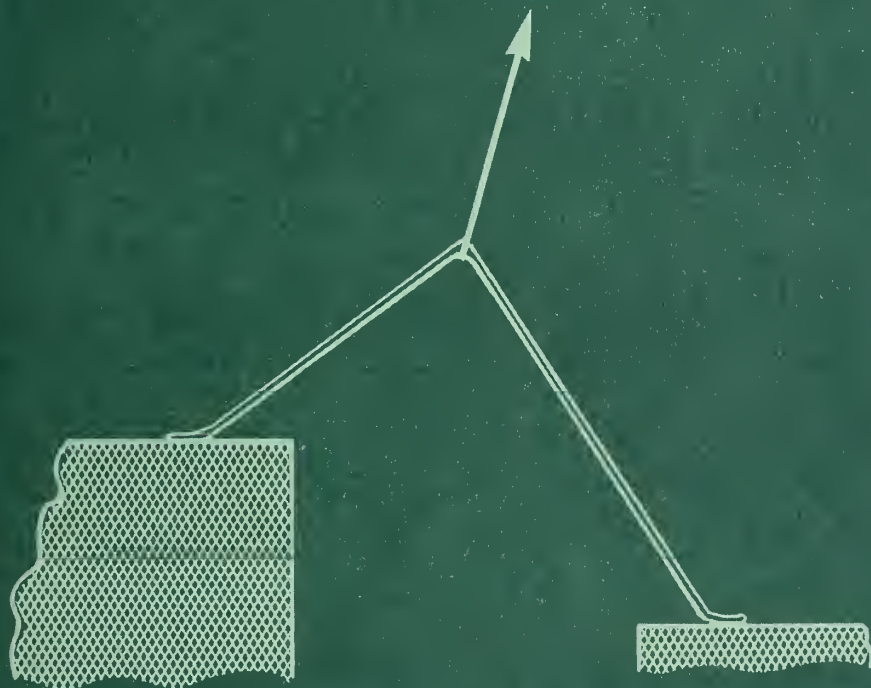NBS SPECIAL PUBLICATION **400-18**

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Semiconductor Measurement Technology:

The Destructive Bond Pull Test

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[2] Located at Boulder, Colorado 80302.

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National Bureau of Standards Special Publication 400-18

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PREFACE

The Semiconductor Technology Program serves to focus NBS efforts to enhance the performance, interchangeability, and reliability of discrete semiconductor devices and integrated circuits through improvements in measurement technology for use in specifying materials and devices in national and international commerce and for use by industry in controlling device fabrication processes. Its major thrusts are the development of carefully evaluated and well documented test procedures and associated technology and the dissemination of such information to the electronics community. Application of the output by industry will contribute to higher yields, lower cost, and higher reliability of semiconductor devices. The output provides a common basis for the purchase specifications of government agencies which will lead to greater economy in government procurement. In addition, improved measurement technology will provide a basis for controlled improvements in fabrication processes and in essential device characteristics.

THE DESTRUCTIVE BOND PULL TEST

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ABSTRACT

This report summarizes the work done at NBS on the destructive bond
pull test as applied to small-diameter (approximately 1 mil or 25 μm)
ultrasonically bonded aluminum wire. This work was performed during
the period from 1969 to 1974. The report begins with a brief summary
of the calculation of the resolution-of-forces operative in the bond
system during the application of the pulling force. Next, comparisons
of the theoretical and experimental dependencies of the pull strength
on the variables involved in the resolution-of-forces calculation are
given. Some of the variables which are not directly involved in this
calculation are then considered and their effects on the measured
pull strength are presented. The report ends with a sensitivity cal-
culation as to how well the variables must be controlled to maintain
the variability of the pull strength within given limits.
Bond pull specifications for large-diameter wire as well as recom-
mended force levels to be used in the application of the nondestructive
bond pull test, both of which have resulted from the pull test work,
are considered in the appendices.

1. INTRODUCTION

This report is an edited summary of the NBS effort on the destructive bond pull test. The rationale for this work lies in the widespread use of this test method in the electronics industry to evaluate the mechanical strength of wire bonds in semiconductor devices and in the large gap between the use of the pull test and the acquisition of reproducible calculable quantities which could be used to quantify the test results. Hence, at the request of several agencies, and with the guidance of standards organizations, an extensive survey of test methods for wire bonds in general [1] and an evaluation of the pull test in particular were begun.

Initial in-house efforts to produce reproducible wire bonds to be used in the evaluation showed that the currently practiced industrial procedures were inadequate. This led to a study of ultrasonic wire bonding techniques. The results of this study pointed to the lack of shock and vibration isolation and the subsequent bond variability due to environmental and operator induced stresses as being primarily responsible for this inadequacy. An offshoot of this investigation was a better understanding of ultrasonic bonding through the use of magnetic pickup, capacitor microphone, and low-power laser detectors of tool motion during the bonding process. Optimized bond quality through bonding schedule studies resulted from this study. An exposition of a mechanism for the formation of ultrasonic bonds also followed from this study. A detailed treatment of these facets of the NBS work appears elsewhere [2].

Once bonder and related problems were solved, work was begun to quantify the results of the pull test. In order to carry out this program, it was necessary to correlate the measured pull strength as determined in the pull test with the stress in the wire, which depends on the geometry of the bond system. This was done through the resolution-of-forces calculation. An extensive series of experiments was undertaken in order to relate observed pull strengths to the results of the resolution-of-forces calculation. To further enhance the understanding of the pull test, certain variables which could not be introduced in the two-dimensional resolution-of-forces calculation were experimentally studied to ascertain their effects on the pull test results. This report is concerned with the results and conclusions of this investigation.

The results of the pull test work have been used by ASTM Committee F-1 on Electronics in the preparation of a document on the pull test method. At the time of this writing, the document is well on its way to becoming an accepted standard. To support this evolution, a round robin is presently being run using test vehicles prepared at NBS. On each specimen, three groups of bonds of different deformation were prepared. One-half of the bonds of each group were pulled to destruction at NBS and the remaining half were pulled at the individual laboratories participating in the round robin. The round robin is not complete; however, preliminary results indicate that the mean pull strengths as determined by NBS and by each of the other participating laboratories differ by about ten percent. It should be noted that these conclusions are preliminary and are based upon raw data. A more

complete treatment of the round robin and the data analysis will appear in the future when the round robin is complete.

The better understanding of the pull test has led to other developments. These include a bond pull specification for large diameter wire as well as statistical and metallurgical rationales for a nondestructive wire bond pull test. These are discussed in appendices C and D respectively. The work on the nondestructive pull test is also being used by ASTM Committee F-1 on Electronics in the development of a recommended practice for carrying out this type of test.

The following section contains a brief summary of a calculation of the resolution of the forces operative in the bond system during the application of the pulling force. A more complete derivation is presented in Appendix A and programs (in several different languages) which may be used for numerical calculation of the resolution-of-forces equations are given in Appendix B.

The discussion of the resolution-of-forces calculation is followed in Section 3 by a description of the fabrication of the specimens used for the single-level and two-level bond studies.

In Section 4, comparisons of the theoretical and experimental dependencies of the pull strength on the variables which are involved in the resolution-of-forces calculation are given. Of particular importance are the loop height, the position of the hook, and the angle between the direction of the pulling force and the normal to the line joining the bond terminals.

In Section 5, consideration is given to some of the variables which are not directly involved in the resolution of forces calculation. The variables considered are the rate of pull and the angle between the direction of pull and the normal to the substrate in the plane perpendicular to both the substrate and the plane of the bond loop.

Section 6 contains a sensitivity computation from which it can be estimated how well the variables must be controlled in order to maintain the accuracy of the results to within a given interval. A summary of the results comprises the final portion of the report.

