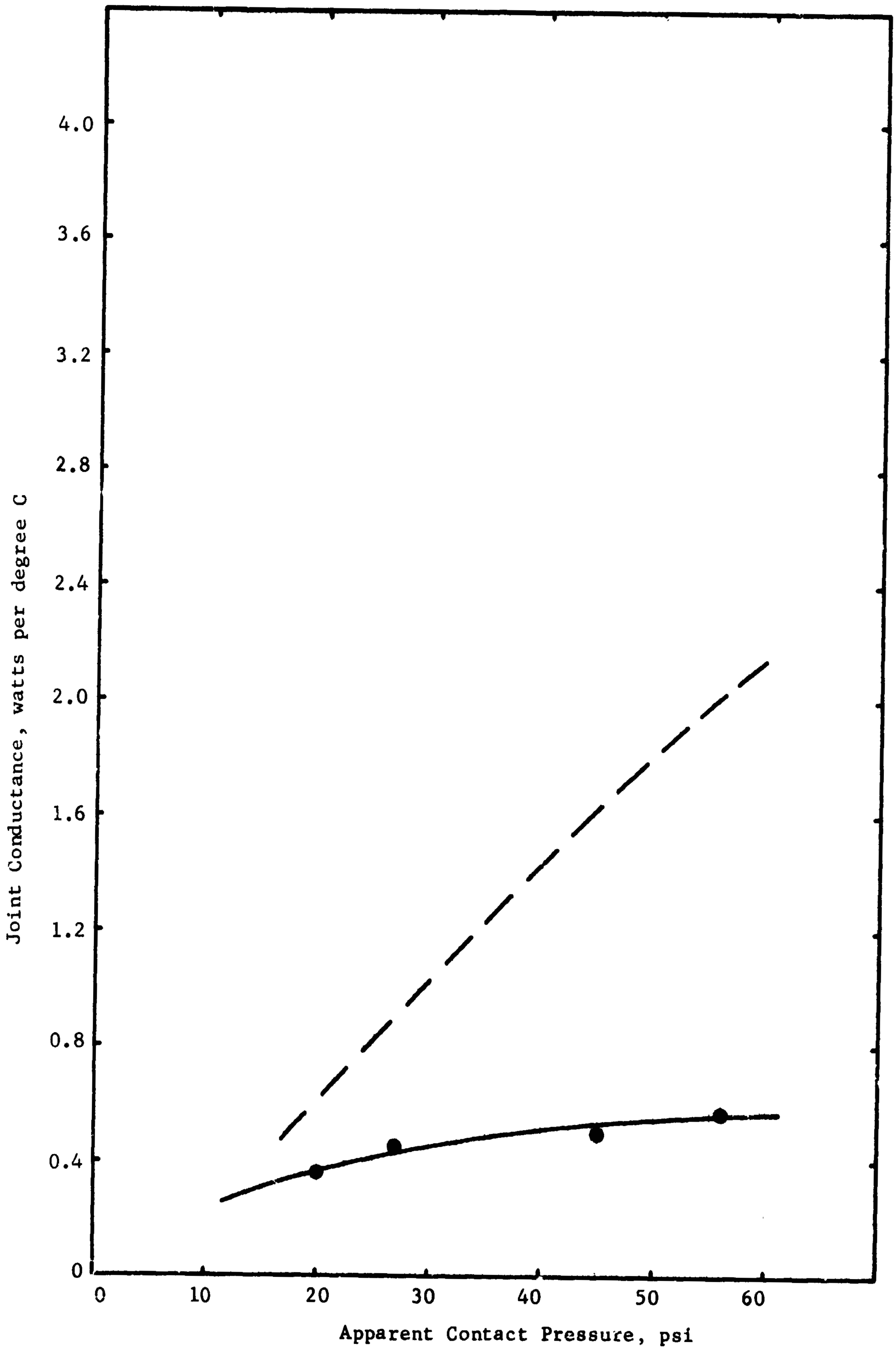


FIGURE 7. JOINT THERMAL CONDUCTANCE OF NOMINAL 63 μin. CLA SURFACES IN CONTACT (Dashed curve represents data after plating and lapping.)

surfaces. This was anticipated in view of the high thermal conductivity of the copper, and the general smoothing effect of the plating.

It is not recommended that any quantitative conclusions be drawn from the Table 2 data for as-machined surfaces. The wide scatter of data for similarly prepared surfaces indicates that mechanisms more complex than can be evaluated through simple profilometer readings are involved in controlling heat flow across joined metal surfaces.

On the other hand, some improvement in conductance due to the copper plating was indicated. If averaging of the data sets in Figures 5 and 6 is permitted, a comparison of before-plating and after-plating conductances is possible. Figure 8 shows an improvement near 40 percent for the nominal 125-μin. CLA surfaces as a result of the plating, and Figure 9 shows an improvement near 20 percent for the nominal 3-μin. CLA surfaces. Obviously, the validity of these values is limited by the small amount of data available, and the scatter of "as-machined" results.

