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Contract No. W-7405-eng-92

A TWO-STAGE MODEL FOR THE SOLID-PHASE BONDING PROCESS

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July 29, 1957

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BMI-1211

The solid-state bonding of simulated single-asperity contacts has been studied, using a gold needle point in contact with a gold flat. The bond strength-time relation at any temperature can be expressed as the sum of three components, of which the first is time independent and corresponds to instantaneous adhesion. The time dependence of the other two terms has been expressed as growth of the bonded area by creep and self-diffusion processes. The rate at which bond strength increases by self-diffusion has been expressed in terms of the equation developed by Kuczynski. In the majority of tests, the growth of the bond by creep was eliminated by conducting the tests at zero load in order to simplify the analytical expression developed for bond growth.

INTRODUCTION

Much work of a practical and empirical nature has been done in the fields of metal cladding and the sintering of metal powders. The lack of generality in much of this work makes desirable a more fundamental study of the factors which control solid-state bonding. This is a report of studies of solid-state bonding in which the factors of time, temperature, and stress are considered significant in the adhesion process. The asperity concept of bonding used here visualizes macroscopic bonding as the adhesion of a large number of small areas of contact, or asperities. In the present work, attention is focused on a single-asperity system consisting of a small hemispherical needle point in contact with a plane surface. This system has been studied under systematic variations of temperature, time, and pressure (applied load).

BACKGROUND INFORMATION

A previous report (BMI-1101) included a discussion of the fundamental aspects of solid-state adhesion. It considered the conditions of adhesion for the ideal case, and the conditions under which adhesion and bond growth can be induced in metal systems. A brief review of these considerations is made here.

In a perfect metallic crystal, the spatial relation of the atoms is characteristic of the metal, with atoms occupying equilibrium positions. These equilibrium positions

are governed by interaction of interatomic forces. The system resists any attempt to alter this equilibrium arrangement. Thus, if a compressive force is applied, it tends to reduce the atomic separation and will be opposed by an elastic repulsive force. The opposite occurs when a tensile force is applied to the system. This increased force of attraction which opposes the applied tensile force is manifested in the bonding of atom aggregates in which metal surfaces are brought into contact and which then exhibit a resistance to separation. Should two perfectly plane and clean surfaces be brought to within several interatomic distances, an attractive force will occur over the whole of the adjacent surface. An equilibrium separation of the surfaces will be attained. Attempts either to reduce or increase the normal interatomic separation across the plane of contact will be opposed by repulsive or attractive forces. Bonding then is said to have resulted at the interface of the surfaces. These ideal conditions are never realized in nature. Any real surface can only approximate the plane condition on the atomic scale. Crystallographic orientation differences at the bonding surfaces also must be considered. Moreover, even under the most favorable experimental conditions, chemically combined or physically adsorbed contaminant films act as barriers to prevent the ideal separation over the whole of the contact plane. Experimentally, allowances must be made for these deviations from ideality, and experimental conditions adjusted to minimize the effects of these deviations.

In the absence of external compressive forces which reinforce the interatomic attractions, two imperfect surfaces will contact each other at a number of points or asperities. Real surfaces exhibiting elastic and plastic properties deform under the influence of applied forces, so that the initial contact points become areas of contact, their size being dependent upon the applied load, the size and number of asperities, and the elastic and plastic properties of the materials. Increased external forces cause additional asperities to come into contact until, finally, the irregular surfaces have deformed sufficiently for interatomic attractive forces to become effective over the whole surface area, as in the case of the atomically plane surfaces. These two limiting states are, however, not identical. Such deformation results in an exceedingly large number of nonequivalent stress and strain conditions. These numerous states do not lend themselves to individual examination and quantitative description. This difficulty can be avoided to some extent by reducing the size of the apparent contact area and, consequently, reducing the complex surface mating problem. As the macroscopic area is decreased, points and areas of contact are decreased until only a single asperity remains to form contact. Bowden and Tabor^{(1)*} have reported that the asperity size in the mating of real metal surfaces is of the order of $20\ \mu$. It is possible, therefore, to simulate and study such a single-asperity system and to make inferences of the cumulative effect of the multitude of such asperity systems which occurs in a macroscopic system. The simulated single-asperity system has been used in a number of investigations. Wilson⁽²⁾ employed such a technique in measurements of contact resistance and mechanical properties of various surface films on metals. Bowden and Rowe⁽³⁾ used similar methods to study metallic adhesion and friction. Spurr⁽⁴⁾ used a somewhat larger asperity to study the effects of creep on static friction. Claypoole⁽⁵⁾ studied friction between a convex glass lens and a flat glass plate. King and Tabor⁽⁶⁾ experimented with friction between a hard steel slider and surfaces of rock salt, lead sulphide, and ice. All of these studies were similar with respect to the experimental approach; in each, an attempt was made to reduce the apparent contact area between the adhering surfaces. Admittedly, in at least several cases, the experimental contacting members formed a much greater area than that which would exist between $20\text{-}\mu$ -size asperities.