1.1 UNITS

The American semiconductor industry has traditionally used mixed English and metric units, but presently there is a trend in the direction of the International System (SI) units. For the purposes of conversion, it should be noted that 1 mil = 0.001 in. = 25.4 μm and that 1 gram force (gf) = 9.8 millinewtons (mN).

2. RESOLUTION-OF-FORCES CALCULATION

The destructive bond pull test, more commonly called simply the pull test, is one of the most widely used test methods employed in the evaluation of the quality of wire bond systems. In its elemental form, the test consists of pulling the wire span between the bond on the terminal and the bond on the semiconductor die with a hook assembly until rupture takes place. The pulling force at which rupture occurs is usually referred to as the pull strength of the bond. The pull force at rupture is most frequently presented in units of grams force.

An analysis of the resolution-of-forces provides relationships between the pull strength and the forces in the bond system *at rupture*. In figure 1, the geometrical variables are presented for a typical two-level bond. The angle ϕ is that between the direction of the applied force F and the normal to the substrate. At the bond on the semiconductor die, the angle between the wire and the surface of the die is denoted by θ_d. At the terminal, the angle between the wire and the plane of the terminal surface is denoted by θ_t. The forces in the wire at the terminal and die are designated by F_{wt} and F_{wd}, respectively. These forces are related to the applied pull force as follows:

$$F_{wt} = F \left[\frac{\cos(\theta_d - \phi)}{\sin(\theta_t + \theta_d)} \right],$$

(1)

$$F_{wd} = F \left[\frac{\cos(\theta_t + \phi)}{\sin(\theta_t + \theta_d)} \right].$$

(2)

For the simple case of a single-level bond pulled normal to the substrate and at the middle of the wire span, $\phi = 0$ and $\theta_t = \theta_d = \theta$. In this instance, the above equations reduce to

$$F_{wd} = F_{wt} = F \frac{1}{2\sin\theta}.$$

(3)

The angular variables θ_t and θ_d are often difficult to measure. However, the angles may be related to the variables h, H, d, and ϵ which are more easily accessible to measurement. It may be seen from figure 1 that h is the height of the wire span (at the point of pull) above the terminal contact surface. The vertical distance between the terminal contact surface and the semiconductor die surface is denoted by H. The horizontal distance between the bond on the terminal and the bond on the die is denoted by d and is usually referred to as the bond-to-bond spacing. Finally, ϵ, where $0 \leq \epsilon \leq 1$, is the dimensionless fractional horizontal distance between the terminal bond and the point of application of the pulling force. In terms of these distance variables, F_{wd} and F_{wt} are related to F for a two-level bond as follows:

$$F_{wt} = F \left\{ \frac{\left(1 + \frac{\epsilon^2 d^2}{h^2}\right)^{\frac{1}{2}} \left[(1-\epsilon)\cos\phi + \frac{(h+H)\sin\phi}{d}\right]}{1 + \frac{\epsilon H}{h}} \right\},$$

(4)

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$$F_{wd} = F\left\{ \frac{\left(1 + \frac{(1-\varepsilon)^2 d^2}{(h+H)^2}\right)^{\frac{1}{2}}\left[1 + \frac{H}{h}\right]\left\{\varepsilon\cos\phi - \frac{h\sin\phi}{d}\right\}}{1 + \frac{\varepsilon H}{h}} \right\}. \qquad (5)$$

If the bond is pulled normal to the substrate ($\phi=0$), eqs (4) and (5) reduce to

$$F_{wt} = F\left(\frac{(1-\varepsilon)}{1 + \frac{\varepsilon H}{h}} \left[1 + \frac{\varepsilon^2 d^2}{h^2}\right]^{\frac{1}{2}}\right) \text{ and,} \qquad (6)$$

$$F_{wd} = F\left(\frac{\varepsilon\left[1 + \frac{H}{h}\right]}{1 + \frac{\varepsilon H}{h}} \left[1 + \frac{(1-\varepsilon)^2 d^2}{(h+H)^2}\right]^{\frac{1}{2}}\right) . \qquad (7)$$

For a single-level bond which is pulled at mid-span, in a direction normal to the substrate, both ϕ and H are zero and ε is equal to one-half. Under these conditions, eqs (4) and (5) reduce to

$$F_{wt} = F_{wd} = \frac{F}{2}\left[1 + \left(\frac{d}{2h}\right)^2\right]^{\frac{1}{2}} . \qquad (8)$$

It should be noted that eqs (1) through (8) may be used for calculating pull strengths only when heel breakage (tensile failure) is observed.

For the convenience of readers interested in numerical computations, Appendix B contains programs in several different languages which make use of eqs (4) and (5) to calculate the pull strength. For purposes of graphical illustration of the predictions of eqs (1) through (8), plots of the force in the wire on the terminal or die divided by the pulling force as functions of the angular variables or the length variables are presented in figures 2 to 4. Also, table 1 contains typical results from the resolution-of-forces calculation for single-level and two-level bonds [3].
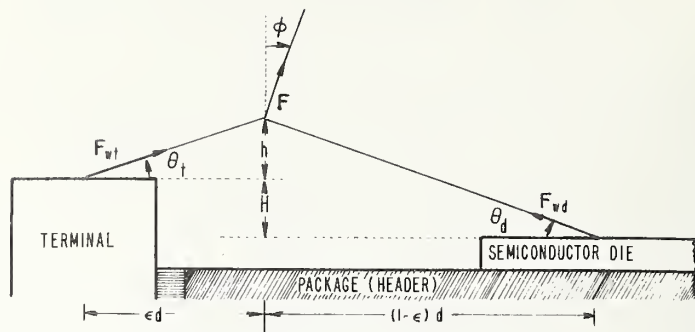
Figure 1.   Geometric variables for the bond pull test.
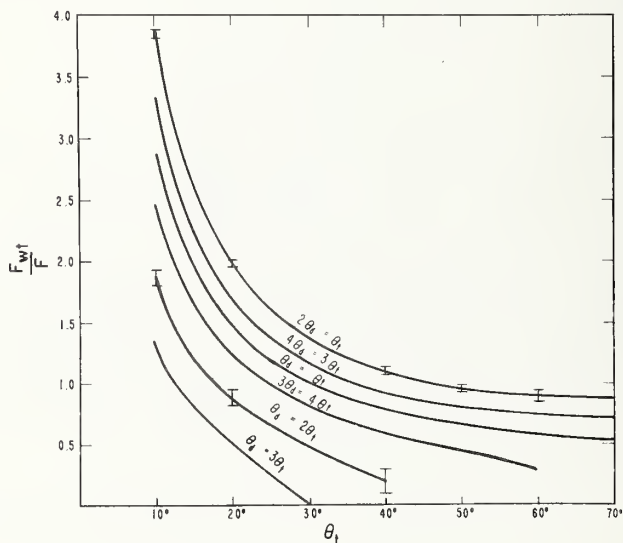
Figure 2.   Dependence of F_{wt}/F on θ_t for various ratios θ_d to θ_t. (The curves are for the case $\phi = 0$.   Horizontal bars above and below the curves for $2\theta_d = \theta_t$ show the effect of changing ϕ to plus and minus 5 deg, respectively.   To obtain the dependence of F_{wt}/F, interchange everywhere the subscripts d and t and change the sign of ϕ).
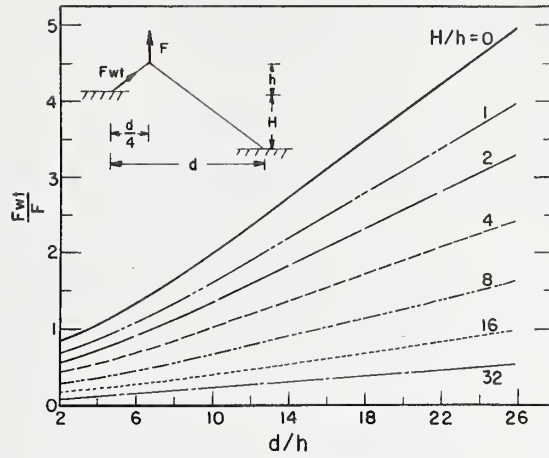
Figure 3. F_{wt}/F as a function of d/h for different values of H/h and for $\epsilon = 1/4$.
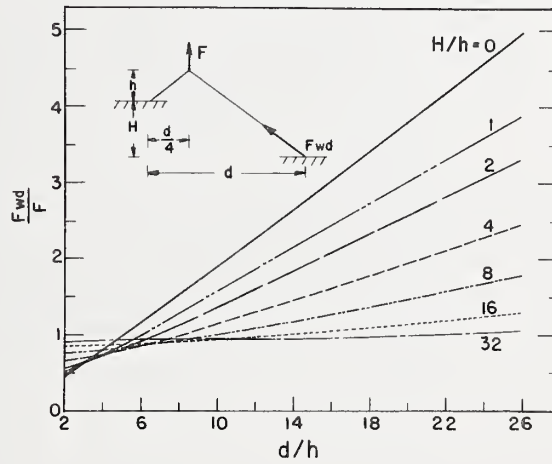
Figure 4. F_{wd}/F as a function of d/h for different values of H/h and for $\epsilon = 1/4$.

