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PRESSURE, ULTRASONIC VIBRATION AND TEMPERATURE EFFECTS ON GOLD-COPPER CONTACTS

by

Arlon H. Meisner

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1968

CERTIFICATE OF APPROVAL

This thesis is accepted and approved in partial fulfillment of the requirements for the degree of Master of Science.

15 May 1968

Date

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Science

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ABSTRACT

An ultrasonic bonder, modified to include heating in the bonding cycle, was used to produce contact between a small gold ball and a polished copper sheet. Contact resistance measurements were used to follow the effects of the bonding parameters.

It was shown that pressure provided intimate contact of the metal surfaces and simultaneously work-hardened the gold ball. Also, the ball surface did not penetrate the copper surface film when loaded normal to the contact interface. However, ultrasonic vibrations at 40,000 cps applied for .5 second produced shear strains at the interface which effectively disrupted the surface film. In this case, the contact surface was fully work-hardened.

By raising the ball temperature to 200°C, real contact area was formed in addition to that produced by pressure. Heating the ball for 1-2 seconds and then applying ultrasonic vibrations prevented full hardening of metal near the interface while at the same time disrupted the surface film.

INTRODUCTION

Solid state bonding is the term used to describe the joining of materials, usually metals, at temperatures below the melting points, although heat may be applied to improve bond quality. Some of the processes that have been developed to produce solid state bonds are thermocompression bonding(1), ultrasonic bonding(2) and, more recently, hot-work bonding(3) which is a combination of the thermocompression and ultrasonic methods. The applications of these processes have led to investigations of the various bonding parameters and material properties involved in solid state bonding to understand the mechanisms of adhesion.

In solid state bonding, pressure is applied to bring into intimate contact the metal surfaces to be joined. The surface of a metal is not smooth but is microscopically rough as a result of asperities on the surface. The load applied at a metal interface is initially supported by these asperities and with the application of force the asperities plastically deform since they are subjected to high localized pressures(4,5). As the load is increased, more plastic flow occurs and metal to metal contact area increases.

Although pressure is of course necessary, it is not of primary importance in forming a solid state bond. In an investigation of thermocompression bonding, Hunter(6) showed that the bonding temperature had more effect on bond strength than bonding force. At temperatures less than 200°C, no substantial bonding of gold wire to a nickel sheet occurred while above 400°C the bond strength exceeded that of the gold wire. Nicholas(7) found that no bonding resulted between clean copper surfaces when simply pressed together at a pressure of 50,000 psi.

Since there is work-hardening at the metal interface, the ability of pressure to increase contact area is lessened with increasing plastic flow. The thermocompression bonding process, which combines heat and pressure, overcomes this barrier to solid state bonding. McKinnon and Hoeckelman(5) found that bonds of aluminum wire to aluminum films were stronger when formed at 400°C than those formed between 200°C and 300°C. This higher temperature increased the contact area and thus facilitated adhesion. Since initial contact and bonding is made at the asperities, some of these asperity bonds fail upon release of pressure due to their lack of ductility. Bowden and Rowe(8) have shown that this failure may be prevented by annealing the asperities before removal of the load. Thus, bonding at a relatively high temperature will simultaneously increase contact area and prevent bond failure when the load is removed.

The presence of surface films, such as oxides, is considered to be one of the major factors in inhibiting a solid state bond. Since these films prevent metal to metal contact, they must be chemically or mechanically removed prior to bonding or mechanically removed during bonding.

Surface films can be partially penetrated by application of load(9). If the surface film is more brittle than its underlying metal, it can more easily be penetrated than can a film whose ductility is comparable to the parent metal(10). By the use of shaped tools, film penetration is more easily accomplished. Using two annealed and anodized aluminum strips pressed together, Holmes(11) found that an annular shaped tool fractured the film at 5% deformation. Film fracture did not occur over most of the interfacial area until after 20% deformation by a .625 inch diameter tool. Surface films can also be penetrated by relative rotation of the contacting metal surfaces. Nicholas(7) has shown that at a load of 2.5 pounds, a rotation of 30 degrees produced a bond having a pull strength of .014 pound whereas without rotation no bonding occurred at a load of 1000 pounds. Anderson(4) has shown that bonding of two gold balls occurred after shear strains were produced by a relative twisting motion at the interface. The conclusion is that since shear strains are necessary to produce adhesion of pure gold, shearing strains are even more necessary to bond metals which form oxide films.

This required relative motion is easily and rapidly produced by the application of ultrasonic vibrations to the metal interface. In this case, ultrasonic bonding, no specially shaped tools are required as in thermocompression or cold pressure bonding. Jones, et al (12), have shown that bonds are produced using ultrasonic vibrations with low loads as compared to pressure welding. Using an anodized aluminum alloy, Bruk(13) investigated the distribution of oxide in the ultrasonic weld areas. He found that the contact pressure cracked the film and tangential forces dispersed some of the oxide particles to the perimeter of the weld zone.

This investigation was undertaken to determine the effects of the major bonding parameters associated with the hot-work bonding process on a metal contact. In particular, the intent was to determine the effects of temperature and ultrasonic vibrations on the interface of a metal contact. As an adjunct to the above, some of the effects of pressure resulted from this investigation. Although there was no significant bonding of the ball and plate, the effects of these bonding parameters determined from this investigation are applicable to conditions under which there is substantial adhesion. This information should also apply to bonding of other metal combinations.

To obtain the necessary data, the method employed by Anderson(4) in his study of shear strain effects was used. This consisted of measuring the contact resistance of a ball and plate as a function of contact diameter while the load on the ball was increased. The changes in this resistance were used to show the effects of the application of heat and vibrations to the contact.

The resistance of a contact is very sensitive to changes at the metal interface. For example, if one asperity punctures a surface film, this metal to metal contact can short-circuit the film resistance(10). Thus, gold was chosen because a gold wire can be formed into a smooth and relatively soft sphere. The smoothness reduced the possibility of prematurely puncturing the film while the initial softness aided in studying the work-hardening characteristics of the interface. Through the use of plasticine scale models, Baker and Bryan(14) have shown qualitatively that little or no flow of metal parallel to the contact surface occurs when forming a ball bond. Thus, the use of a sphere in this investigation also aids in preventing undesired film penetration.

The hot-work bonding process was chosen because the associated equipment is capable of producing either a thermocompression or ultrasonic bond. Hence, the major bonding parameters of these methods can be studied individually or in combination.

THEORETICAL TREATMENT

When two apparently smooth surfaces are brought into contact, the applied load is supported by microscopic projections, termed asperities, on the surfaces. Therefore, solid state bonding takes place at these interfaces. Then questions concerning the effect of a bonding parameter on the bonding behavior of two solids can be answered by determining its effect on the contacting surfaces.

It has been found empirically that the relationship between force and contact area for a spherical indenter impressed on a metal surface is

$$F = k\,A_a{}^n \qquad (1)$$

where k is a proportionality constant, A_a is the apparent area of contact, i.e., that area which can be directly measured and n is a material constant related to the work hardening index. The value of n is greater than unity when the metal is being work-hardened and becomes unity when the metal is fully work-hardened. In this investigation, Meyer's Law [Eq. (1)] will be applied to the case of a soft ball impressed on a metal plate.

The electrical resistance of a contact is the consequence of two surface conditions. One is the constriction of current from the bulk of a material through the contact asperities and the other is the presence of a surface film.

The constriction resistance of a single circular contact is(10)

$$R = \frac{\rho_b}{2r} \qquad (2)$$

in which ρ_b is the bulk resistivity and r is the contact radius. In terms of d, the contact diameter, this becomes

$$R = kd^{1} \qquad (3)$$

The true area of contact is the sum of individual contact areas. Then, assuming that the diameters of these contacts are equal, this real area is

$$A_r = k_1 d^2 \qquad (4)$$

Using this in Eq. (3) gives for the total constriction resistance

$$R_c = k_2 A_r^{-\frac{1}{2}} \qquad (5)$$

To put this in terms of measurable quantities, Meyer's Law and the relationship

$$A_r = \frac{F}{p} \qquad (6)$$

are used. In this equation p is the flow pressure. Assuming that the flow pressure is constant, the constriction resistance becomes

$$R_c = k_3 A_a^{-n/2} \qquad (7)$$

or

$$R_c = k_4 d_a^{-n} \qquad (8)$$

where d_a is the apparent contact diameter.