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*See References at end of the report.

It generally is observed that not only does adhesion occur instantaneously upon contact of clean surfaces, but also that if the surfaces are retained in contact, there is an enhancement of the adhesion. The mechanism for this time-dependent increase in bonding is a subject about which there is some disagreement. Parks⁽⁷⁾ proposed that pressure welding or solid-state bonding is a recrystallization-controlled process with the rate of welding dependent – as is the recrystallization rate – upon the degree of cold work in the adhering surfaces. Ainbinder and Klokova⁽⁸⁾ discounted this idea, at least in the case of copper and aluminum at room temperature, on the grounds that the heating effect of cold working is insufficient to cause recrystallization. Shaler⁽⁹⁾ concluded that, in the sintering of powder compacts, there is a combined effect of atomic interactions, creep, and viscous flow which accounts for densification and increase in strength. Kuczynski⁽¹⁰⁾ concluded from measurements of the rate of sintering between small spherical particles and plane surfaces that volume diffusion is the predominant mechanism for material transport leading to an increase of contact area. Kuczynski's approach seems valid to the extent that it has been used to measure the coefficients of volume self-diffusion of copper and silver, with good agreement with the results of other investigators.

EXPERIMENTAL MODEL

A two-stage model has been postulated for the solid-state bonding process, in which the first term describes the initial bond area and the second term describes the growth of the bonded area. This second term is further divided into two parts, expressing growth by creep and by self-diffusion. The total bonded area thus can be expressed as a sum:

$$A = A_0 + A_c + A_d ,$$

where

A_0 = initial contact area

A_c = area formed by creep

A_d = area formed by diffusion.

Figure 1 shows schematically the bonding process in a single-asperity system, and the increments of area involved in this model. All three areas are dependent on temperature; A_c and A_d also are time dependent, whereas A_0 is primarily load dependent. Any of the three area components can be made equal to zero by proper control of the experimental conditions. A_0 can be eliminated by bringing the asperities into contact without external load. A_c can be made equal to zero by reducing the applied load to zero. A_d can be eliminated by maintaining the asperities in contact for a negligible period of time. The equation developed by Kuczynski⁽¹⁰⁾ for the sintering of metal powders has been used to express the area formed by diffusion. This equation is given as:

$$\frac{x^5}{a^2} = \frac{40\sigma\delta^3 D_v t}{kT} ,$$

FIGURE 1. SCHEMATIC DIAGRAMS SHOWING THE EFFECTIVE BONDED AREA AT ASPERITY CONTACT UNDER VARIOUS CONDITIONS OF LOADING

in which the following values are used:

x = radius of the contact area, cm

a = radius of sphere (needle point), cm

σ = surface tension, dynes per cm

δ = interatomic distance, cm

D_v = coefficient of volume diffusion, cm^2 per sec

t = time, sec

k = Boltzmann's constant, dyne cm per deg K

T = temperature, deg K

This equation was developed for an initial contact-area radius of zero at zero time from the integration:

$$\int_0^x x^4 dx = \frac{8\sigma \delta^3 D_v a^2}{kT} \int_0^t dt .$$

Under conditions of zero maintained load (to minimize creep), this equation can be modified to include the initial area A_0 . This is done by integrating between the limits of x_0 and x as:

$$\int_{x_0}^x x^4 dx = \frac{8\sigma \delta^3 D_v a^2}{kT} \int_0^t dt .$$

The solution of this equation can be written as:

$$x^5 = x_0^5 + \frac{40\sigma \delta^3 D_v a^2 t}{kT} .$$

The total area A then becomes:

$$A = \pi x^2 = \pi \left(x_0^5 + \frac{40\sigma \delta^3 D_v a^2 t}{kT} \right)^{0.4} .$$

From tests made at zero time, the breaking-force measurements are used to obtain values for A_0 , where $A_0 = \pi x_0^2 = \frac{F_0}{S}$. F_0 represents the breaking force at zero time, and S the ultimate tensile strength. It was this model for the asperity-bonding process which governed much of the experimental procedure and testing program used in this research. So far as possible, creep effects have been minimized by reducing the applied load to zero after establishing the initial bond area.

EXPERIMENTAL PROCEDURES

Specimen Preparation

To conduct simulated single-asperity bonding tests, both the plane surface and asperity components of the bonding couple are required. The asperities consist of needle points prepared from 0.036-in. -diameter fine gold wire. These are formed by electropolishing the wires in aqua regia to a tip radius of between 0.5 and 1.5×10^{-3} cm. The plane bonding surface was the end face of a 1/4-in. -diameter gold cylinder in the annealed and electropolished condition. It was found that the worked surface layer present when the plane bonding surfaces were mechanically polished gave erratic bonding behavior. This was attributed to an increased rate of self-diffusion.

Apparatus for Single-Asperity Bonding Experiments

In order to study the asperity bonding process using the model discussed above, it is necessary to control the conditions of stress, temperature, and time to which the system is exposed. The basic torsion balance (Figure 2) described in BMI-1101 is used to apply the load and to measure the breaking force. This equipment establishes normal loading conditions between the gold needle fixed in the balance beam and the plane gold surface. The gold flat was fastened in a platinum-wound resistance furnace. With this device, it is possible to measure the force applied to the needle and the force required to break the bond. An electric circuit recently was set up to continuously record the voltage drop across the contact interface. From these measurements, the contact area may be calculated.

The direct current circuit includes a 1-1/2-v dry cell in series with a milliammeter, the needle-flat couple, and suitable resistances for regulating the current. A millivolt recorder was connected across the specimen couple to measure the potential drop through the contact constriction. Current was regulated so that the potential drop did not exceed 0.5 mv in order to avoid resistance-heating effects at the contact.

Testing Procedure

Experiments were conducted in a dry-air atmosphere. The specimens were cleaned in dichromic acid and then rinsed in distilled water and ethyl alcohol. Then the specimens were placed in the torsion balance apparatus and allowed to come to temperature. Contact was established by slowly rotating the torsion member of the balance. The rate of load application, governed by the motor speed and gear system, was about 0.5 g per min. After the specimens had been in contact for the prescribed period of time, the motor was reversed until separation of the specimens occurred. The breaking force then was measured and recorded.

- Notes: 1. All critical temperatures are indicated by thermocouples.
2. Apparatus housed in vacuum chamber.

FIGURE 2. TORSION-BALANCE DEVICE

EXPERIMENTAL RESULTS

The experimental results of primary interest in this discussion are listed in Table 1 and are shown graphically in Figures 3, 4, 5, 6, 7, and 8. Figures 3, 4, 5, 6, and 7 present the data as individual results, whereas Figure 8 shows the averaged values of normal breaking forces. Each data point represents an individual test with a virgin needle of tip radius about 1×10^{-3} cm.