Table 1. Typical Results from Resolution-of-Forces Calculation for
Single-Level and Two-Level Bonds

Single Level	H = 0	d = 1.0 mm	F = 10 gf	
h(mm)	ϵ	ϕ(deg)	Fwt(gf)	Fwd(gf)
0.1	0.50	0	25.5	25.5
0.2	0.50	0	13.46	13.46
0.3	0.50	0	9.72	9.72
0.4	0.50	0	8.00	8.00
0.5	0.50	0	7.07	7.07
0.3	0.25	0	9.76	6.73
0.3	0.50	0	9.72	9.72
0.3	0.75	0	6.73	9.76
0.3	0.50	-10	8.56	10.58
0.3	0.50	0	9.72	9.72
0.3	0.50	10	10.58	8.56
Two Level	H = 0.5 mm	d = 1.0 mm	F = 10 gf	
h(mm)	ϵ	ϕ(deg)	Fwt(gf)	Fwd(gf)
0.1	0.50	0	7.28	11.16
0.2	0.50	0	5.98	9.56
0.3	0.50	0	5.30	8.58
0.4	0.50	0	4.93	7.92
0.5	0.50	0	4.71	7.45
0.3	0.25	0	6.89	6.45
0.3	0.50	0	5.30	8.58
0.3	0.75	0	2.99	9.31
0.3	0.50	-10	3.75	9.34
0.3	0.50	0	5.30	8.58
0.3	0.50	-10	6.69	7.55

3. FABRICATION OF TEST SPECIMENS

The bonding pads which were used for the work reported were fabricated on 0.010-in. (0.25-mm) thick, 1.0-in. (25-mm) diameter silicon wafers, coated with 0.5 μm of steam-grown silicon dioxide and 0.5 to 1 μm of evaporated aluminum. The aluminum was etched to leave 0.005-in. (0.13-mm) square bonding pads by means of standard photolithographic techniques. An example of the bonding pad array is given in figure 5 [4].

For two-level studies, strips of silicon 0.05-in. (1.3-mm) wide, obtained by scribing and breaking a prepared substrate, were affixed with a high temperature glue to another substrate so that the bonding pad arrays lined up as shown in figure 6. Thus two-level substrates were obtained with rows of bonding pads raised by the thickness of the silicon strip (about 0.25 mm) above the bonding pads on the base substrate. It was necessary to position the silicon strip carefully on the base substrate so that a constant spacing between the upper pad and the lower pad was maintained along the length of the strip [5].

Except where otherwise indicated, the wire bonds tested were 0.001-in. (25-μm) diameter aluminum (1% silicon) wire ultrasonically bonded to the aluminum pads. Also, except where otherwise noted, the bonds were made on a single bonding machine and were tested so as to establish their reproducibility. The variables which were constrained by the mode of fabrication were d, the bond-to-bond spacing, and H, the height of the terminal above the die. For the experiments reported, d has the value of 1.0 mm and H has the values of zero (for single-level bonds) or 0.25 mm (for two-level bonds).

The bonding tools used to fabricate the bonds had a smooth front and a sharp back. The sharp back assists the clamp in severing the wire after the second bond has been formed. However, the sharp back of the tool causes the first bond heel to be slightly more deformed than the second bond heel. The result is that the second bond is stronger under tensile failure (heel breakage) for the same force-power-time combination than the first bond.

As the resolution-of-forces applies to the heel breakage failure mode, the force-power-time combination for bond fabrication was chosen, except as otherwise indicated, such that heel breakage was the principal failure mechanism.
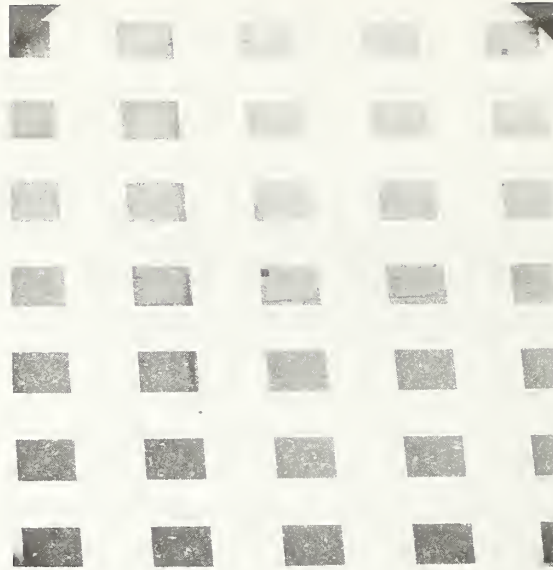
Figure 5. Scanning electron micrograph of bond pad array used for single-level studies.
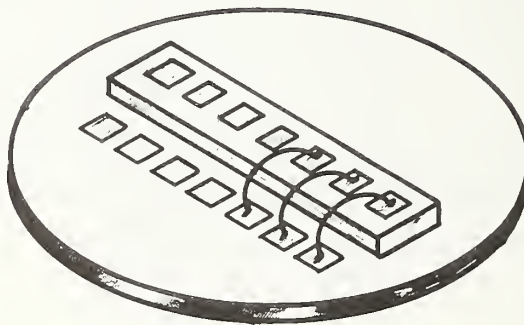
Figure 6. Pictorial illustration of two-level substrate.

4. VARIABLES INVOLVED IN THE RESOLUTION
OF FORCES CALCULATION

In this section, consideration is given to the variables which are involved in the resolution-of-forces calculation. These are the position of the hook, ε, the angle β (the angle formed between the direction of the pulling force and the normal to the line joining the bond terminals), and the loop height, h. In studying each variable, an extensive series of experiments was carried out in order to compare the prediction of the resolution of forces with the measured pull strengths.

4.1 POSITION OF HOOK (ε)

4.1.1 SINGLE-LEVEL BONDS

An experiment was performed to demonstrate the effect of the position of the pulling hook on the measured pull strength of a single-level ultrasonic bond pair. The results of the experiment are shown in figure 7 in which the measured pull strength, F, of the bond pair is plotted against the position of the hook along the span of wire. The plotted points are the mean pull strength and the error bars represent the 95 percent confidence intervals for the mean.

These experiments indicate that when the wire is pulled on the side nearest the first bond, it is this bond that breaks at the heel due to tensile failure. Conversely, the second bond breaks by tensile failure when the force is applied nearest to it. A transition point, where the probability for either bond to break is nearly the same, occurs at the maximum value of measured pull strength. In the present case this point is found to be displaced more toward the second bond, as might be expected since the bonding machine used in these tests yields a stronger second bond than first.