Figure 10 illustrates a potential improvement in conductance when the contact surfaces are lapped as well as plated. Again, the limited data do not permit a comprehensive evaluation of the effects of the leveling copper plating on conductance. The fact that the change is significantly greater than for cases in which plating only was employed emphasizes the importance of flatness in minimizing contact resistance.

The curves representing data for as-plated joints are included in Figures 5, 6, and 7 for convenience in evaluation.

Results of the measurements have indicated that thermal conductance across joined surfaces can be enhanced by application of bright leveling copper. However, it was not possible within the scope of this

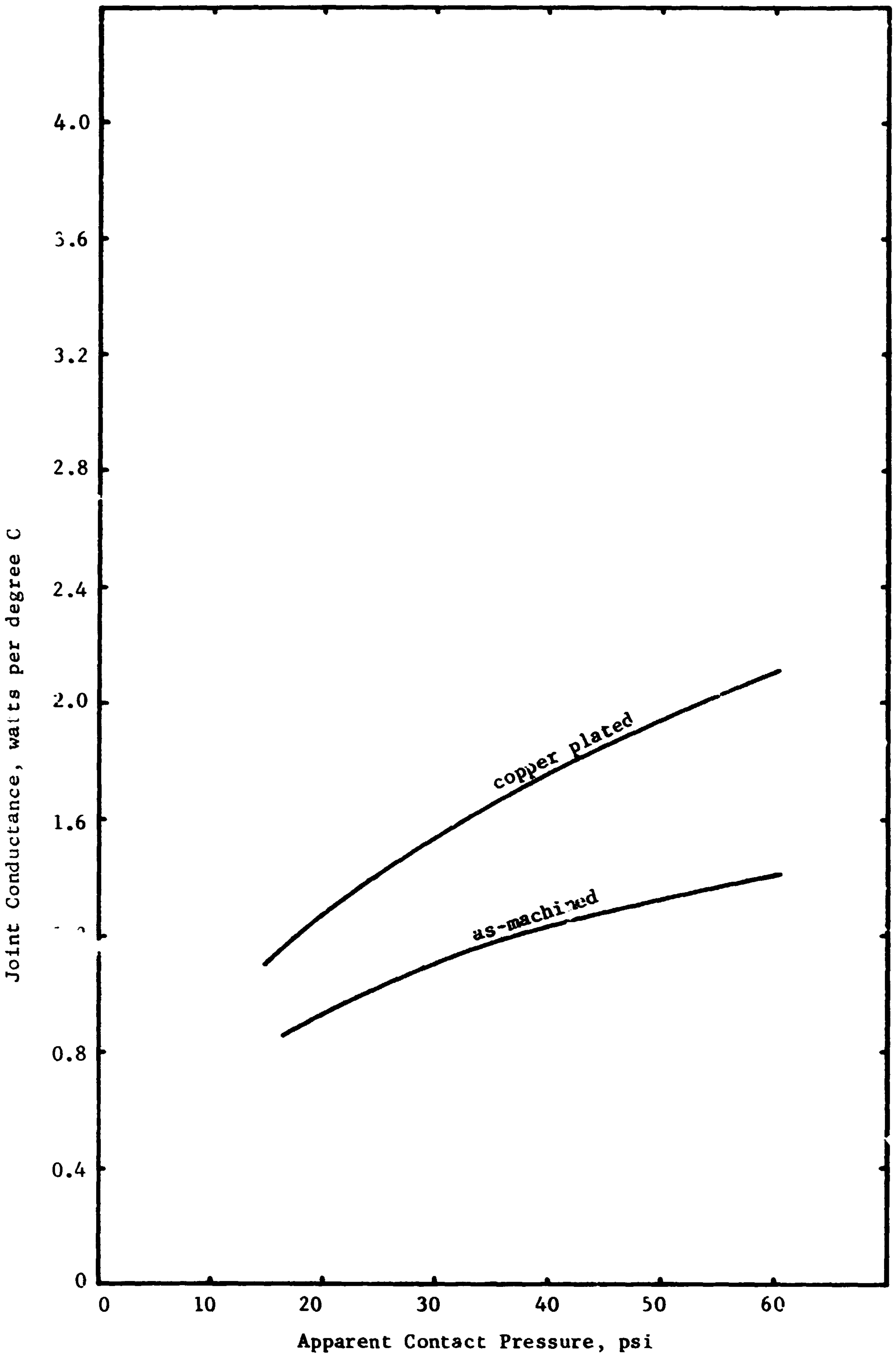


FIGURE 8. COMPARISON OF JOINT THERMAL CONDUCTANCES WITH AND WITHOUT BRIGHT LEVELING COPPER ON NOMINAL 125 μin. CLA SURFACES (Averages of data)