TABLE 1. AVERAGED VALUES OF BOND STRENGTH
CORRECTED TO ROOM TEMPERATURE

Bonding Temperature, C	Bond Strength, g, After Indicated Time, min								
	0	2	5	10	15	20	30	40	60
400(a)	—	—	.75	1.0	1.0	—	1.0	—	1.25
600(b)	1.2	—	—	2.0	—	—	3.25	—	4.0
650(c)	3.75	7.25	10.0	9.0	—	12.75	—	15.0	16.0
700(c)	4.3	6.4	7.7	10.5	—	11.1	—	14.0	14.9
800(c)	4.0	7.0	9.75	12.8	—	18.0	—	22.8	25.0

(a) Loading conditions: 200-mg preload, 10-mg maintained load.

(b) Loading conditions: 400-mg preload, 10-mg maintained load.

(c) Loading conditions: 100-mg preload, 0-mg maintained load.

The following loading procedure was used at 650, 700, and 800 C. A preload of 100 mg was applied and then reduced to zero. This condition of zero applied load was maintained for the proposed testing period. At 400 C, a preload of 200 mg was applied initially and then reduced to 10 mg for the remainder of the testing period. At 600 C, a preload of 400 mg was applied and then reduced to 10 mg. This preloading procedure was adopted in order to establish a finite contact area having sufficient strength so that slight temperature fluctuations and slight but unavoidable background vibrations would not disturb or destroy the bond. Moreover, by maintaining a very small load, the effect of creep on growth of the bonded area would be minimized. It was not feasible to conduct the measurements of breaking force at room temperature, because of the thermal stresses which accompany cooling of the specimens. Therefore, all measurements were made at the bonding temperature, and the corresponding room-temperature breaking forces were calculated. This was done by using a room-temperature tensile strength for annealed gold as 18,000 psi, and by estimating the tensile strength of gold at elevated temperatures from information by Carreker, Guard, and Lenhart⁽¹¹⁾. The individual bond strengths were transformed to room temperature by the appropriate correction factor of room-temperature strength divided by estimated strength at temperature. Data in Table 1 and in Figure 8 have been corrected to room temperature.

FIGURE 3. ORIGINAL DATA ON BREAKING LOAD VERSUS TIME AT 400 C

FIGURE 4. ORIGINAL DATA ON BREAKING LOAD VERSUS TIME AT 600 C

FIGURE 5. ORIGINAL DATA ON BREAKING LOAD VERSUS TIME AT 650 C

FIGURE 6. ORIGINAL DATA IN BREAKING LOAD VERSUS TIME AT 700 C

FIGURE 7. ORIGINAL DATA IN BREAKING LOAD VERSUS TIME AT 800 C

FIGURE 8. AVERAGE BREAKING LOADS VERSUS TIME AT TEMPERATURE

DISCUSSION

As seen in Figure 8 the general form of the curve of breaking force versus time is similar at each bonding temperature. The breaking force may be separated into two components following an equation of the form $F = F_0(T) + F_t(T, t)$. This general relationship is depicted in Figure 9 which is a graphical representation of the bonding model shown pictorially in Figure 1. $F_0(T)$ is the time-independent force component that is a measure of the instantaneous adhesion of the needle and flat. This term is temperature dependent because the mechanical and physical properties of the material vary with temperature. $F_t(T, t)$ may be considered the growth component of the breaking force, a function of both temperature and time. Interpretation of the experimental results requires that a more explicit equation be obtained. Figure 10 shows a logarithmic plot of breaking force versus time at various testing temperatures. The plots are linear with a slope n of

$$n = \frac{d \ln F}{d \ln t},$$

where values for n range from 0.27 to 0.38. These plots correspond to an exponential relation: $F = Ct^n$, where C is a constant. This equation considers only the time-dependent component of the breaking force, and thus is given the notation, F_t , where $F_t = Ct^n$. The added time-dependent component, F_t' is the increment of area increase due to creep. This term has been eliminated in the majority of the tests reported here in order to simplify the expressions, by running the tests at zero applied load after an initial preload. The effects of creep are discussed briefly in a later paragraph.