It should be noted that limited tests on aluminum wire doped with 1% magnesium rather than silicon indicated, as expected, that there is no difference with respect to the dependence of the pull strength on the geometrical variables. The resolution of forces calculation relates the forces to geometrical variables only, while wire metallurgy determines the tensile strength of the wire [6].

4.1.2 TWO-LEVEL BONDS

The effect of varying the position of the pulling hook on pull strength was studied on two-level bond pairs where the first bond was made either to the low pad or to the high pad. Specimen preparation procedures restricted the study to a single value of H, the height of the terminal above the die. The results, plotted in figure 8 as measured pull strength normalized to its value at midpoint as a function of hook position, are in agreement with calculations based upon tensile failure except for positions between midpoint and the low pad. It should be noted that in this region the pulling hook was observed to slip along the wire loop toward the midpoint position; thus the measured pull strength lies above the predicted value [5].
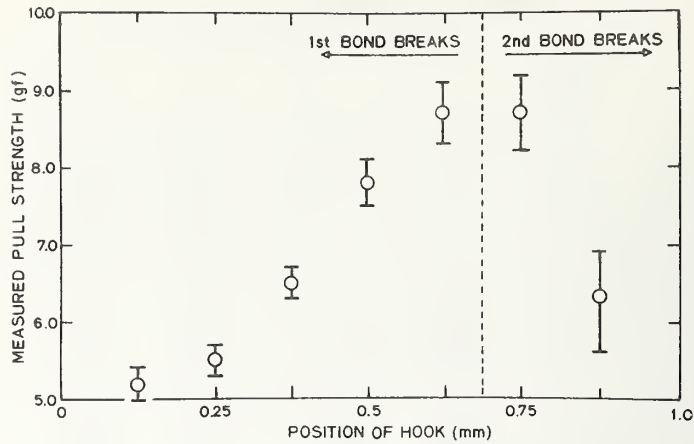
Figure 7. Measured pull strength of single-level bond pairs for different hook positions. (The first bond is at 0 and the second bond is at 1 mm).
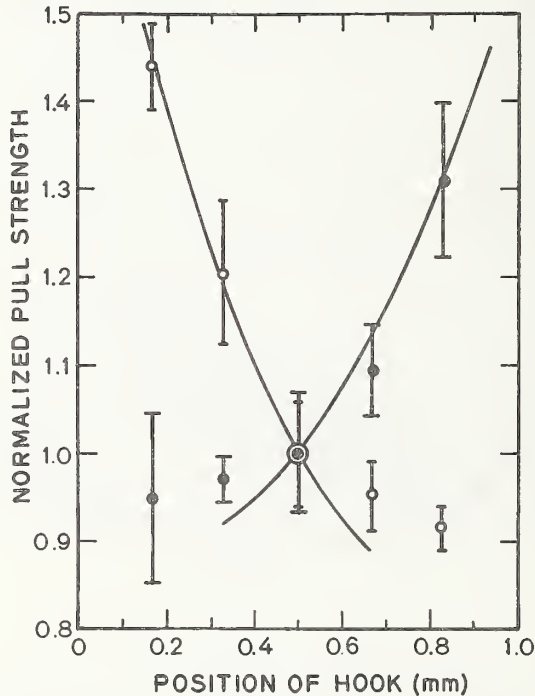
Figure 8. Measured pull strength of two-level bond pairs as a function of the position of the pulling hook. (The values are normalized to the mean pull strength at mid span, 0.5 mm. Solid points are for the first bond made to the high pad; open points are for the first bond made to the low pad. In each case the second bond is at 0 mm and the first bond is at 1.0 mm. The data points represent the mean of 10 bonds all of which ruptured by tensile failure at the heel of the first bond. Error bars indicate one sample standard deviation above and below the mean. The solid curves were calculated by resolution-of-forces.)

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4.2 ANGLE β

4.2.1 INTRODUCTION

While the discussion of the resolution-of-forces has been cast in terms of the pull angle ϕ it is often more convenient to represent the results of pull test experiments (particularly for two-level bonds) in terms of a different angle. This angle, denoted by β, is defined as that formed between the direction of the pulling force and the normal to the line joining the bond terminals (positive in the direction toward the second bond). The angle β is related to the angle ϕ by the equation $\beta = \beta_o \pm \phi$ where the positive sign obtains if the first bond is the higher (in which case β_o, the angle between the substrate and the line joining the bond terminals, is negative), and the negative sign obtains if the first bond is the lower (in which case β_o is positive). The various angles are illustrated in figure 9.

4.2.2 SINGLE-LEVEL BONDS

Single-level bond loops were pulled at the midpoint of the loop at angles between 0 and 45 deg. in both directions. It should be noted that $\beta_o = 0$ for single-level systems and hence $\beta = \phi$. The results are shown in figure 10. The mean values of the measured pull strength are denoted by the plotted points and the error bars represent the 95 percent confidence intervals for the mean. The results show higher pull strengths for β negative which is to be expected since the second bond is stronger than the first. When the larger component of the force is applied to the first bond, the measured pull strength is lower and when the larger component of the force is applied to the second bond, the measured pull strength is higher [6].

4.2.3 TWO-LEVEL BONDS

The results of the single-level experiments for the larger values of β yielded some insight into the pull test for two-level bond pairs. For a two-level bond system, there are two ways the bond loop may typically be positioned for pulling as shown in figure 11. First, the substrate or package may be held level, which places each of the bonds at different heights, and the force applied in a direction normal to the substrate. Alternatively, the substrate may be tipped to bring both bonds to the same vertical height; the configuration produced is more nearly similar to a single-level bond case, and the force is applied in a direction normal to an imaginary line joining the two bonds. The configuration in the level substrate case is similar to that of a single-level bond system where the pulling is done at some angle β_o. It is apparent that tipping or not in the two-level bond system is essentially equivalent to varying the angle β. Although this comparison of single-level and two-level bond systems is in terms of bond loop geometry only, one would expect that the general results shown in figure 10 would be applicable to the two-level system. That is, if the angle of pull is inclined toward the second bond (applying the larger component of force to the first bond) the measured pull strength is less than if the angle of pull is inclined toward the first bond (applying the larger component of

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Figure 9. Geometric variables for the pull test for bonds made on two-level substrates for pulling normal to the substrate. (For this case, the angle ϕ between the normal to the substrate and the pulling direction is zero. The distance d is the total bond-to-bond spacing in the plane of the substrate.)

Figure 10. Measured pull strength of single-level bond pairs as a function of the angle of pull in the plane of the bond loop. (The inset shows the relationship of the angle of pull to the normal to the line joining the bonds. Note that the angle is positive when the pull force is inclined toward the second bond and negative when the pull force is inclined toward the first bond.)

a. Level substrate; nominal pull angle β = β$_0$.

b. Tipped substrate; nominal pull angle β = 0.

Figure 11. Pull configurations for two-level bonds. (The direction of pull is indicated by the arrow.)
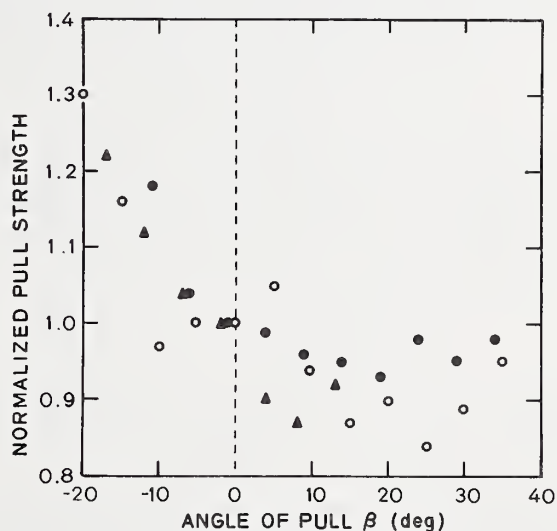
Figure 12. Measured pull strength of bond pairs as a function of the angle of pull in the plane of the bond loop. (The values are normalized to the mean pull strength at 0 deg. Solid points are for two-level bond pairs made with the first bond to the high pad (circles) and with the first bond made to the low pad (triangles); open circles are previously reported data for single-level bond pairs. Except for the solid circles, which represent the mean of 30 bonds, the data points represent the mean of 10 bonds, all of which ruptured at the heel of the first bond. Error bars have been omitted to reduce clutter; typically the sample standard deviation is between 0.05 and 0.1.)