For a surface film of resistivity ρ_f and thickness t, the film resistance is

$$R_f = \frac{\rho_f t}{\pi r^2} \qquad (9)$$

where r is again the contact radius. In the same manner as that used for the constriction resistance, the total film resistance is found to be

$$R_f = k_5 d_a^{-2n} \tag{10}$$

In this equation the film thickness is assumed constant.

Taking the ratio of the real area and apparent area gives

$$\beta = \frac{A_r}{A_a} = \frac{F}{pA_a} \tag{11}$$

When the metal is fully work-hardened, p will be the maximum flow pressure. Hence,

$$\beta_{min} = \frac{F}{A_a\ p_{max}} \tag{12}$$

Thus, β_{min} can be calculated from measured data. The actual value of β will be larger than β_{min} but smaller than unity.

In this investigation, Equations (1), (8), (10) and (12) will be used to analyze the effects of pressure, ultrasonic vibrations and temperature on the contact surface between gold and copper. A large change in the contact resistance is considered an indication of surface film penetration and changes in the slope of resistance versus diameter reveal film penetration and surface hardness variations.

EXPERIMENTAL APPARATUS AND PROCEDURE

To apply the equations of the foregoing section, the contact resistance, contact diameter and applied load were measured. Each of these measurements along with the apparatus used to produce the contact are described below.

Bonder

Shown in Figure 1 is the modified 100 watt Sonobond Ultrasonic Bonder. The main elements of this bonder are the ultrasonic horn, bonding tip (not visible), load spring and heating current connection. The molybdenum horn is coupled to a transducer which is driven from an ultrasonic generator. The motion of the transducer is converted into standing ultrasonic waves in the horn. These standing waves produce a vibratory motion of the bonding tip and thus relative motion of the metals to be joined.

The generator delivers up to 100 watts at 40,000 cps into a 38 ohm load. The power was constant for all contacts at a level (about 30 watts) such that the horizontal displacement of the bonding tip was about $\pm 10^{-4}$ inch from its normal position. This value was obtained through the use of a Phylatron displacement sensor which converts the change in capacitance between sensor and object to a voltage. A calibration curve then gives the displacement of the object. The force at which the ultrasonic vibrations were applied was not sufficient to produce a bond at the above displacement. This was necessary since it was found that with the higher ultrasonic power required to produce a bond the remaining available load was not sufficient to produce a significant change in the contact. However, the ultrasonic power used was adequate to reveal the effects of the vibrations.

The bonding tip, shown in Figure 2, was resistance heated by current from a power transformer. The current was held reasonably constant during a heating cycle by a feedback circuit. To measure temperature, a chromel-alumel thermocouple was fused to the top of the bonding tip. The approximate temperature that a gold ball would be heated to was determined by placing a thermocouple ball between the tip and a copper sheet. With the top of the tip at about 300°C the temperature of the thermocouple ball was approximately 200°C.

Contact Resistance Measurement

In Figure 2 can be seen four electrical connections; two to the copper plate and two to the gold wires on which the gold ball is formed. This 'crossed-wire' technique was used to eliminate the measurement of undesired voltages(15). A discussion of this arrangement is given in the appendix. An electrical schematic is shown in Figure 3. The voltmeter, used as a nullmeter, is a Kiethly 148 Nanovoltmeter capable of measuring to 2×10^{-10} volts. The Kiethly 260 Nanovolt source was used to provide an opposing voltage to that produced by a current through the contact. The Leeds and Northrop standard .1 ohm resistor in conjunction with the Leeds and Northrop K-3 millivolt potentiometer was used to measure the contact current. The current reversing switch is also discussed in the appendix.

Contact Diameter Measurement

To enable the measurement of the contact diameter while the ball was under load, use was made of a Bausch and Lomb binocular Microscope.

One standard eyepiece was replaced by a filar eyepiece which contains a movable hairline and calibrated dial. At the magnification used, the dial was calibrated to ± 1.5 microns. The axis of the microscope was adjusted to be parallel to the ball-plate interface and the ball was back illuminated to produce a silhouette.

Materials and Sample Preparation

For these experiments, .005 inch diameter gold wire of 99.999 percent purity was used. This wire was received in the hard condition but the formation of a ball resulted in very soft gold. The formation of a ball was easily done by holding two gold wires closely together and heating the ends in a flame. For these experiments, balls of about .035 inch were used. The ball diameter was not precisely controlled since Anderson(4) reports that the value of n does not change for ball diameters from .005 to .050 inch.

After forming the ball, it was found that the surface was contaminated. The method of cleaning the ball was that described by Renault(16) and is as follows:

1. Boil 10 minutes in a strong sodium hydroxide solution.
2. Boil 10 minutes in a 50 percent hydrochloric acid solution.
3. Ultrasonically clean for 5 minutes in trichlorethylene.
4. Ultrasonically clean for 5 minutes in pure ethyl alcohol.

This cleaning procedure produced a rough surface and hence it was necessary to heat the ball for a short time to obtain a smooth surface. In this manner a soft, smooth and almost true spherical ball was formed. Electron micrographs using replica techniques of a flame formed gold ball surface showed no surface roughness at a magnification of 11,000 diameters$^{(4)}$.

For the metal plate, copper of 99.999 percent purity, fully annealed was obtained in the form of a 1/32 x 3/4 inch strip. The copper was polished using diamond paste and ultrasonically cleaned. An oxide film was allowed to form in laboratory air before using the plate.

Procedure

To obtain a plot of log force versus log area, the slope of which gives n[Eq. (1)], the load on a ball was increased in increments and the area measured at each load value. Since the ball was not a true sphere, the contact area was elliptical. Thus, eight measurements of the diameters were made and the area calculated from the maximum and minimum diameter using

$$A_a = \pi/4 \left(\frac{d_a + d_b}{2}\right)^2$$

The force was obtained from a spring calibration curve.

The contact resistance is very sensitive to disturbances of the surface film. Thus, care had to be taken to avoid unwanted shear strains at the contact. For this reason, when measuring the contact resistance at each increment of load, only one diameter measurement was taken. It was assumed that a particular diameter increased with increasing load in the same manner as did the average diameter.

Ultrasonic vibration effects were determined by increasing the load in steps to about one-half that available, introducing the vibrations for .5 second and then continuing to increase the load. At each increment, the contact resistance and diameter were measured.

In the case of a temperature effect, at each force increment the ball was heated to about 200°C for 2.5 seconds and allowed to cool to room temperature. The resistance and diameter were measured before and after the heating cycle.

To show the effects of a simultaneous application of heat and ultrasonic vibrations, the ball was loaded in steps to about one-half the available load and heated for 1.5 seconds to 200°C. The ultrasonic vibrations were applied for the last .5 second of the heating time. The ball was then further deformed by increasing the load. After each load increase, contact resistance and diameter were measured.

RESULTS AND DISCUSSION

To use the equations previously outlined, the value of n must be determined. Using Meyer's Law [Eq. (1)], the slope, n, is 1.67*, as shown in Figure 5. Anderson(4) found the value of n to be 1.35. Although these two values do not agree, the value of n found here is quite consistent throughout the experiments and thus provides the basis for determining the effects of bonding parameters. This consistency also shows the validity of assuming that a particular diameter increases in the same manner as the average diameter.

Pressure Effects

Since the value of n as found in Figure 5 is greater than unity, Meyer's Law indicates that the gold ball was being work-hardened with increasing deformation. The other effect which can be determined from these data is shown in Figure 6. This plot shows the minimum ratio of real area and apparent area as calculated from Eq. (12). The value of p_{max} used in Eq. (12) was 30,000 psi(4). It is apparent from this figure that the real area increased more rapidly than apparent area and thus the gold made more intimate contact with the copper surface at higher loads.

Surface Film Resistance

Figure 7 shows the result of measurements of contact resistance and apparent contact diameter for increasing loads. The magnitude of the slope is about twice the value as determined from Figure 5.

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*All straight lines were obtained from a linear regression computer program unless otherwise noted.

Equation (10) indicates this contact resistance was due primarily to a surface film. Also, since the magnitude is greater than 2, the gold in the vicinity of the interface was not fully work-hardened during deformation.