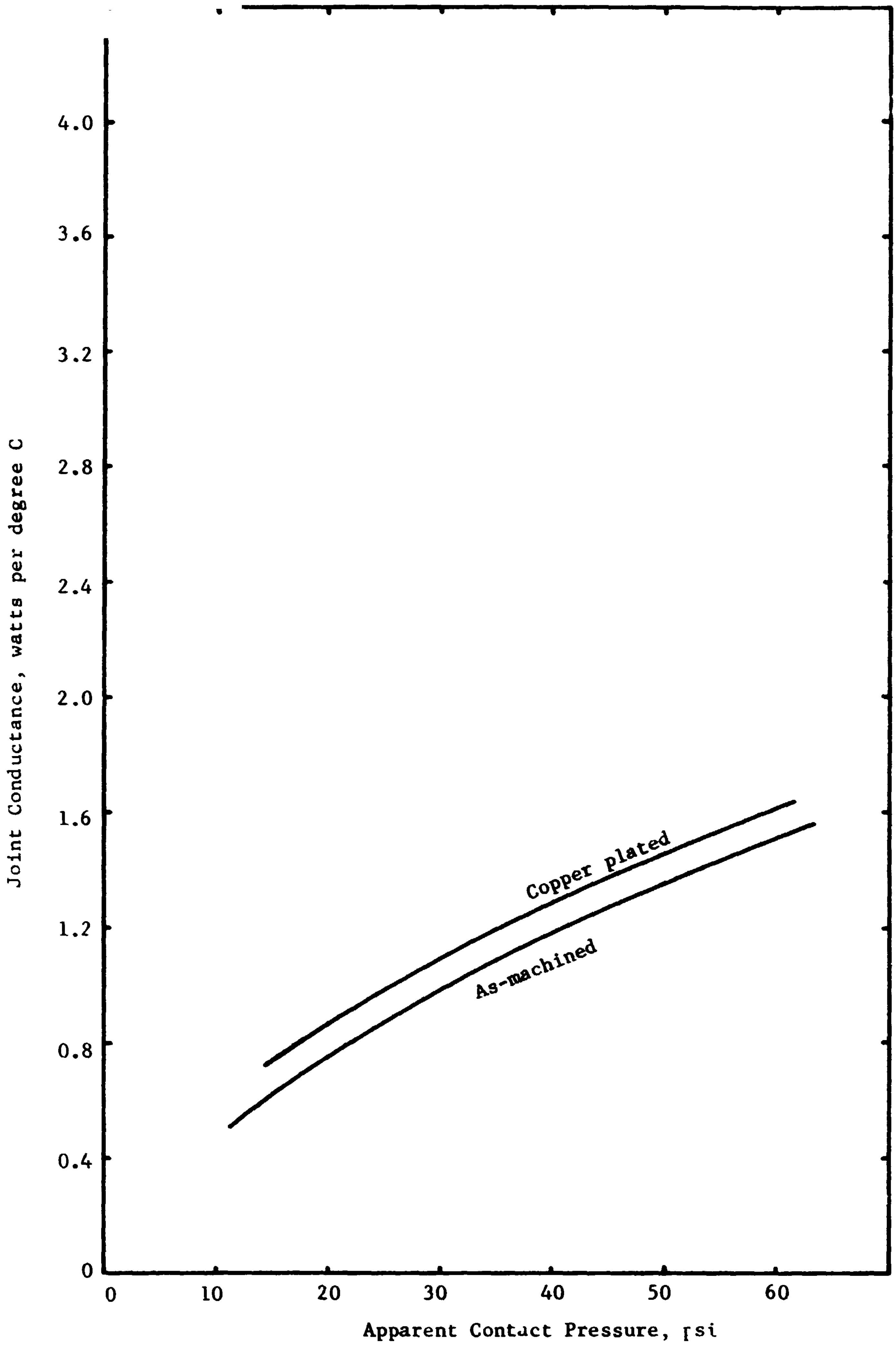


FIGURE 9. COMPARISON OF JOINT THERMAL CONDUCTANCES WITH AND WITHOUT BRIGHT LEVELING COPPER ON NOMINAL 8 μin. CLA SURFACES (AVERAGES OF DATA)