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force to the second bond). However, it should be noted that this analogy does not take into consideration the effects of the angles of the wire at the bond heels for the two situations.

To confirm this hypothesis, the effect of varying the pull angle β was studied for two-level ultrasonic bond pairs. Measurements of pull strength were made by tilting the substrate while pulling the loop vertically. The results are shown in figure 12 both for bond pairs with the first bond made to the high pad and for bond pairs with the first bond made to the low pad. The pull angle shown is β for the former case and $-\beta$ for the latter. For comparison, data for single-level bond pairs are also included; in this case the pull angle is ϕ, the angle between the direction of pulling force and the normal to the substrate. It can be seen that the trend in all three cases is about the same [5].

4.3 LOOP HEIGHT (h)

4.3.1 SINGLE-LEVEL UNANNEALED BONDS

A series of tests was conducted to determine the effect of variations in bond angle (or ratio of loop height to bond-to-bond spacing) on the measured pull strength of single-level bond pairs pulled at the center of the loop in a direction perpendicular to the plane of the pads. Eight groups of 10 single-level bond pairs were made with different loop heights and spacings. The bond angle varied from 25.7 to 50.3 deg. The bond pairs were then pulled to destruction. The exclusive failure mode was breakage at the heel of the first bond.

Results of the experiment are shown in figure 13. The mean measured pull strength and 95 percent confidence intervals for the mean are plotted for each group against the bond angle. The solid curve was calculated from the resolution-of-forces equation for the symmetrical case under study:

$$F = 2F_w \sin \theta, \tag{9}$$

where F is the measured pull strength, F_w is the force in the wire, and θ is the bond angle [7].

A further study was undertaken of the dependence of measured pull strength on loop height or bond angle to gain greater insight into the extent of applicability of the resolution-of-forces calculation. Analysis of the results, shown in figure 14, supports the conclusion that the pull strength calculated by resolution-of-forces does fit the experimental data. Above $h/d = 1/3$, several of the data points fall below the predicted value of pull strength. This may be explained as follows. As the loop height increases, more normal pulling force is exerted on the bonds. The results of the study of the influence of the bond angle α (see sec 5.2) suggest that this might cause some peeling of the bond before breakage at the heel occurs, which in turn, by stressing a more deformed region, might lower the measured pull strength [8].

This conclusion is reinforced by the results of measurements of pull strengths of
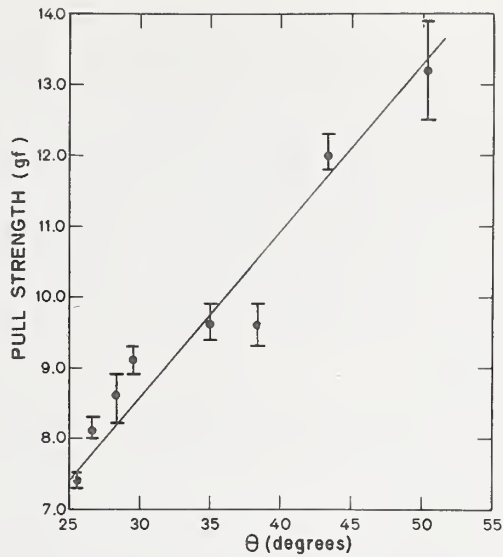
Figure 13. Measured pull strength as a function of bond angle (θ), (The solid line, F = 17.2 sin θ, is calculated from the resolution-of-forces; the numerical factor is twice the breaking force in the wire. The error bars represent the 95 percent confidence intervals for the means.)

Figure 14. Pull strength of unannealed round-wire bonds as a function of loop height. (The data points represent the mean for up to 10 bonds; only bonds which ruptured at the heel were included. Error bars represent one sample standard deviation. The solid curve is calculated from resolution-of-forces using the wire tensile strength indicated by the arrow.)

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0.0015 in x 0.0005 in (38 μm x 13 μm) ribbon-wire bonds as a function of loop height shown in figure 15. The solid data points are average pull strengths for groups of up to 10 bonds each, excluding those bonds that failed due to lift-off of one of the bond pairs. For the two open data points at the two highest loop heights, values resulting from bond lift-offs were included in the average pull strength calculation. Up to a loop height of about 0.010 in. (0.25mm), the variation of pull strength as a function of loop height is in agreement with the resolution-of-forces calculation, but at larger loop heights, the measured pull strength is lower than the predicted value [9].

4.3.2 SINGLE-LEVEL ANNEALED BONDS

A series of experiments was performed to determine the pull strength variation with loop height of annealed single-level bonds. On a single substrate, groups of bond pairs were made at four loop heights with a nominal bond-to-bond spacing of 0.040 in. (1.0 mm). About half of these bonds were pulled to breaking in groups of ten at five different rates of pull. The remaining bonds were annealed at 505°C for 25 min. and then groups of ten were pulled at each of the five rates. In agreement with previous measurements, the unannealed bonds did not exhibit any dependence of pull strength on rate of pull. Although there is an indication that the annealed bonds show some dependence of pull strength on rate of pull, the major problem encountered in the interpretation of the measurements on annealed bonds lies in the fact that there is considerable elongation of these bonds during pulling. The loop heights of annealed bonds at bond rupture are substantially larger than they are in the original unannealed state. In figure 16, pull strength is shown as a function of loop height at rupture for the unannealed and annealed bonds studies. The differences in loop height between the annealed bonds and the unannealed state at which all bonds were made is evident by comparing the loop height of each of the four unannealed points and their respective annealed points. As before, experimental data for unannealed bonds is in good agreement with that predicted by the resolution-of-forces analysis (solid curve) up to a loop height that corresponds to an h/d ratio of about 1/4. No such agreement could be obtained for the data (solid points) obtained from annealed bonds. However, it can be seen that most of these points are for loop heights much larger than those for which agreement between experiment and theory is obtained for unannealed bonds. This lack of agreement has been attributed to the weakening effect of bond peel at large loop heights.