Temperature Effect on Contact Area

To determine how effective temperature is in increasing real area of contact as compared to pressure, a gold ball was heated to 200°C for 2.5 seconds after each increment of load increase. Contact resistance and diameter were measured before and after each heating cycle. The results are presented in the table on page 17. An analysis of this data shows that an average increase, due to pressure, of .014 mm in the apparent contact diameter reduced the contact resistance by an average $.15 \times 10^{-3}$ ohm. However, an increase of only .009 mm due to heat decreased the resistance by 1.51×10^{-3} ohm. There are no large drops in resistance for small increases in diameter which indicates that the surface film had not been penetrated. Hence, the decrease in resistance was a result of an increase in real area of contact.

Assuming a circular contact, the change in area as a result of changing the diameter is

$$\Delta A = {}^{\pi}/_{4}(2d + \Delta d)\,\Delta d$$

at the diameter d. At an apparent diameter, say, of .5 mm, the average change in area due to pressure would be about .011 mm^2 and

TABLE

Force lb.	Before Heating Resistance 10^{-3} ohms	Diameter mm	After Heating Resistance 10^{-3} ohms	Diameter mm
2.56	17.46	.334	8.16	.352
2.91	8.03	.362	6.00	.370
3.26	5.48	.386	4.32	.392
3.63	4.70	.407	3.85	.409
3.95	3.80	.421	3.14	.427
4.35	3.12	.445	2.27	.450
4.67	2.39	.458	1.78	.465
5.05	1.52	.476	1.31	.491
5.42	1.48	.498	1.12	.507
5.75	1.08	.523	.649	.527
6.15	.644	.540	.450	.557

when the ball was heated the average area increase would be approximately .007 mm^2. Taking the ratio of the decrease in resistance per unit apparent area increase due to temperature and the resistance decrease per unit area due to pressure gives

$$\frac{\Delta A_p \, \Delta R_t}{\Delta A_t \, \Delta R_p}$$

The magnitude of this product with respect to unity will show the temperature effect on real area as compared to the pressure effect. For the values previously calculated, this product is greater than unity and hence temperature is more effective than pressure in increasing real area of contact.

Effects of Ultrasonic Vibrations on a Contact Surface

The plot of resistance versus diameter presented in Figure 8 shows the effects of ultrasonic vibrations at the metal interface. The initial slope of this plot indicates that a surface film was present (similar to Figure 5) and the gold at the interface was being work-hardened. When shearing strains were produced by the ultrasonic vibrations, the resistance decreased by about an order of magnitude. Since the apparent area increased at this point, the resistance drop could be due to an increase in real area.

Now film resistance is inversely proportional to real contact area as shown by Eq. (9). Therefore, a calculation of the percentage change in area will also give the possible change in resistance due to an area change. Assuming a circular contact and real area equal to apparent area ($\beta = 1$), the increase in area due to ultrasonic vibrations is about 18% as calculated from the data of Figure 8. Thus, only 18% of the resistance decrease can be attributed to increased area. It is concluded then that the shear strains disrupted the surface film and produced metal to metal contact. After penetration of the film, the slope is approximately unity. Hence, the contact surface was fully work-hardened. Equation (8) also shows that the resistance was a result of the current constriction effect since the magnitude of the slope is less than 2. The change in slope in Figure 8 from -1 to -3.16 is the result of the parallel combination of a constriction resistance and a film resistance. The surface film had been removed from an area of about .34 mm diameter. Then, upon increasing pressure, gold which had not been fully hardened made contact with the surface film where the new contact area was being formed. Now the constriction resistance was not changing appreciably since the surface in this area was fully hardened whereas the film resistance changed more rapidly since the gold forming this area was not hardened. Eventually then, the gold area contacting the surface film became sufficiently large such that the resultant film resistance dominated the slope of the contact resistance versus diameter but not the contact resistance magnitude.

Effects of Temperature and Ultrasonic Vibrations on a Contact Surface

Figure 9 shows the effects of introducing both heat and ultrasonics to the contact surface simultaneously. The line drawn with slope -3.2

fits the data points reasonably well which shows that there was a surface film present and that the contact surface was work-hardening. Upon raising the temperature at the interface to 200°C and applying ultrasonic vibrations to the contact, there was a large drop in contact resistance. In this case, a calculation of the possible drop in resistance due to an area increase yields about 23%. Again, the change in resistance is primarily due to disruption of the film and subsequent metal to metal contact. The magnitude of the ultrasonic vibrations has been shown sufficient to fully work-harden the contact surface. Here, however, the magnitude of the slope after film disruption is 1.67 and not unity. Thus, the metal in the vicinity of the interface had not been fully hardened and the resultant resistance values were due to the constriction effect rather than a surface film. Shown in Figure 10 is a typical gold contact area which was a result of pressure, ultrasonic vibrations and heat. Area 1 was due to the initial application of pressure, Area 2 was the result of the application of heat and ultrasonic vibrations and Area 3 was the surface formed by further deformation of the ball. Although there were three areas on the contact surface, no change in the slope (Figure 9) occurred after film penetration. Since Area 1 and Area 2 were not hardened, the real contact area increase in these regions was larger than would have occurred if the surface was fully hardened. Thus, new area formed on the surface film did not become sufficiently large such that the new film resistance could significantly alter the slope.

CONCLUSIONS

The effects of pressure, ultrasonic vibrations and temperature on the contact surface of a gold ball and copper plate have been investigated.

It has been shown that as pressure on the gold ball increased, real area of contact increased. However, the metal at the interface work-hardened and hence the effectiveness of pressure to increase real contact area was decreased. By heating to a temperature sufficient to soften the ball, it was found that the increase in real area, as indicated by contact resistance, was substantially larger than that produced solely by pressure.

In producing the ball contact, pressure had little effect on the disruption of a surface film. However, it has been shown that ultrasonic vibrations at 40,000 cps in the plane of the contact surface penetrated a surface film and produced metal to metal contact. Simultaneously, these vibrations fully hardened the interface metal.

By preheating the ball before introduction of ultrasonic vibrations, it was found that full-hardening of the interface was prevented while at the same time a surface film was disrupted.

RECOMMENDATIONS FOR FURTHER STUDY

The areas for future study are: further investigation of bonding parameter effects on contacts; and, study of these parameters as related to metal adhesion.

Concerning the first, an investigation of surface oxide layer penetration by pressure should be of interest. This would involve the use of shaped bonding tools and consideration of oxide thickness, oxide ductility (in relation to the parent metal) and temperature. The penetration of oxide films by shaped tools could then be compared to penetration of the same oxide films by ultrasonic vibrations using flat bonding tools. Ultrasonic vibrations will produce heat through friction and thus will raise the temperature of the contact. This temperature rise could be studied by the use of small thermocouples, measurement of contact resistance to determine if full hardening of the contact surface is prevented and possibly by measurement of thermal voltages generated at the contact.

Concerning metal adhesion, a study of bond strength as a function of temperature for various metal purities should prove worthwhile. A sidelight here would be to determine if there was a correlation of bond strength and the hot-working temperature of the metal. Also of interest would be to determine the correlation of bond strength and contact resistance.

Although not a bonding study, the effects of ultrasonic vibrations on the recrystallization of metals versus the effects of pressure deformation would be of interest. This could be done by deforming a metal with and without ultrasonic vibrations and then studying the metal recrystallization.

Equipment Modifications

The bonder used in this investigation should be modified if it is to be used in future studies in which contact resistance is measured. A method of loading other than by a compressed spring should be designed. The loading method should be constructed such that no vibrations are produced at a contact interface when the load is changed. It may also be desirable to mount the bonder on a vibration-free table. If a study is undertaken in which Meyer's Law is applied and significant adhesion is produced, the available load should be increased in order that sufficient data can be obtained.

APPENDIX

The "crossed-wire" technique provides a direct measurement of a contact resistance and thus eliminates the need to subtract from a measured resistance the calculated wire and plate resistances. Figure 4 shows resistances of the contact separated for analysis. Here, R_{Cu} includes the copper plate and wire resistances and R_{Au} is composed of the gold and copper wire resistances. R_c is the contact constriction resistance, R_f is the contact film resistance and R_b is the bulk resistance of the gold ball. E_t is that part of the thermal voltages (due to bimetal contacts), which is measured by the voltmeter. The various thermal voltages are lumped into E_t for ease of circuit analysis. I is current supplied by a battery and I_m is current flowing in the measuring circuit.