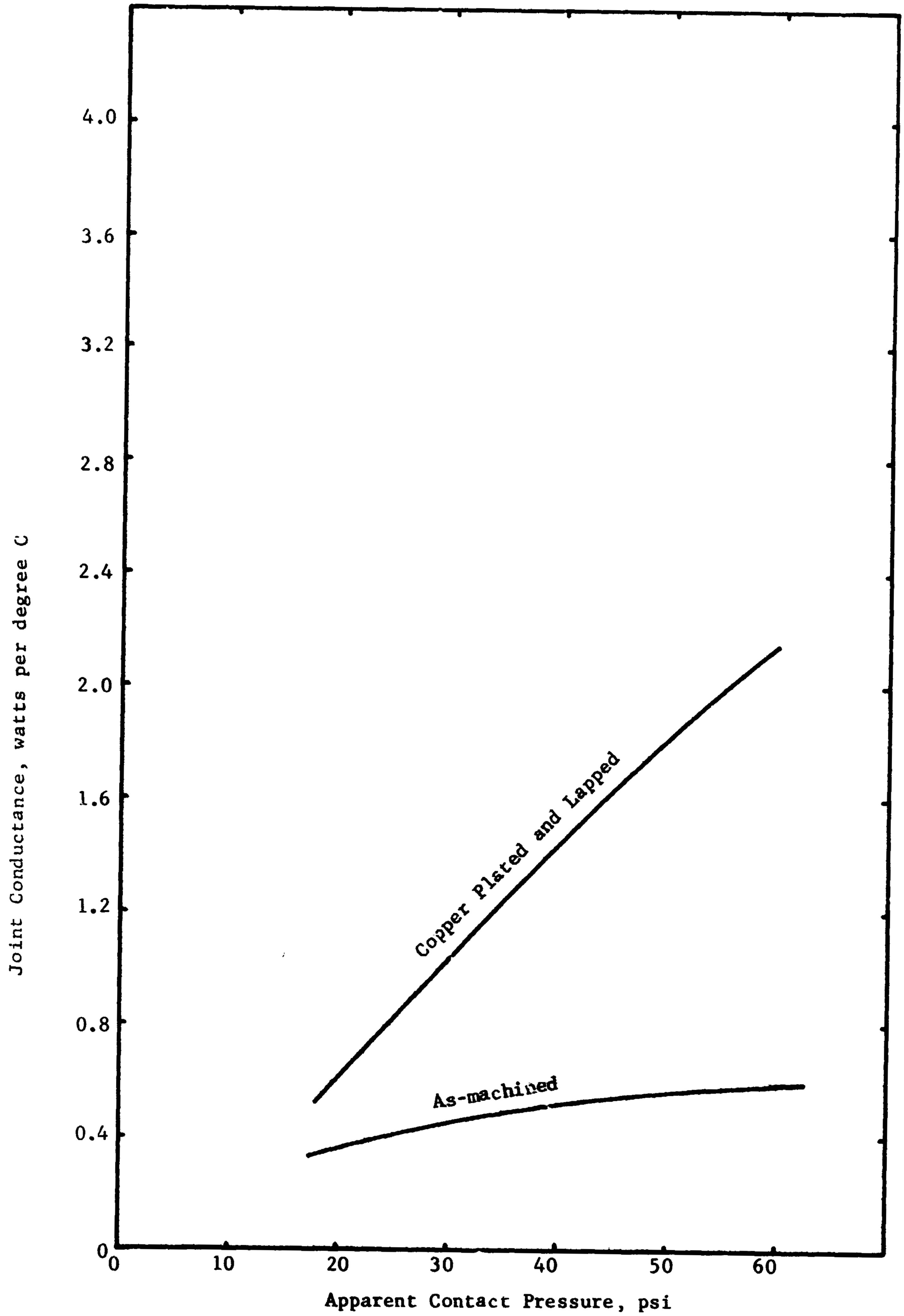


FIGURE 10. COMPARISON OF JOINT THERMAL CONDUCTANCE WITH AND WITHOUT BRIGHT LEVELING COPPER PLUS LAPPING ON NOMINAL 63 μin. CLA SURFACES (AVERAGES OF DATA)

study to evaluate quantitatively that amount of improvement. This is due primarily to the fact that thermal resistances across similarly prepared joining surfaces in the as-machined condition vary widely. (It is obvious that profilometer readings alone are not sufficient to characterize contact surfaces.) The data on Figures 5, 6, and 7 illustrate two important points relative to this scatter: (1) on the basis of this work, the probable correlation of surface microfinish (as-machined) and thermal resistance is not indicated, and (2) in some cases, as-machined surfaces had lower contact resistance than surfaces after plating. The major points here are that actual contact areas can vary widely and unpredictably among similarly machined surfaces, and that plated surfaces can give more uniform and predictable results but, in the absence of good flatness, can have only limited contact area and thus higher-than-necessary resistance.

RECOMMENDATIONS FOR FUTURE WORK

Since it is reasonable to assume that contact resistance is minimized when the contact surfaces are flat and smooth, efforts in future work should be directed toward development of simple techniques to achieve these conditions. It is possible that a combination of surface preparation and plating would be most effective.

We suggest a study in which efforts are first made to produce unplated joint-conductance specimens that will produce repeatable conductance data. Lapping is an attractive means of producing surfaces with a high degree of flatness, for example, and lapped specimens may exhibit the desired degree of repeatability in thermal measurements. If this is the case, the effect of the application of bright leveling copper platings of less than 1-mil thickness should then be investigated.

The results of such an investigation, if successful, could be used for specifications of flatness and surface treatment of aerospace-component mechanical joints where high conductance is needed for thermal control.

* * * * * * * * * *

Data and calculations for this study are recorded in Battelle-Columbus Laboratory Record Books No. 27,950 and 27,969. The Battelle project number is G-0477.

APPENDIX A

PROCEDURE FOR ACID COPPER PLATING OF ALUMINUM ALLOY 6061 IN A STAINLESS STEEL FIXTURE

The procedure for plating copper adherently on alluminum alloy 6061 rod was as follows:

(1) Each 1-inch diameter rod was vapor degreased in trichloroethylene.