From the unannealed bond data, the percentage increase in pull strength required to bring the grand average of all pull strength group means at each loop height to coincidence with the theoretical curve was calculated. A linear relationship was obtained between percent correction in pull strength against measured pull strength. This was extrapolated to the larger loop height values appropriate to the annealed bonds. When the annealed bond data were corrected using this curve, the open points shown in figure 16 were obtained. It can be seen that these points appear to be in reasonable agreement with the theoretical curve shown [10].
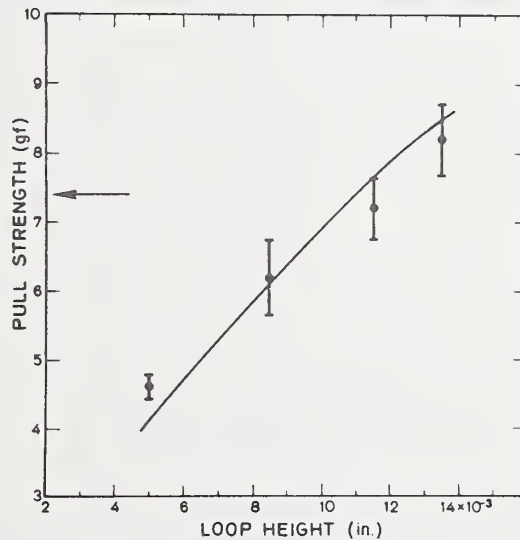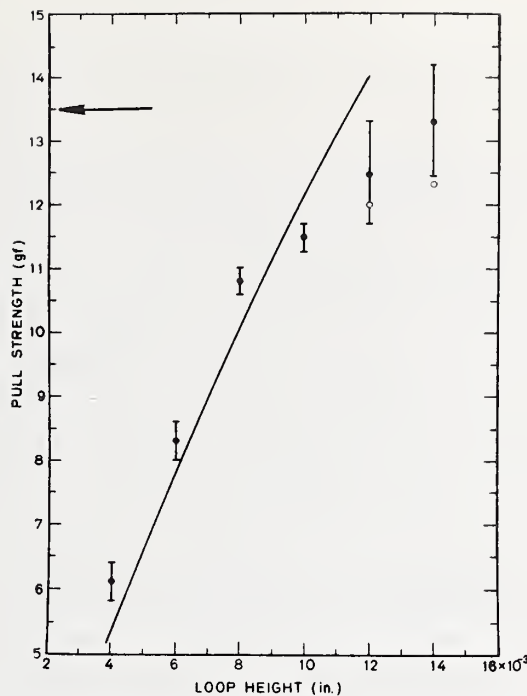
Figure 15. Pull strength of ribbon-wire bonds as a function of loop height. (The data points represent the mean for up to 10 bonds. Solid circles include only bonds which ruptured at the heel; open circles include bonds which ruptured at the heel and which failed by lift off. Error bars represent one sample standard deviation. The solid curve is calculated from resolution-of-forces using the wire tensile strength indicated by the arrow.)
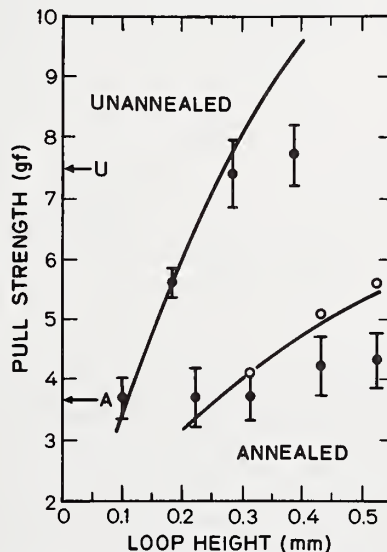
Figure 16. Pull strength of unannealed round-wire bonds and annealed round-wire bonds as a function of loop height. (Each solid data point represents the mean for a group of 10 bonds, the error bar represents one sample standard deviation. See text for a discussion of the open data points. The solid curves are calculated from resolution-of-forces using the wire tensile strength indicated by the arrows: U - unannealed, A - annealed).

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4.3.3 TWO-LEVEL BONDS

For these loop height experiments, the two-level bonds had the following values of the variables held constant: d = 1.0 mm, ε = 0.5, φ = 0, H = 0.25 mm. Groups of 10 bonds were made at 7 different loop heights. This was done both for the first bond made on the high pad and for the first bond made on the low pad. In all cases failure occurred at the heel of the first bond. The measured pull strengths are plotted against loop height in figure 17 for both cases (solid points – first bond high, open points – first bond low). The plotted points represent the mean value of the 10 bond pulls and the error bars indicate one sample standard deviation on either side of the mean. The solid lines represent the values predicted by a resolution of the forces for each case. The agreement between the trend of the theoretical curve and that of the experimental points for the first bond made to the high pad appears to be good for loop heights less than about 0.3 mm. For higher loops, the apparent pull strength is reduced as observed for both single level round and ribbon wire bonds (see sec 4.3.1).

The results for the case of the first bond made on the low pad generally show overall pull strengths less for a given loop height than those for the first bond made on the high pad. This is in agreement with the experimental measurement of the effects of angle β (see fig 12) in which higher pull strengths were observed for negative values of the pull angle β than for positive values [11].

This experiment was also carried out on bonds prepared on a different bonding machine. The results of this experiment are presented in figure 18 where the normalized pull strength is plotted against loop height. The results are in agreement with the above observations [5].
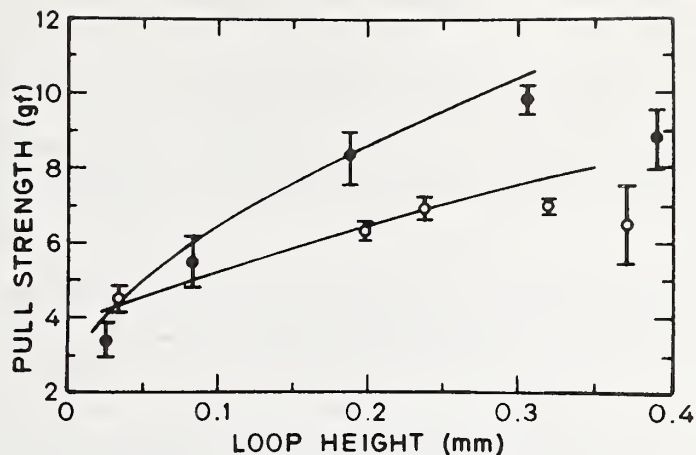
Figure 17. Measured pull strength of unannealed, round-wire, two-level bonds as a function of loop height above the high pad. (Solid points are for the first bond made on the high pad; open points are for the first bond made on the low pad. The data points represent the mean of 10 bonds, all of which ruptured at the heel of the first bond. Error bars indicate one sample standard deviation above and below the mean. The solid curves were calculated by resolution-of-forces.)
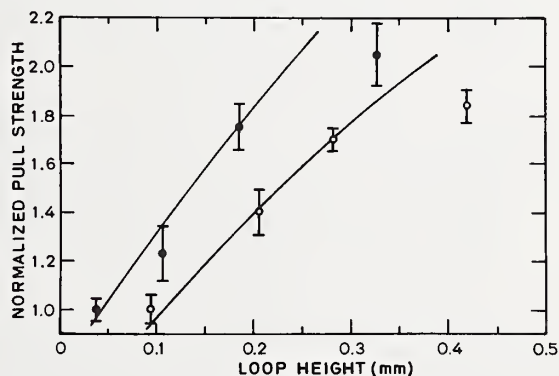
Figure 18. Normalized pull strength of unannealed, round-wire, two-level bonds as a function of loop height above the high pad. (The values are normalized to the mean pull strength at the lowest loop height. Solid points are for the first bond made on the high pad; open points are for the first bond made on the low pad. The data points represent the mean of 10 bonds, all of which ruptured at the heel of the first bond. Error bars indicate one sample standard deviation above and below the mean. The solid curves were calculated by resolution-of-forces. The bonds used in this experiment were made on a different bonding machine from that used to provide the data for figure 17.)

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5. VARIABLES NOT INVOLVED IN RESOLUTION-OF-FORCES CALCULATION

In this section, two of the variables which are not involved in the resolution-of-forces calculation are considered. These variables are the rate of pull and the angle α (the angle between the direction of pull and the normal to the substrate in the plane perpendicular to both the substrate and the plane of the undistorted bond loop).

5.1 RATE OF PULL

As the resolution-of-forces calculation is of a static nature, an investigation was undertaken to see if there were appreciable effects on the pull strength brought about by any transient effects induced by a rate dependent pull force. This is especially important as in industrial use of the pull test the wire is frequently pulled rapidly or jerked which may give rise to large transient effects. This is of potentially greater importance as the elongation of the wire increases, since the effects of larger transients may be accentuated by greater wire elongation.

In a first series of experiments, a group of 10 unannealed bonds was pulled to destruction at 11 different pull rates ranging from 1.0 gf/s (9.8 mN/s) to 12.5 gf/s (122 mN/s). The results of this experiment are presented in figure 19 where the mean pull strength (with the 95 percent confidence intervals for the mean) is plotted against the pull rate. The slope of the curve was determined to be essentially zero. It was, therefore, concluded that the pull rate has no significant effect on the bond pull strength for the range of pull rate between 1.0 and 12.5 gf/s (9.8 to 122 mN/s) [12].