The input current I does not flow into the measuring circuit since the meter input resistance is orders of magnitude larger than the contact resistance. Also, voltage drops on R_{Cu} and R_{Au} due to the input current are not measured. Therefore, the only unwanted resistance that is measured is R_b. An approximate calculation of R_b gives about 10^{-4} ohms. Since this calculation is inexact, due to the configuration, and the calculated value is smaller than a measured value, the bulk resistance of the gold is neglected. Although this gives errors in the absolute value of contact resistance, large resistance and slope changes and not absolute values are important for these experiments.

The purpose of the current reversing switch is to provide for removal of a thermal voltage from the measured voltage. Since thermal voltages anywhere in the circuit affect supplied current, E_t cannot simply be measured under open-circuit conditions and then subtracted from a measured voltage. With current I_1 directed into R_{Cu}, the measured voltage is

$$V_1 = I_1(R_c+R_f) - E_t$$

and with I_2 directed out of R_{Cu}, V_2 is

$$V_2 = -\left[I_2(R_c+R_f) + E_t\right]$$

or

$$-V_2 = I_2(R_c+R_f) + E_t$$

The addition of these voltages gives

$$V_1 - V_2 = (R_c+R_f)(I_1+I_2)$$

or

$$R_c + R_f = \frac{V_1-V_2}{I_1+I_2} .$$

But the measured value of V_2 is negative so

$$R_c + R_f = \frac{V_1 + |V_2|}{I_1+I_2}$$

Thus, the thermal voltages are easily removed from the measured voltage to give the correct contact resistance.

As stated previously, current loading due to the voltmeter was neglected in the measurements. Assuming a contact resistance of 10^{-3} ohms, 10^{-2} amperes produces a voltage drop of 10^{-5} volts. In this case the 10^{-7} volt scale would be used (contact voltage is partially nulled by use of the nanovolt source). Now the ratio of sensitivity and input resistance of the nanovoltmeter is 10^{-11} amperes on all scales. Hence, the input resistance is 10^{4} ohms on this particular scale. Current loading of the meter is then 10^{-6} amperes which is sufficiently small in comparison to the circuit current to neglect.