(2) All but the bottom 1/2 inch of each rod was stopped off with platers tape (3M Electroplating Tape No. 470).

(3) The bottom of each rod was then immersed in 6 oz/gal Diversey 202* etching cleaner for one minute at 170F followed by hot water rinsing at 120F.

(4) The rod was then immersed in Diversey* 6162 deoxidizer and desmutter containing No. 61 solution at full strength with 6 oz/gal of No. 62 powder for one minute at 160F followed by a cold water rinse. This solution is cloudy and requires stirring before use.

(5) The rod was then immersed in a 40 oz/gal Diversey Zinc-8 displacement solution for 30 seconds at 70F followed by two 20-second water rinses at 120 and 70F, respectively.

(6) Steps (4) and (5) were then repeated. The 6162 solution in Step (4) removed the initial zinc displacement coating.

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* Diversey Chemical Company, Div. of Diversey Corp., 212 W. Monroe St., Chicago, Illinois.

(7) After the above double zincate treatment, each rod was immersed in a cyanide copper strike solution containing 5.5 oz/gal copper cyanide, 7.5 oz/gal sodium cyanide, 1.0 oz/gal free sodium cyanide, 4 oz/gal sodium carbonate, and 8 oz/gal Rochelle Salts for 2 minutes at 20 amp/sq ft, then reduced to 30 amp/sq ft for 2 more minutes at 130F, followed by cold water rinsing.

(8) The tape was replaced with a 0.017-inch-thick sleeve of heat-shrinkable vinyl previously prepared on a similar rod but covering most of the aluminum rod except for about 15 mils from the end to be plated.

(9) The rod was inserted into the stainless steel fixture, bolted into position with the rod recessed about 5 mils using a machined Lucite plastic positioning rod, and immersed into a 5 percent by weight sulfuric acid at 70F for 10 seconds.

(10) Without rinsing, the whole assembly was immersed facing downward, parallel to a phosphorized and bagged copper anode at the bottom of a 16-liter-air-agitated leveling acid copper bath containing 32 oz/gal cupric sulfate, 6.5 oz/gal sulfuric acid, and Dayton Bright copper leveling agents Nos. 78 and 780 and plated at 40 amp/sq ft at 75F at the rate of about 0.0013 mil/hr on the 6061 alloy. A carpenter's level was used to insure that the rod was parallel with the anode.

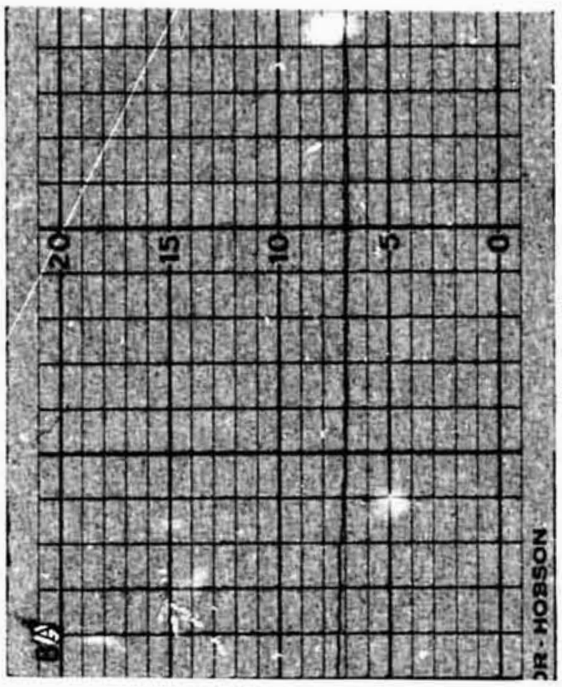
(11) After removing the assembly from the plating bath and cold water rinsing, the plated rod was removed from the fixture

and dried. The nonadherent copper on the stainless steel fixture was removed and kept for possible micrometer thickness and surface roughness measurements.

Lancaster Electroplating of Lancaster, Ohio, is an example of organizations capable of plating leveling acid copper on 6061 aluminum alloy. The Udylite Corporation of Detroit, Michigan, and the Dayton Bright Copper Company of Dayton, Ohio, are two suppliers of acid copper leveling agents They should be able to supply names of additional plating shops.