In a second series of experiments, the investigation of the effect of the rate of pull on pull strength was extended to cover rates of 1.0 and 77 gf/s (9.8 and 764 mN/s). As with the first series of experiments, all bonds were made with the same bonding schedule in sequence by one operator. Also, this schedule was set up such that the failure mode was breakage at the heel of the first bond. Groups of 60 bonds each were then pulled at rates of 1.0 and 77 gf/s (9.8 and 764 mN/s) resulting in times to pull a bond of approximately 9 and 0.12 s. The date obtained indicated that there was no statistically significant difference in the measured pull strengths for either pull rate from those in figure 19.[+]

The above experiments were performed on single-level unannealed bonds where heel breakage was the failure mode. For bonds which fail by peeling or lift-off, it is assumed that the rate of pull would have a large effect on the measured pull strength since peel failure appears to be rate sensitive. However, it is very difficult to show this statistically as a procedure to make bonds reproducibly that will fail by peeling has not been found. Attempts have resulted in pull strengths which have greater variations from bond-to-bond, at a given pull rate, than between groups pulled at different rates. Therefore, a pull-rate experiment as described was not performed for bonds which fail by peel. However, it appears that the nature of the failure mode may affect comparisons of pull strengths.

[+]Recent work (Kessler, H. K., in *Semiconductor Measurement Technology:* Progress Report, Bullis, W. M., Ed., NBS Special Publication 400-25 - to appear) indicates that the pull strength of gold wire is also pull-rate independent.
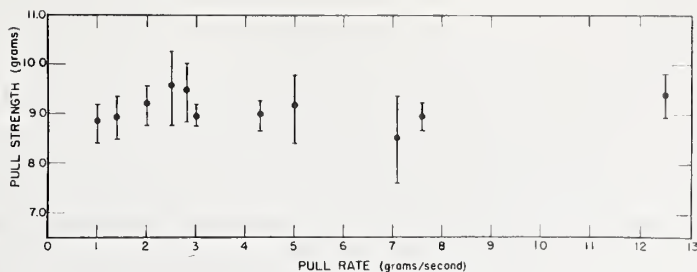
Figure 19. Measured bond pull strength as a function of
pull rate. (The error bars represent the 95 percent con-
fidence intervals for the mean.)
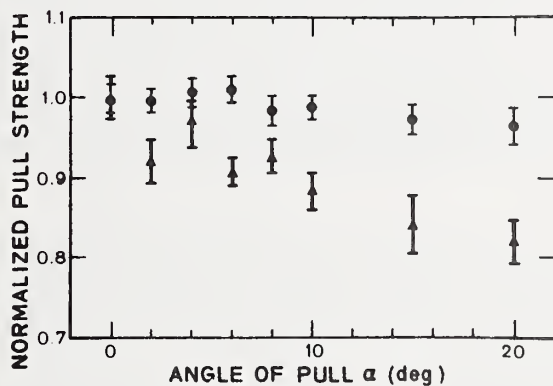
Figure 20. Normalized pull strength as a function of pull
angle, α, for round-wire bonds with small ($\bullet$) and large ($\blacktriangle$)
deformation. (Error bars represent the 95 percent confidence
interval for the mean. The values are normalized to the mean
pull strength at each deformation at α = 0 deg.)

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and rates of pull [13].

5.2 ANGLE α

5.2.1 INTRODUCTION

     The resolution-of-forces calculation as presented in Section 2 and the Appendix of this
report is essentially a two-dimensional calculation. That is, only those forces operative
in the plane of the bond loop are considered. A series of experiments was undertaken to in-
vestigate the effects of pulling the bond in a direction not in this plane on the measured
pull strength. The angle α is defined as that between the direction of pull and the normal
to the substrate in the plane perpendicular to both the substrate and the plane of the un-
disturbed bond loop. Since the principal effect of pulling at a finite value of α is to
rotate the plane of the bond loop, the ratio of the force of pull and the force exerted
along the wire is the same for all values of α. This would lead one to conclude that no
great dependence on the measured pull strength on α would be expected. However, the rota-
tion of the plane of the bond loop does not include rotation of the bond heel. This tends
to put the bond heel under an anisotropic stress with respect to the line between the bonds.
This anisotropic stress may be expected to be accentuated by greater bond deformation. This
reasoning points to the possibility of decreased measured bond pull strength with increased
α. This decrease is expected to be most pronounced with a large deformation.

5.2.2 SINGLE-LEVEL BONDS

     Single-level round-wire bonds were made on three metallized substrates with 0.001-in.
(25-μm) diameter aluminum (1% silicon) wire and a bond-to-bond spacing of 0.04 in. (1.0 mm).
All the bonds on a particular substrate were made with the same power setting, but different
power settings were used in making the bonds on different substrates to obtain bonds with
different degrees of bond deformation. On each substrate, about 35 bonds were pulled at the
midpoint of the loop for eight values of α from 0 to 20 deg. The pull angle φ, in the plane
of the bond loop, was 0 deg. For each group, the mean pull strength and the 95 percent con-
fidence interval for the mean was determined; the measured pull strengths of bonds that did
not break at the heel were excluded from the calculations. The pull strengths were then
normalized to the mean value obtained at α = 0 deg. The results for bonds on two substrates,
with small deformation (1.25 to 1.50 wire diameters) and large deformation (2.25 to 2.50
wire diameters), are shown in figure 20. The zero degree value for pull strength of the
bonds with large bond deformation was approximately half that of the bonds with small bond
deformation. Bonds made on the third substrate had excessively large bond deformation but
yielded results essentially the same as those observed for bonds with large bond deforma-
tion.

     The results show that as α increases, the measured pull strength decreases. This ap-
pears to be a result of the twisting or tearing of the bond heel as the wire is pulled out
of the plane normal to the substrate plane. These results show that, although the value
of angle α has little effect on the measured pull strength of bonds with small to moderate

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bond deformation, the effect is more pronounced for the bonds with greater bond deformation.
Although it was not experimentally demonstrated, it is hypothesized that if the failure mode
were by peel significantly lower pull strengths would occur at large values of α. This rea-
soning follows that presented in the introductory material. For peel failure at α=0, the
force tending to lift the bond acts uniformly over a large area. For α ≠ 0, the force
tends to be concentrated on one side of the bond and hence initiates lift-off at a lower
pull force. It should be possible to control the position of the pulling hook so that the
angle α is less than 10 deg by visual inspection, but more precise positioning may be re-
quired for bonds with large deformation [14].

5.2.3 TWO-LEVEL BONDS

The experiments on the effects of the angle α on the pull strength were carried out for
small deformation two-level bonds in which the first bond was made on the high pad. Bond
pairs were made on two different bonding machines designated as machine A and machine B.
The measured pull strength, normalized to its value for α = 0, is presented as a function
for α for both cases in figure 21. As with the analysis of the single level data, only
those failures due to rupture at the first bond were included in the data. The curves in
figure 21 show roughly the same general trends in both cases except for differences in the
standard deviations. The results are in general agreement with the measurements of pull
strength made on single-level bond pairs of small deformation [5].
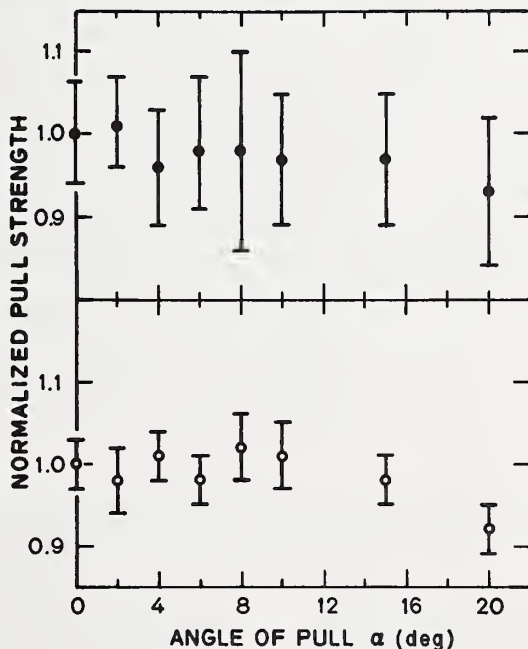
Figure 21. Measured pull strength as a function of angle of
pull, α, for two-level bond pairs. (The values are normal-
ized to the mean pull strength at α = 0 deg. Solid points
are for bond pairs made on bonding machine A. Open points
are for bond pairs made on machine B. Error bars represent
one sample standard deviation above and below the mean.)