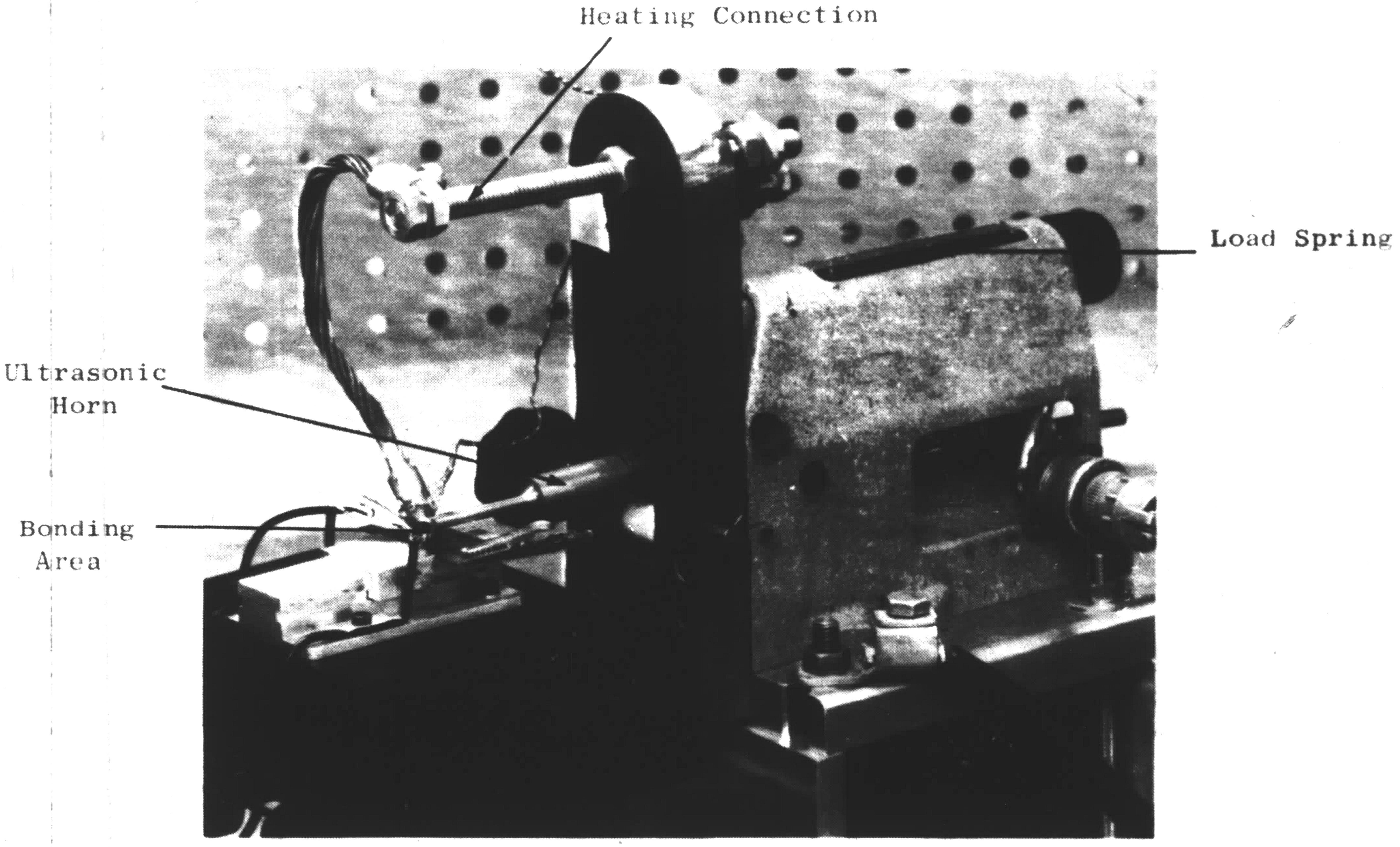


Figure 1

Modified Sonobond Ultrasonic Welder

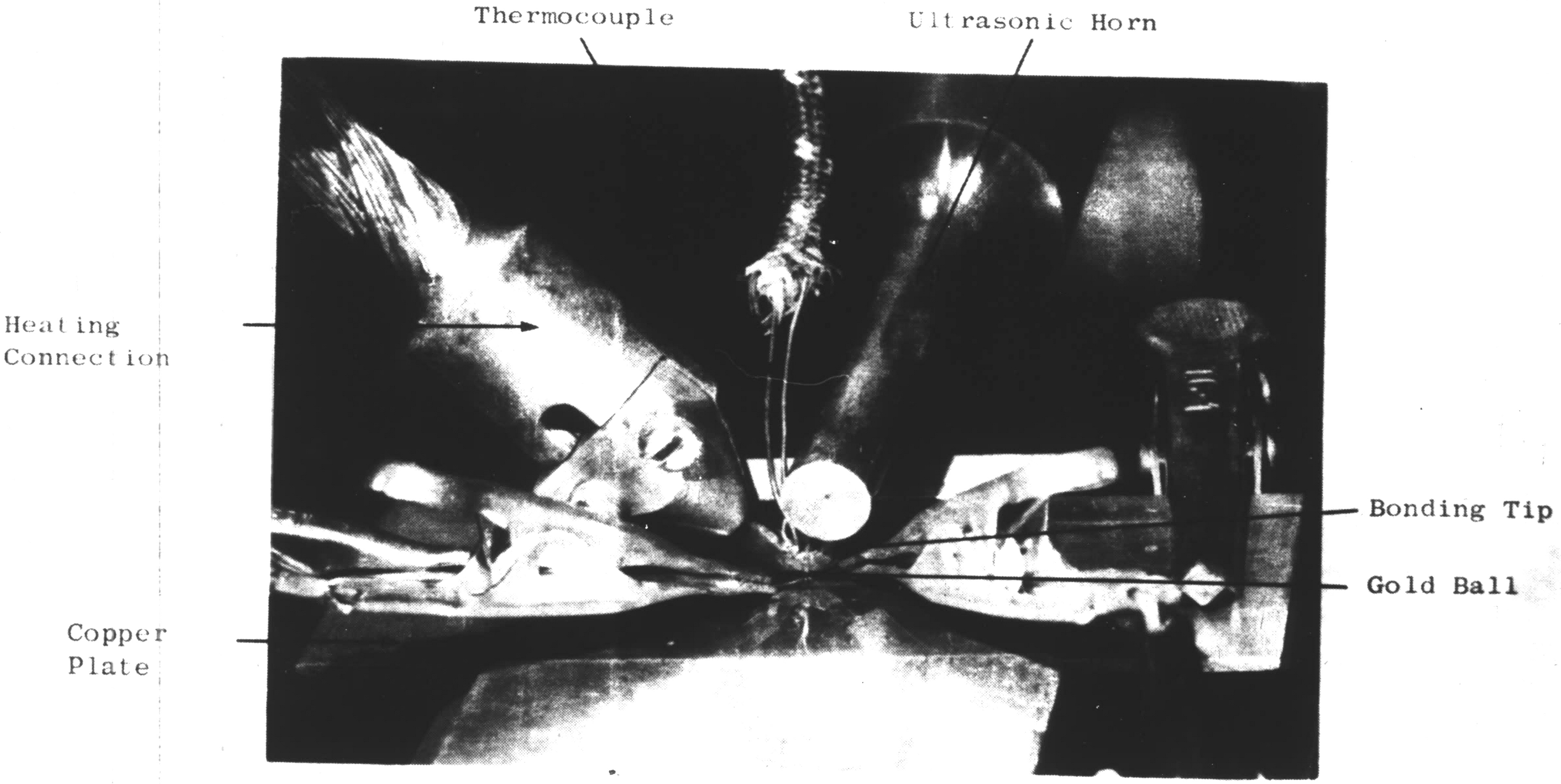


Figure 2

View of Bonding Tip Showing Heating and Resistance Measuring Connections

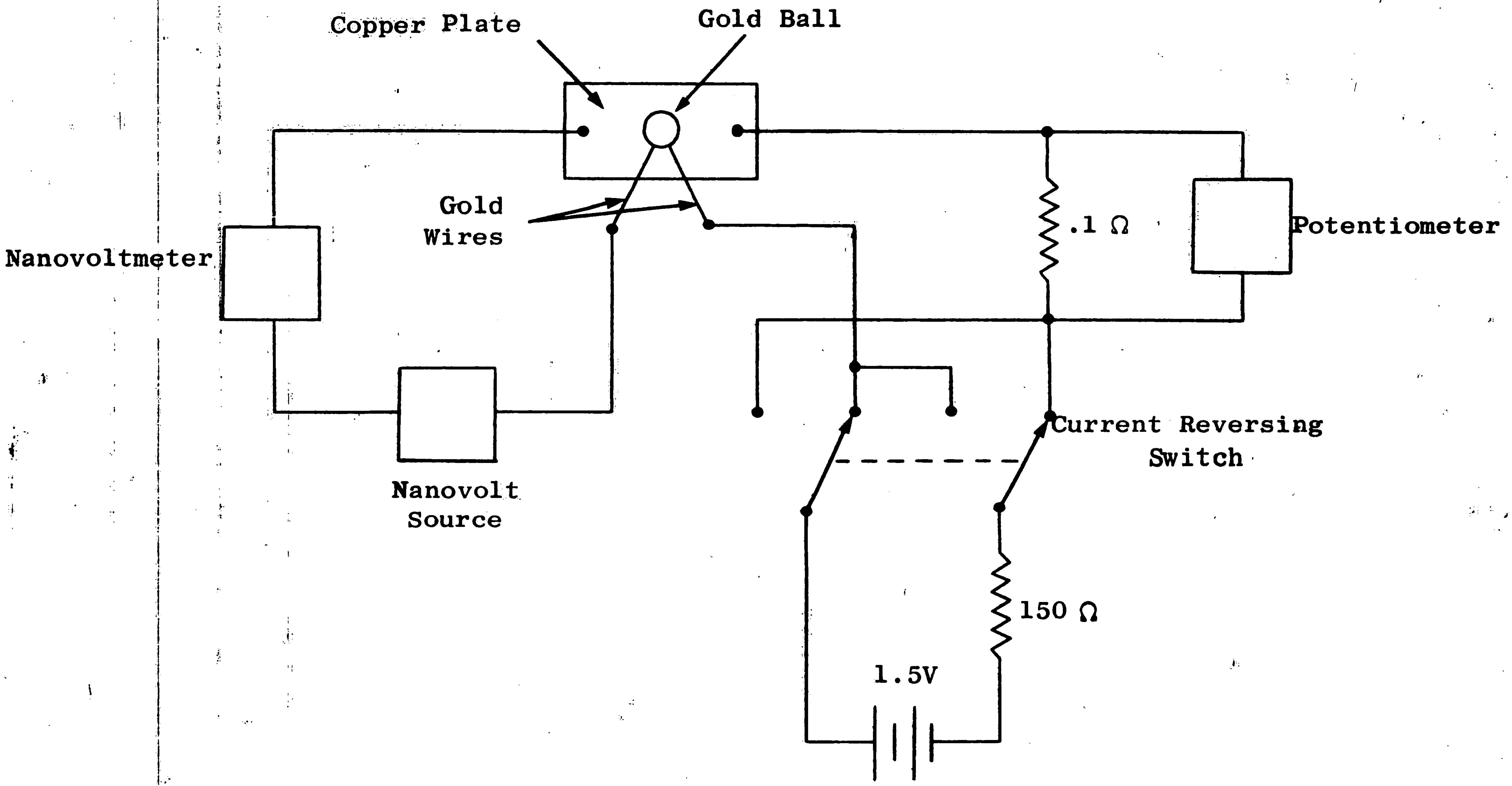