The exponential form of the term describing the increase of bond strength also is observed in studies of sintering and bonding.^(9, 10) The exponent n with values between 0.27 and 0.38 is similar to that found by Kuczynski⁽¹⁰⁾ and Bocksteigel⁽¹²⁾, in which an exponent of $2/5$ was theoretically derived and experimentally verified. The exponent obtained experimentally from the present studies and the theoretical exponent of 0.4 are in reasonable agreement. Kuczynski's work showed that an exponent of $n = 0.3$ occurs in the case of mass transport by surface diffusion. Bocksteigel⁽¹²⁾, however, has shown by mathematical treatment that an exponent of about 0.3 can be expected in the sintering of nonspherical particles (of paraboloid form). It is almost certain that such a condition of nonsphericity exists in the present work, both because of deformation during preloading of the needle point and by formation of a parabolic shape during the needle electropolishing process.

Using the Kuczynski expression, the breaking strength F then becomes:

$$F = S\pi \left[\frac{40\sigma \delta^3 a^2 D_v t}{kT} \right]^{0.4}$$

where S is the tensile strength. Likewise, the experimental breaking forces measured in the present work should be proportional to the contact area:

FIGURE 9. GENERAL FORM OF BREAKING FORCE-TIME CURVE FOR SINGLE-ASPERITY BONDING TESTS

FIGURE 10. AVERAGED BREAKING LOADS VERSUS TIME AT TEMPERATURE

$$F = S\pi \left[x_0^5 + \frac{40\sigma\delta^3 a^2 D_v}{kT} t \right]^{0.4} \quad (1)$$

The initial contact radius x_0 is a function of the mechanical properties of the material, the load applied to form the contact area, and the temperature at the contact interface. The situation in which a sphere and a flat surface of the same material are brought together under load is complex. Deformation occurs both in the surface and in the sphere. The mechanical constraints are different in the two components because of differences in shape; also, the constraints caused by friction forces between the indenter and the surface must be considered. In the present experiments at high temperatures, the components are considered to be essentially free from surface films and, therefore, in a condition for unobstructed bonding. Friction forces and resultant constraints probably are of considerable magnitude. Two major simplifications in the problem may be made. The indenter can be considered a rigid body, and friction restraints at the interface may be neglected. If these simplifications are made, it can be shown⁽¹³⁾ that the radius of contact x_0 under a load W is:

$$x_0 = \sqrt{\frac{W}{3P\pi}}$$

where P is equal to the yield strength of the plane surface. Although this value for x_0 can be substituted directly into Equation (1), resulting in a fully descriptive expression for bonding under the given experimental conditions, the results obtained do not agree well with experimental values. The size of the bonded area will govern the strength of the initial bond, and the mechanical properties of the asperity material will control the mechanical area of contact under a given load. However, the mechanical area of contact and the area of metallurgical bonding are not necessarily identical. This has been observed in electrical-resistance calculations of contact area. An expression used by Holm⁽¹⁴⁾ in his treatment of the theory of electrical contacts relates measurable electrical quantities to the area of electrical contact. For the system of a conducting sphere in contact with a semi-infinite conducting plane, the radius of contact (x) is given as $x = \frac{\rho}{2R}$,

where $R = \frac{E}{I} = \frac{\text{potential drop across contact interface}}{\text{current through the contact}}$, and ρ = electrical resistivity.

It would be expected that if the mechanical- or electrical- contact area were equivalent to the metallurgically bonded area, and if the breaking force of a bond were equal to $S \cdot A$, then the time dependence of the electrical contact area and of the bond strength would be the same. In other words, it would be expected that

$$\frac{d \ln (\text{electrical contact area})}{d \ln t} = \frac{d \ln F}{d \ln t}$$

This is not observed experimentally. For instance, at 800 C, $\frac{d \ln F}{d \ln t} = 0.38$, but for corresponding area measurements $\frac{d \ln A}{d \ln t} \cong 0.13$. Insufficient information is available

at present for resolving the difficulties of the complex strain behavior at the bond interface and the nonequivalence of mechanical- and metallurgical- bond area. It is of interest, however, to compare experimental results with those predicted by the Kuczynski analysis.