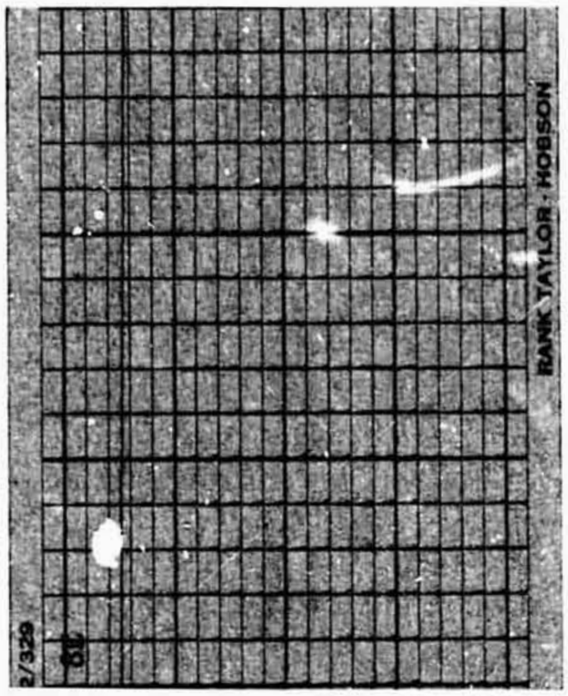
APPENDIX B

TALYSURF RECORDS OF SPECIMEN SURFACE FINISH



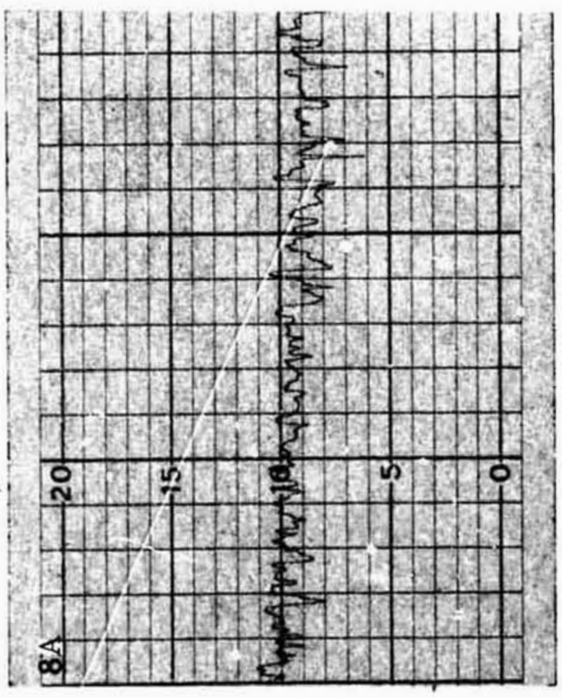
V = 20 μ in. H = 0.002 in.

Plated



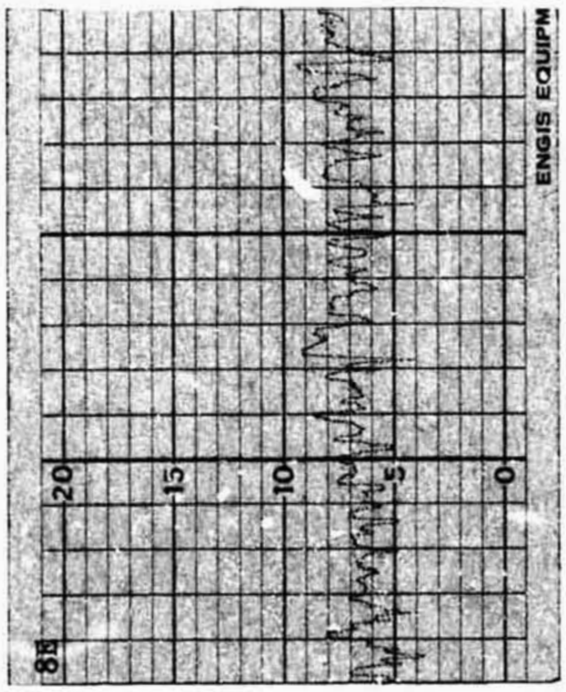
V = 50 μ in. H = 0.002 in.

Plated



V = 10 μ in. H = 0.002 in.*

As Machined

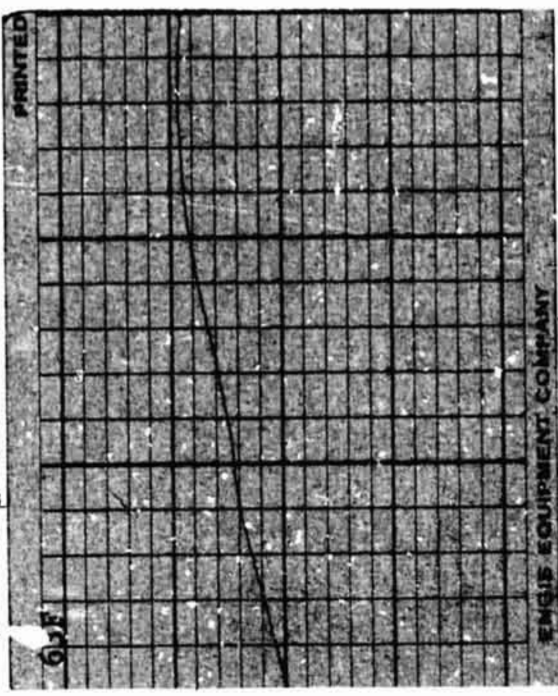


V = 10 μ in. H = 0.002 in.