Figure 3

Schematic of Resistance Measuring Circuit

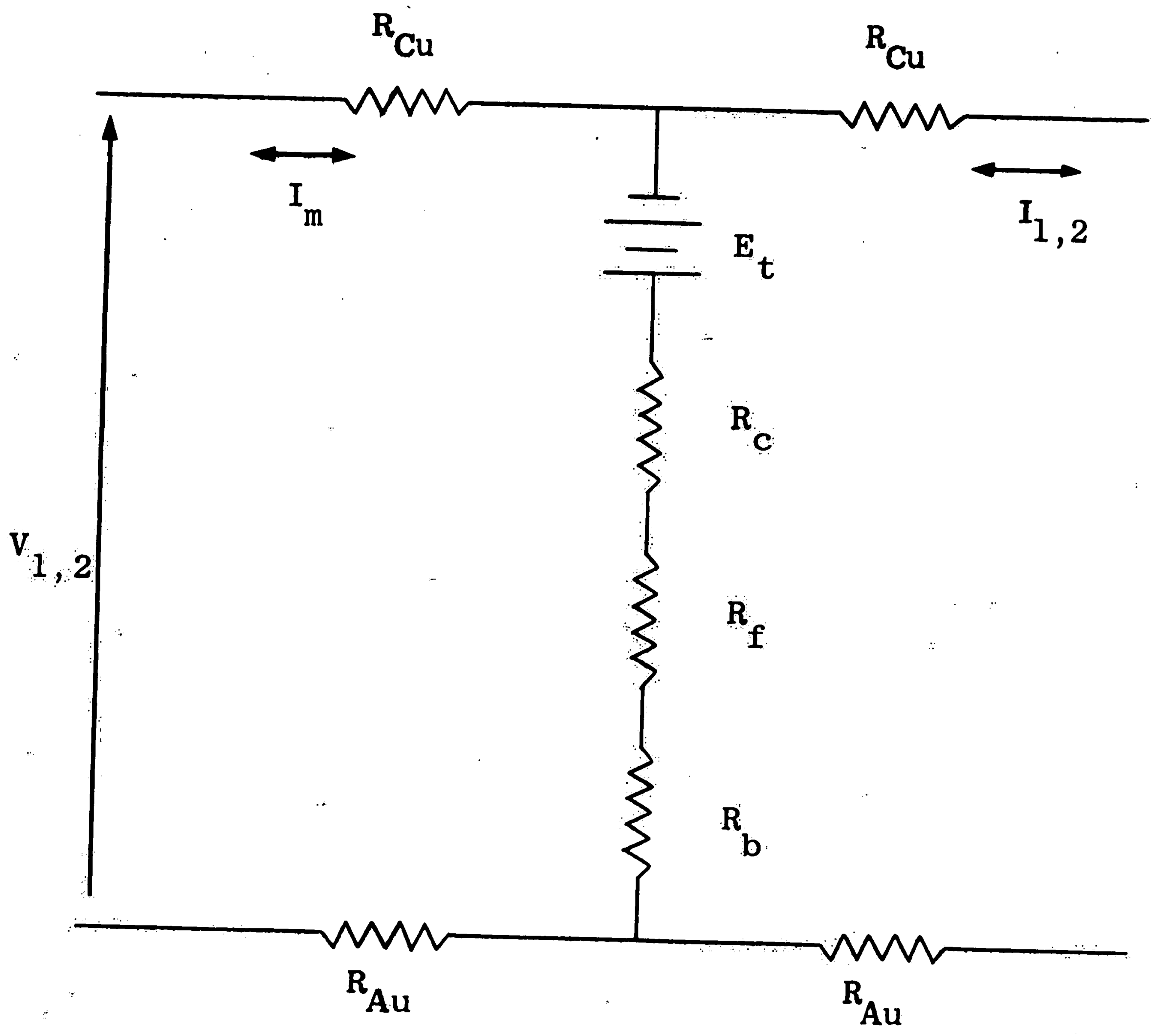


Figure 4

Equivalent Electrical Circuit of a Contact

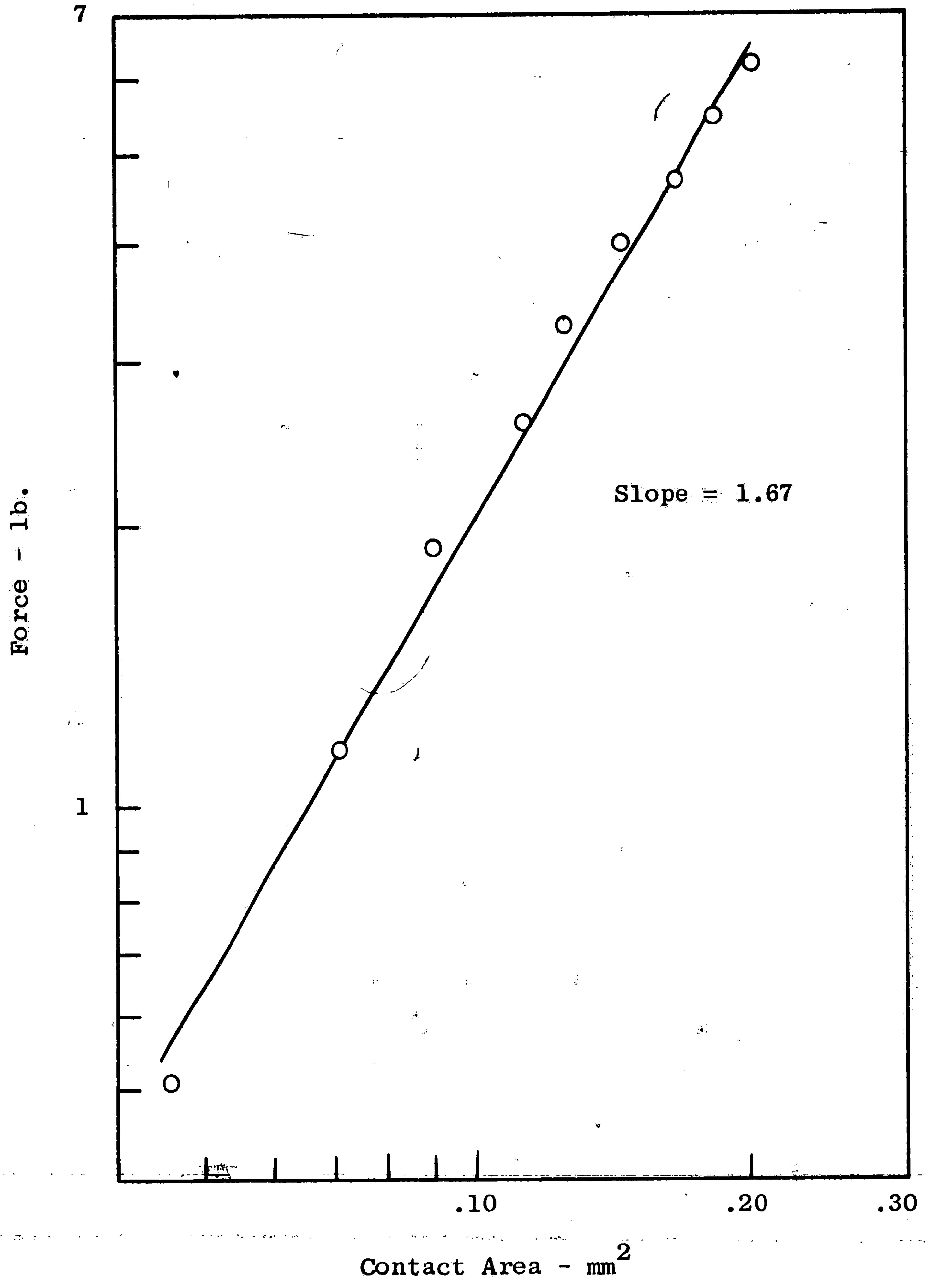
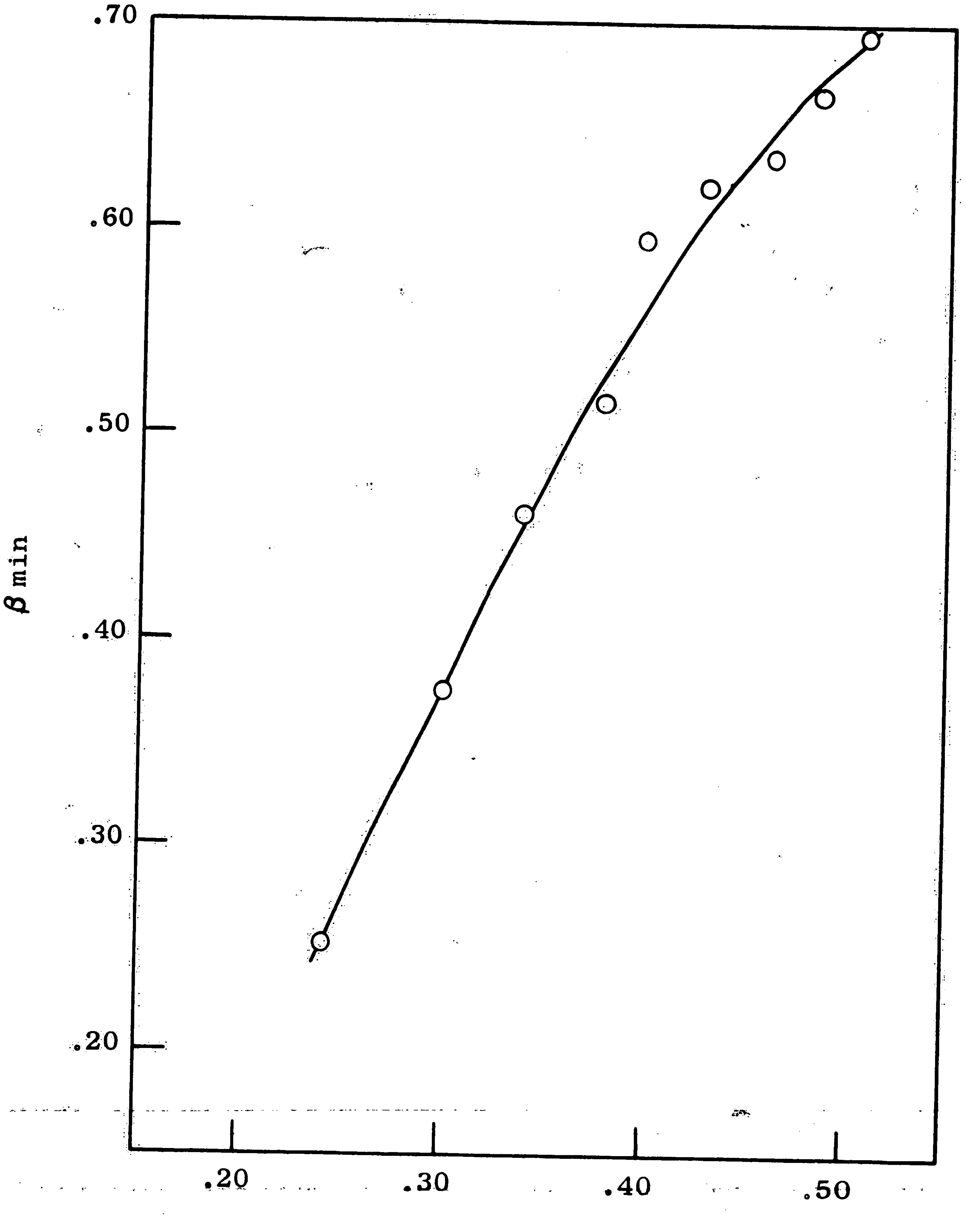