Consider data obtained at 700 C. From the equation

$$F = S\pi \left[x_0^5 + \frac{40\sigma\delta^3 a^2 D_v t}{kT} \right]^{0.4},$$

the instantaneous bond strength should be $F_0 = S\pi x_0^2$. Experimentally, the zero-time bond strength, corrected to room temperature, is 4.0 g. Therefore

$$A_0 = \frac{4.0}{454 \times 18,000} = 4.9 \times 10^{-7} \text{ in.}^2$$

or

$$x_0 = 1 \times 10^{-3} \text{ cm.}$$

After a 10-min bonding period, the measured bond strength is 9.5 g, so that there is an experimental increase in bond strength of 5.5 g.

The predicted increase in strength can be determined by substituting appropriate values into the strength equation. If

$$\sigma = 1399 \text{ dynes per cm}$$

$$\delta^3 = 23.1 \times 10^{-24} \text{ cm}^3$$

$$a^2 = 1 \times 10^{-6} \text{ cm}^2$$

$$D_v, 973K = 4.49 \times 10^{-11} \text{ cm}^2 \text{ per sec}$$

$$k = 1.38 \times 10^{-16} \text{ dyne cm per deg K}$$

$$T = 973 \text{ K}$$

$$t = 600 \text{ sec,}$$

then the equation

$$F = S\pi \left(x_0^5 + \frac{40\sigma\delta^3 a^2 D_v t}{kt} \right)^{2/5},$$

which reduces to

$$\begin{aligned} F &= \frac{4.54}{6.4} (18000 \pi) (1 \times 10^{-15} + 0.00026 \times 10^{-15})^{2/5} \\ &= \frac{4.54}{6.4} (18000 \pi) (1.0003 \times 10^{-15})^{2/5} \\ &= 4 \text{ g.} \end{aligned}$$

In other words, the Kuczynski expression predicts a negligible increase in area in 10 min at 700 C, whereas experimental results show an increase of more than 100 per cent in the same time period. Assuming the Kuczynski equation to be valid for this case, it appears that the quantity, a , in the expression may be a major cause of error. It is possible to calculate the value of a which will result in a predicted strength value equal to the experimental bond strength. The value of a which fits the experimental results is 0.174 cm instead of the initial radius of curvature of 1×10^{-3} cm. In the original Kuczynski equation, the derivation was made for the sintering of a sphere to a plane surface. It was assumed that the contact area resulting from sintering was small relative to the radius of the sphere. This assumption becomes less valid as the area is increased, or when the initial area is formed by preloading as in these experiments. Deformation of the needle point could result in a considerable increase in the radius of curvature of the needle point. However, no measurements of needle-tip radii after deformation are available at present. Further, the needle has an approximately parabolic cross section (Figure 11) so that the radius of curvature increases as the distance from the central axis is increased. These considerations, used in a qualitative sense, indicate that the effective radius of curvature of the needle point must be considerably greater than the original measurement before deformation, and also that modification of the Kuczynski equation is needed for this application. Another possible source of discrepancy is in the value for the diffusion coefficient. The application of a stress may result in at least a transient increase in the diffusion rate. Comparisons of experimental bond strength increases and the predicted increases at 600, 650, and 800 C reveal discrepancies similar to those at 700 C.

FIGURE 11. PHOTOMICROGRAPH OF REPRESENTATIVE GOLD NEEDLE

No mention has been made of the growth of bond by creep. As yet, no complete study of creep effects has been made. It is reasonable to assume that a significant contribution to area growth is made by this mechanism, especially in the early stages of bonding.