As Machined

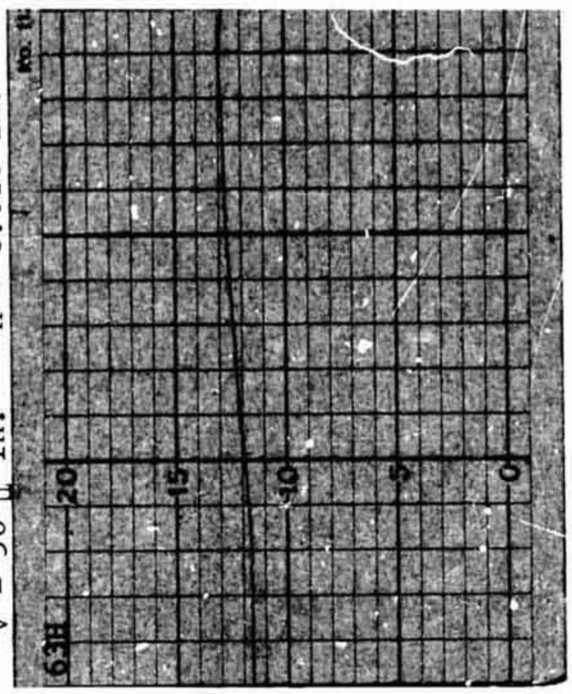
* V and H indicate vertical and horizontal scales, respectively, for one small division on strip chart

V = 20 μ in.   H = 0.010 in.



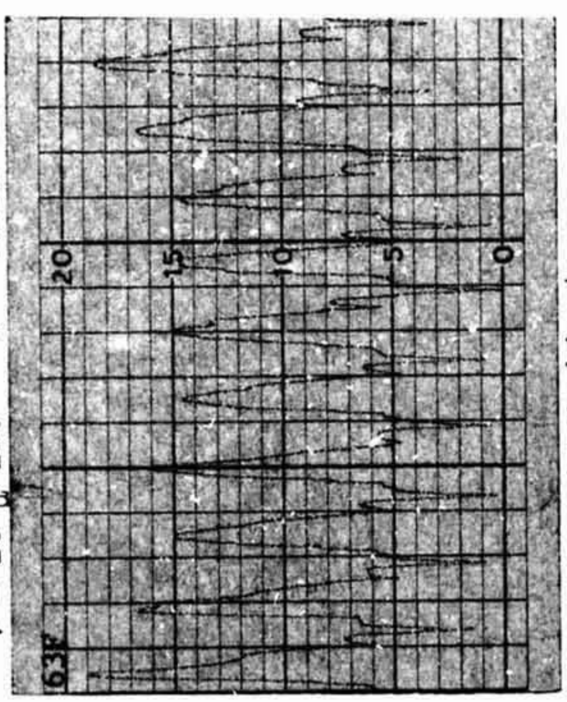
Plated

V = 50 μ in.   H = 0.010 in.



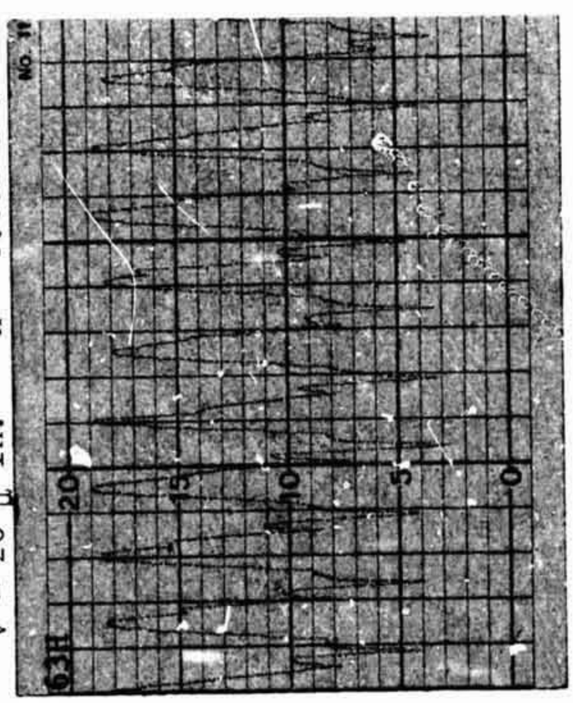
Plated

V = 20 μ in.   H = 0.002 in.