Figure 5

Force Versus Area Showing the Application of Meyer's Law



Contact Diameter - mm

Figure 6

Ratio of Real Contact Area and Apparent Area
Versus Contact Diameter

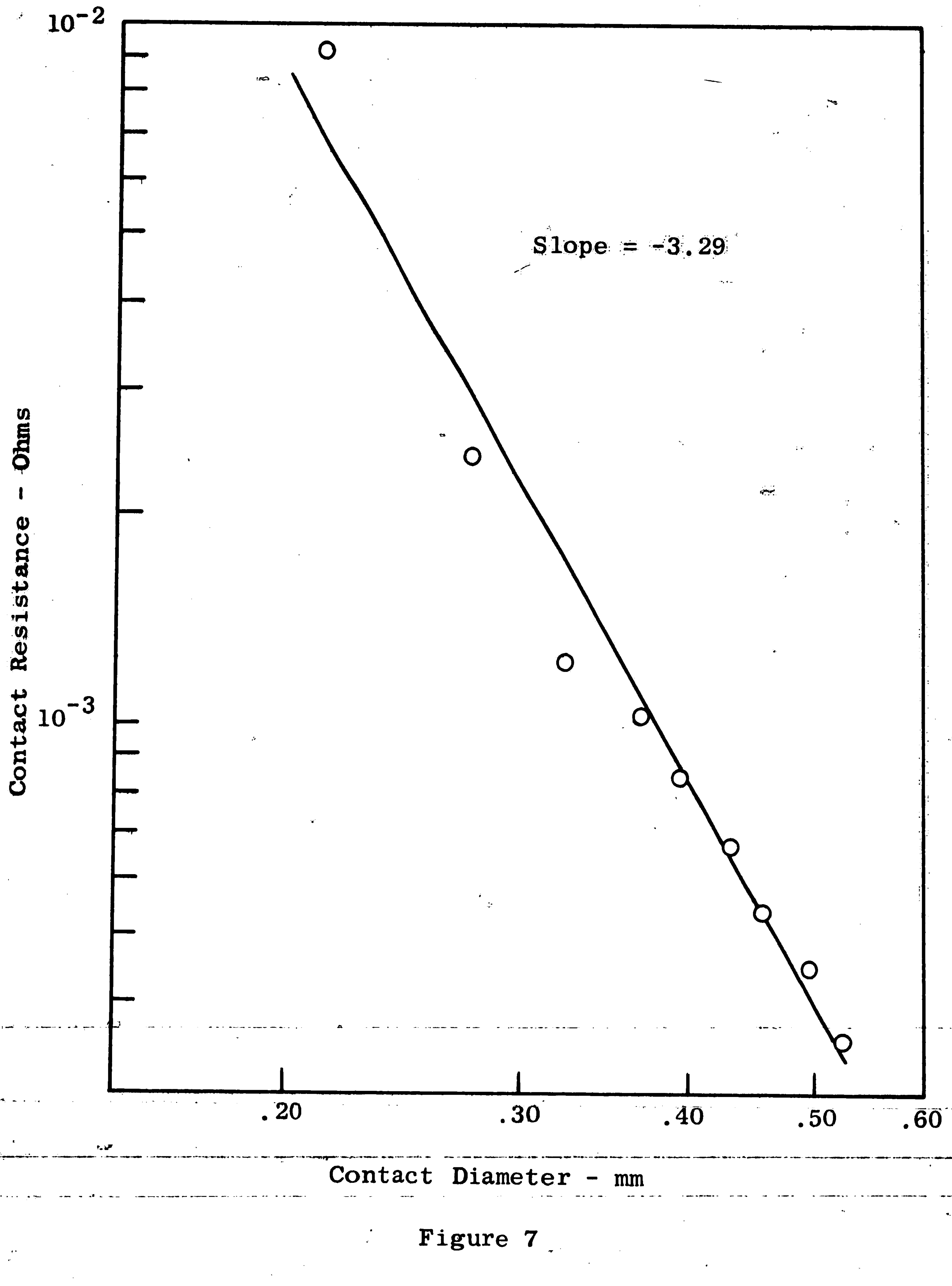


Figure 7

Contact Resistance as a Function of Diameter for Increasing Load

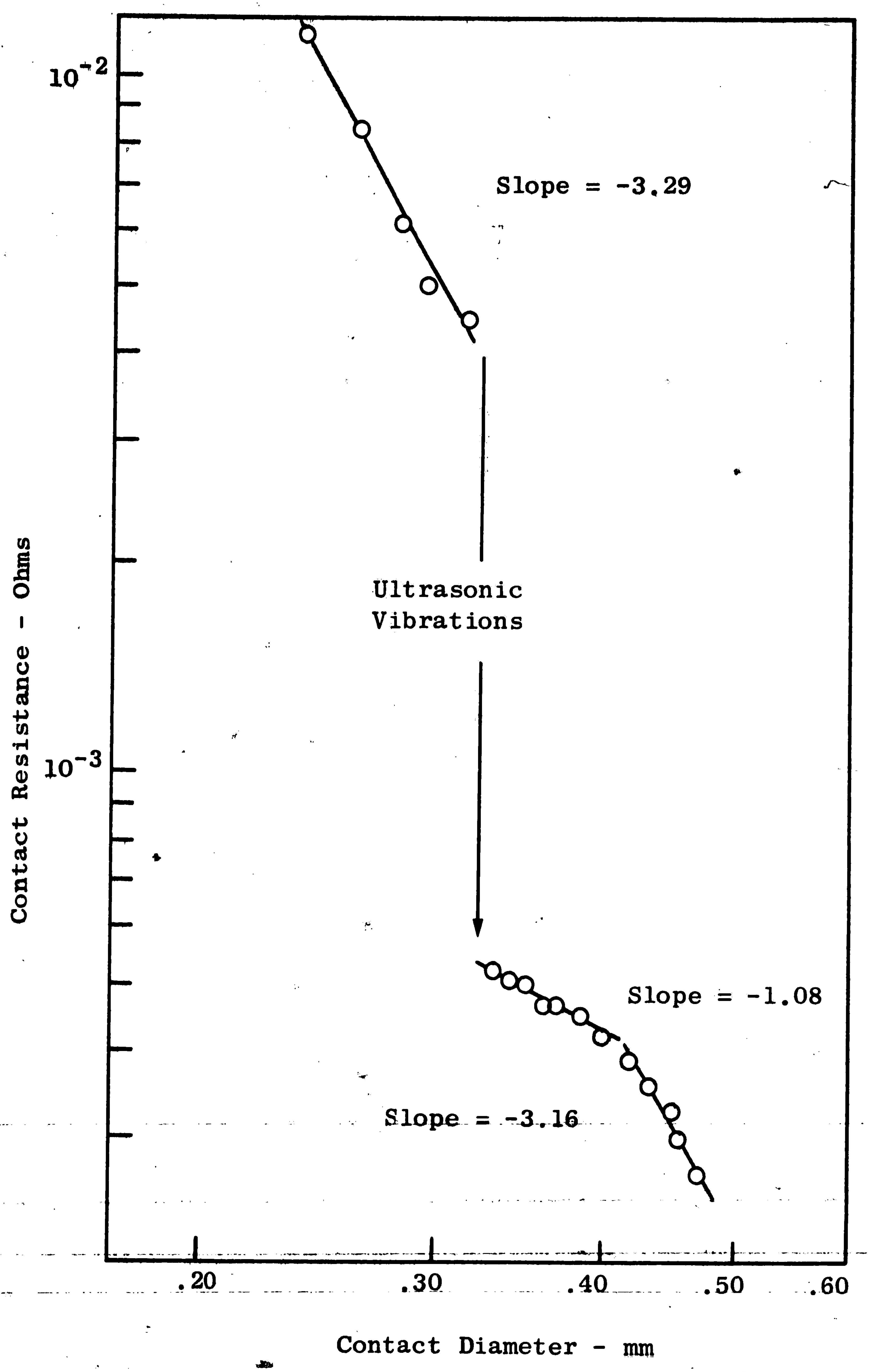


Figure 8

Resistance versus Diameter Showing Effects of Ultrasonic Vibrations

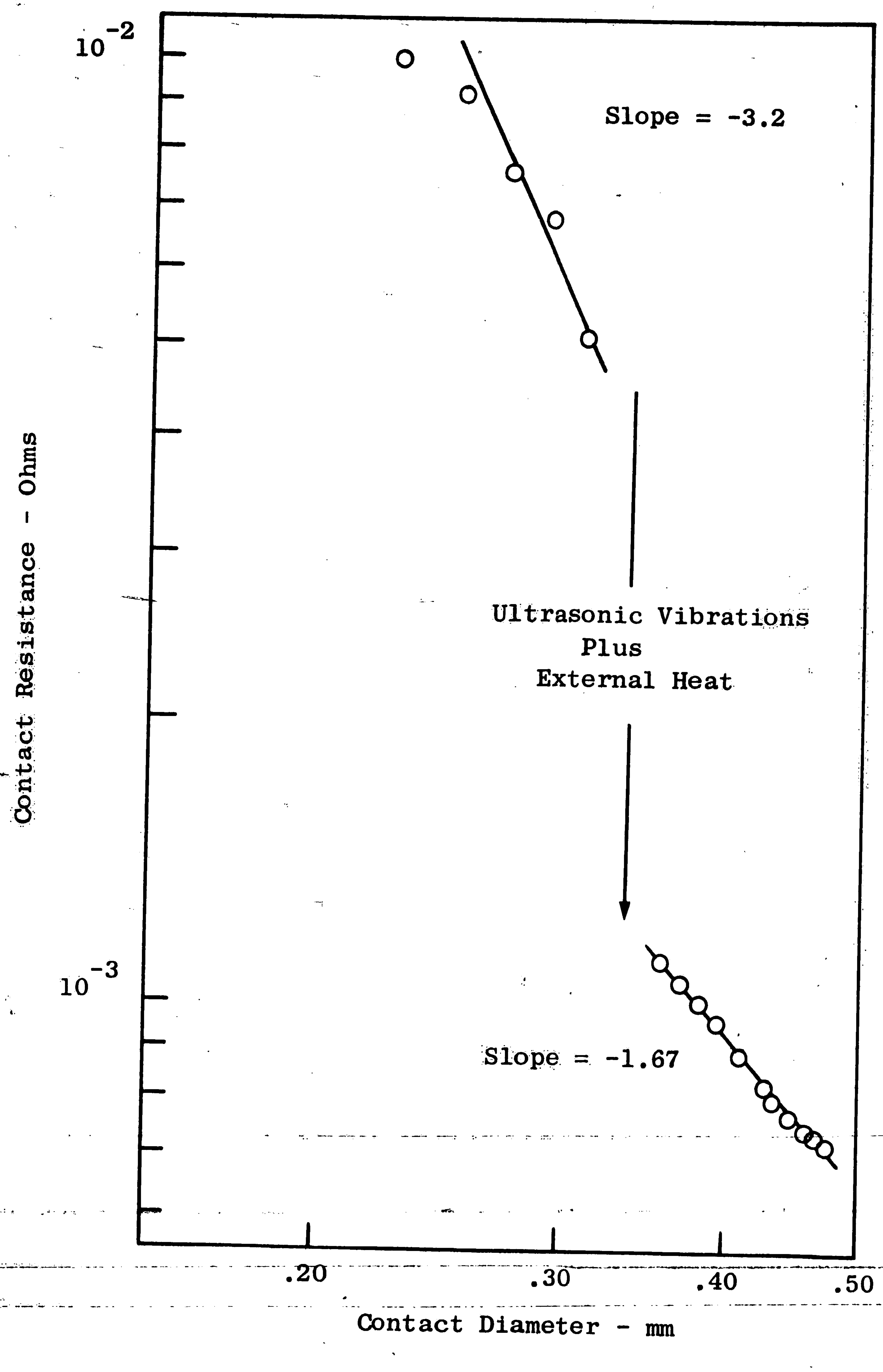


Figure 9