Figure 12 shows the result of a single experiment to observe the effect of load (and, therefore, creep) on bond strength. A noticeable increase in bond strength is seen as the maintained load is increased. Preliminary studies have been made of the penetration of a steel ball into a plane gold surface. In these experiments, a 1/16-in. - diameter steel ball was impressed into a gold surface under constant load for various periods of time. Logarithmic plots of projected impression area versus time are shown for several temperatures in Figure 13. The relations are approximately linear with slopes ranging between 0.12 and 0.16. Thus

$$\frac{d \ln (\text{projected area})}{d \ln t} = n .$$

The area-time relation is, therefore, of the form

$$A = A_0 (1 + Ct^n) ,$$

where A_0 is the area at zero time and C is a constant. This form of the equation is similar to Andrade's⁽¹⁵⁾ relation for tensile creep under constant stress in which $\ell = \ell_0 (1 + \beta t^{1/3})$. Both tensile strain in Andrade's investigations and projected impression area in the present work approached limiting values with increasing time.

In many of the early bonding experiments, an excessive amount of scatter was observed in bond strengths. This was attributed to the presence of an uncontrolled amount of cold work in the mechanically polished surfaces of the gold flats. More recent experiments, done with electropolished flats, gave more reproducible results and lower strengths.

The effect of cold work on bonding was studied using electropolished flats made from rod stock that had been cold reduced by various amounts. Results of these tests are shown in Figure 14, which compares the bonding behavior of annealed and cold-worked flats at two temperatures. At 300 C, the difference in bond strength is slight, and indicates a slightly higher strength for the annealed flats. This may result from the smaller penetration of the needle into the cold-worked surface and a consequent smaller bond area. The growth of the bond area by diffusion would be slow at this temperature. At 400 C, a minimum is observed in the strength-time curve for the cold-worked flat. This may result from recrystallization of the worked material, which was found to take place after about 5 min. This is followed by a more rapid increase in bond growth at longer exposure times. Although these results are scattered and not entirely conclusive, it is clear that a cold-worked surface definitely affects the bonding process. Further studies of this important effect should be made. It is clearly an important parameter in any practical application of solid-state bonding.

FIGURE 12. EFFECT OF APPLIED LOAD ON BOND STRENGTH

FIGURE 13. HOT HARDNESS OF GOLD

Projected Area of Im-
pression Versus Time at
Load

FIGURE 14. BREAKING LOAD VERSUS TIME AT LOAD FOR ANNEALED AND COLD-WORKED FLATS

CONCLUSION

It has been found that the relation between bond strength and bonding time is similar to that predicted by Kuczynski. This lends support to the theory that contact-area growth at single asperities is predominantly volume-diffusion controlled. However, even though the experimental and theoretical exponential relations are in good agreement, the experimental magnitudes of area growth are greater than those predicted by the theory. The theory contains in the expression for bond-area growth the factor $a^{0.8}$, where a is the initial radius of curvature of the spherical surface contacting the plane surface. This condition of sphericity cannot exist under the experimental conditions of temperature and load. Considerable flattening and a resultant increase in radius of curvature must occur under load application. The discrepancies could be reduced if the increase in radius of curvature (and, consequently, the factor $a^{0.8}$) were sufficient. It also must be considered that the original relation by Kuczynski to describe sintering was determined for the case of a sphere in contact with a plane surface with negligible initial contact area. The experimental procedure of preloading results in a finite initial area, as evidenced by appreciable initial bond strengths. Reference to experimental results at 700 C reveals that at zero time a 4-g bond strength is obtained. The corresponding contact area A_0 is

$$A_0 = \frac{4}{454 \times 18000} = 4.9 \times 10^{-7} \text{ in.}^2 = \pi x_0^2$$

$$\text{and } x_0 = 1 \times 10^{-3} \text{ cm}$$

This value of x_0 is of the order of the initial needle point radius, and therefore, it is seen that the 100-mg load at 700 C is sufficient to deform the needle to a point well past the spherical tip. Proportional deformations are suffered by the needle at other testing temperatures. It must also be mentioned that the theoretical growth equation is not an exact expression. Approximations were made by Kuczynski in the original analysis to simplify the final form of the relation. Therefore, it may be necessary not only to compensate for differences in contact conditions, but also to modify the approximations made by Kuczynski for application to the present problem.

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