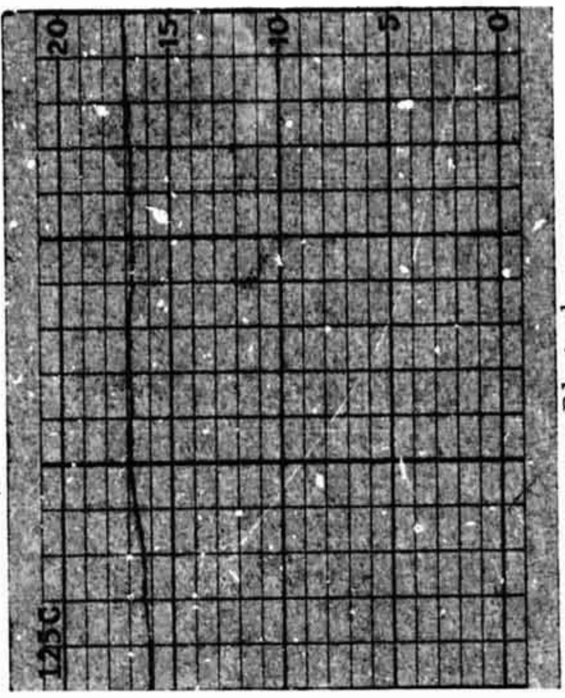
As Machined

V = 20 μ in.   H = 0.002 in.



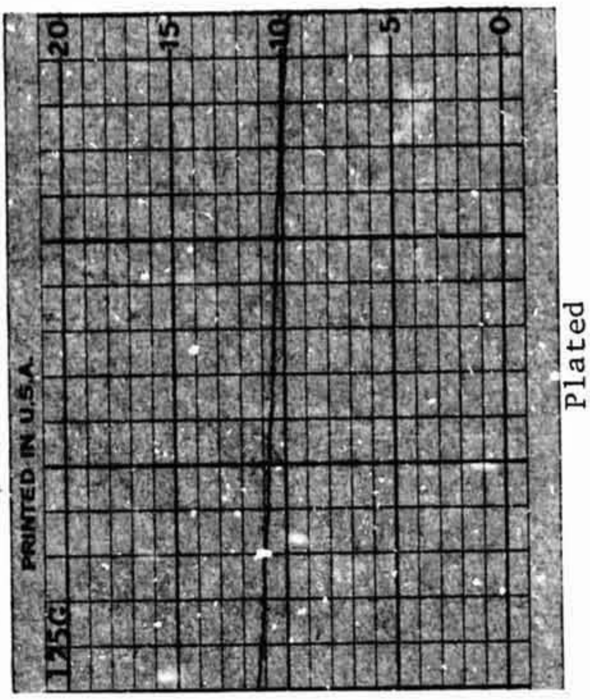
As Machined

V = 50 μ in. H = 0.002 in.



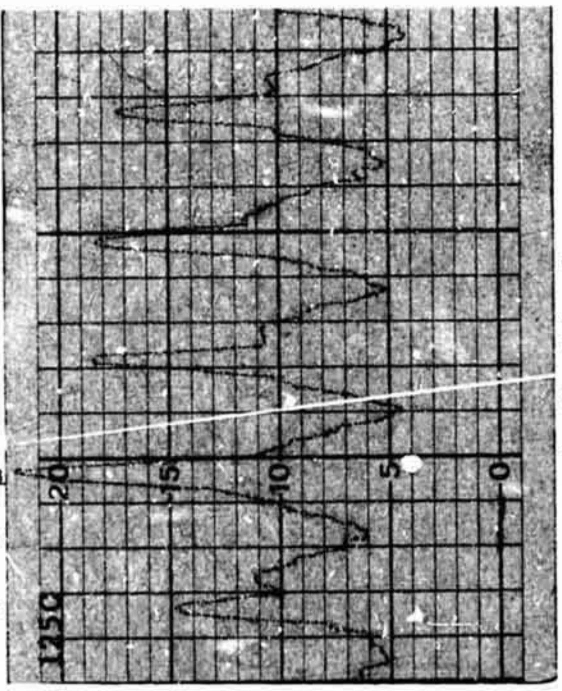
Plated

V = 50 μ in. H = 0.002 in.



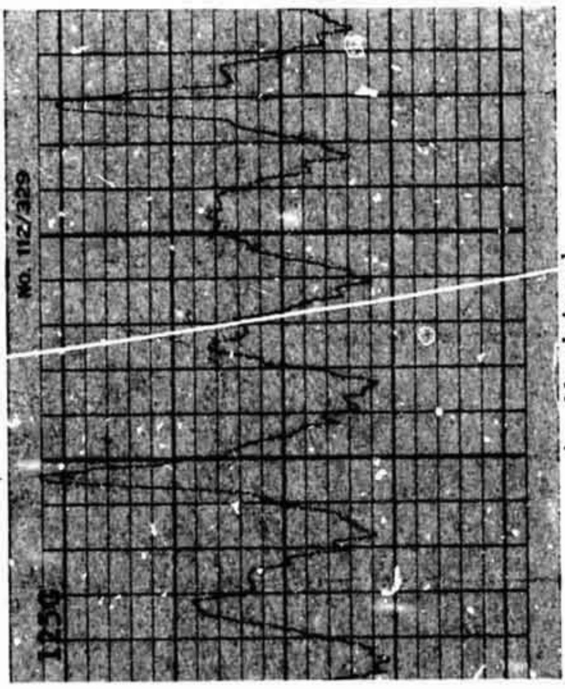
Plated

V = 50 μ in. H = 0.002 in.



As Machined

V = 50 μ in. H = 0.002 in.



As Machined