Resistance Versus Diameter Showing Effects of Ultrasonic Vibrations and Temperature

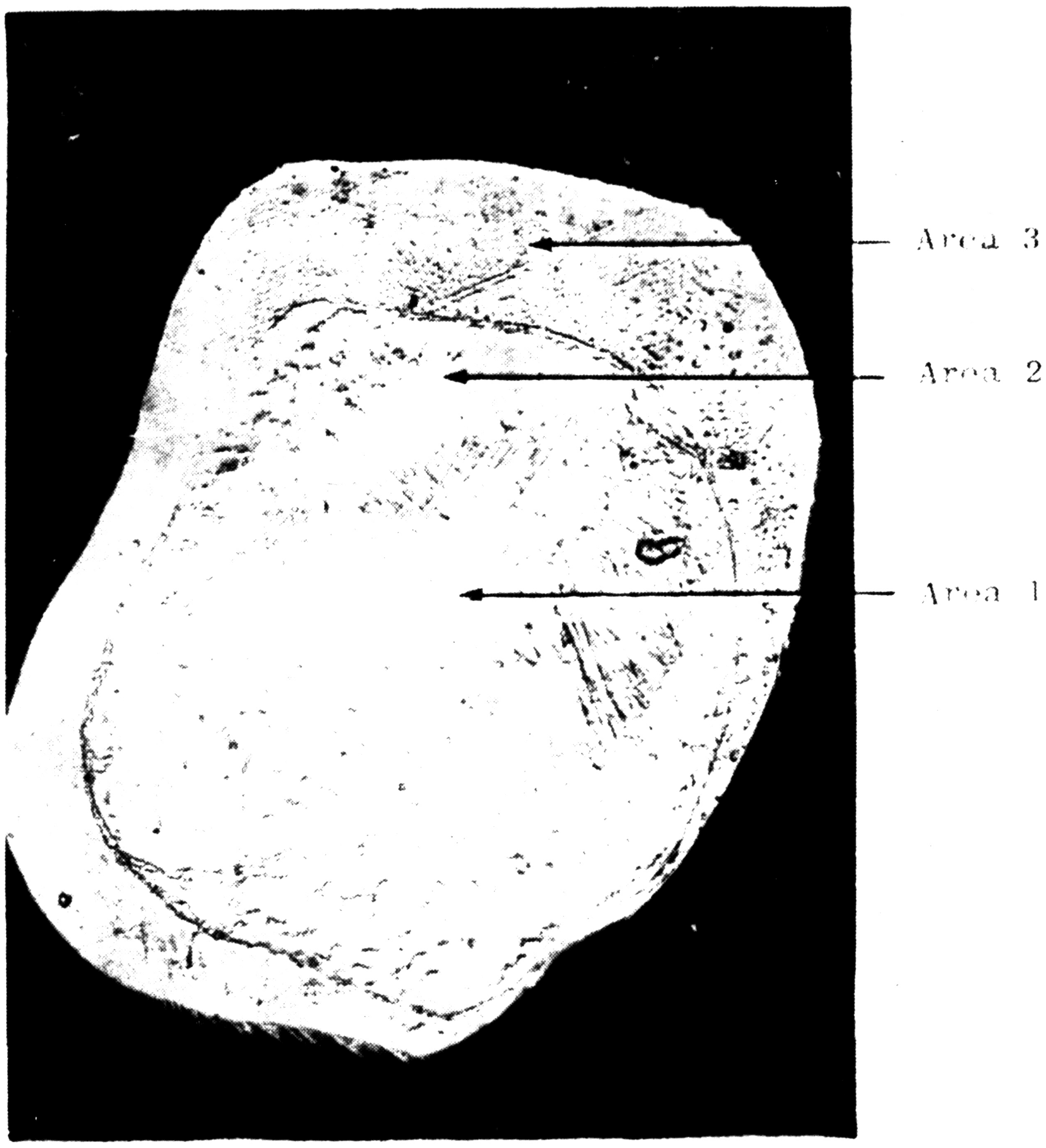


Figure 10

Photomicrograph of the Contact Surface
of a Deformed Gold Ball (200X)

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EDUCATIONAL BACKGROUND

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Mississippi State University	Graduated 1961
Bachelor of Science, Electrical Engineering (Honors)	
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