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6. SENSITIVITY CALCULATION

The sensitivity of the measured pull strength of wire bonds to variations in experimental conditions was analyzed for the case, appropriate to unannealed aluminum ultrasonic bonds, in which measured pull strengths are in agreement with those predicted by resolution-of-forces. The normalized variation in pull strengths of the bond to the terminal, $\Delta F(t)$, and of the bond to the pad on the die, $\Delta F(d)$, were studied as a function of the position of the pulling hook, ϵ; the loop height above the terminal post, h; the height of the terminal post above the die, H; the bond-to-bond spacing, d; and the pull angle with respect to the normal to the substrate, ϕ.

To illustrate the application of this analysis, computations were made for a transistor in a TO-18 can. The TO-18 configuration was used as bond geometry variables were given in manufacturer's specifications. Each of the five quantities was varied about its nominal value while the other four quantities were held constand, and $\Delta F(t)$ and $\Delta F(d)$ were computed. The results are summarized in table 2; the quantities are listed in order of decreasing effect on the measured pull strength. Except for variation of ϕ, the variation is expressed in percent of the nominal value.

It can be seen that, for the device described, the pull angle ϕ has the greatest effect on $\Delta F(t)$ and $\Delta F(d)$. Of the five parameters, the pull test operator controls only ϕ and ϵ; the reproducibility of h and d is dependent on the bonding machine, and that of H is dependent on the header lot and die thickness. In making wire bonds in this laboratory, h and d can be reproduced to ±3.0 and ±3.8 percent (one standard deviation), respectively. Typical manufacturer's specifications for TO can-type headers suggest that variations in post height of ±30 percent may be expected. An estimate of the overall variation to be expected in determining pull strength was obtained by calculating values of $\Delta F(t)$ and $\Delta F(d)$ as a function of ϕ for two cases for the sample device. In one case each of the other four quantities assumed its smallest value, in the other each assumed its largest value. The results for these simulations of the application of the pull test in an industrial environment, shown in figure 22 indicate that, for the heel break (tensile) failure mode, variations in ϕ of 10 deg can produce differences in pull strength from the zero degree case of as much as 30 percent [15].

Table 2 — Calculated Dependence of $\Delta F(t)$ and $\Delta F(d)$ on Pull Test Conditions for a TO-18 Transistor

Quantity	Change	$\Delta F(t)$	$\Delta F(d)$	Change	$\Delta F(t)$	$\Delta F(d)$
ϕ	+10 deg	-11%	+14%	+20 deg	-19%	+37%
	-10 deg	+20%	-8%	-20 deg	+50	-13
d	+10%	-7%	-6	+20%	-13	-11
	-10%	+8%	+6	-20%	+16	+13
h	+10%	+5%	+5	+20%	+11	+10
	-10%	-5	-5	-20%	-12	-10
ε	+10%	+4	-3	+20%	+9	-5
	-10%	-3	+4	-20%	-6	+9
H	+10%	+2	+0.5	+20%	+3	+1.0
	-10%	-2	-0.5	-20%	-3	-1.0
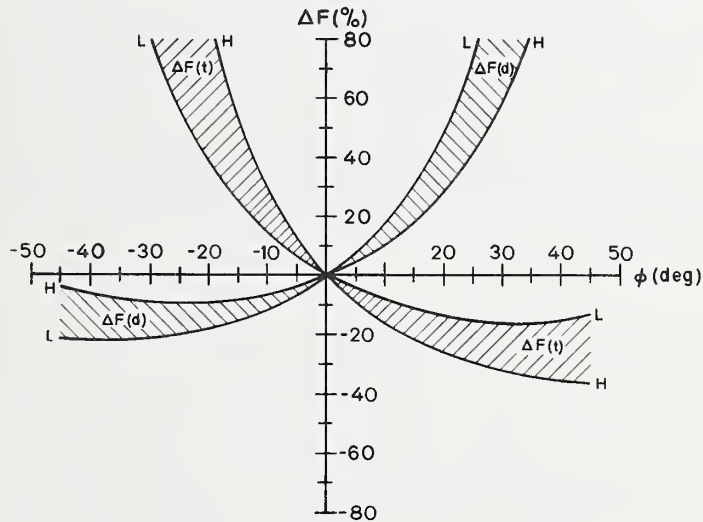
Figure 22. Normalized variation in calculated pull strength for the terminal bond, $\Delta F(t)$, and die bond, $\Delta F(d)$ as a function of pull angle ϕ.

(For case L:
  d = 38.5 mils (0.98 mm);
  h = 11.6 mils (0.29 mm);
  ε = 0.375; and
  H = 3.5 mils (0.09 mm).)

(For case H:
  d = 41.5 mils (1.05 mm);
  h = 12.4 mils (0.31 mm);
  ε = 0.625; and
  H = 6.5 mils (0.17 mm).)

7. <u>SUMMARY</u>

It has been shown for 0.001-in. (25-μm) diameter ultrasonically bonded aluminum (1% silicon) wire that the variations in measured pull strength as functions of bond loop height and position of the pulling hook are in agreement with those predicted by resolution-of-forces for single- and two-level unannealed wire bond pairs provided that the ratio of the loop height, h, to bond-to-bond spacing, d, is less than about 1/3. For annealed bonds, agreement was not found. This was attributed to the fact that the stretching of the wire loop during pulling always resulted in h/d values greater than 1/3. It should be noted that these conclusions are drawn from those experiments where heel breakage (tensile failure) is the exclusive failure mode.

The decrease in measured pull strength with increasing pull angle α in both single- and two-level bond pairs, more pronounced on bonds with large deformation, appears to be a result of the twisting or tearing of the bond heel as the wire is pulled out of the plane normal to the substrate plane. In the series of measurements on the effects on pull strength of varying the pull angle β, for both single- and two-level unannealed wire bonds, a large decrease in pull strength was observed as β went from -45 to 0 deg; as β went from 0 to +45 deg, the decrease was much less marked. This is consistent with the facts that the second bond is stronger than the first bond and therefore the measured pull strength is lower when the larger component of force is applied to the first bond, and higher when applied to the second bond.

Examples of the practical applications of the work reported here are to be found in the sensitivity calculation; the bond pull specifications for large-diameter wire; and a non-destructive bond pull test.

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Appendix A
Resolution-of-Forces Calculation

This appendix is intended to provide some of the details necessary to obtain eqs (1) through (8) of Section 2 of this report. Referring to figure 1, the vector diagram of figure A1 may be constructed. Considering the applied pulling force at an infinitesimal increment in force before rupture takes place, balancing of the forces along the x direction and the y direction requires that

$$F_{wt} \cos \theta_t = F \sin \phi + F_{wd} \cos \theta_d, \qquad (A1)$$

and

$$F \cos \phi = F_{wt} \sin \theta_t + F_{wd} \sin \theta_d, \qquad (A2)$$

respectively.

Solving eq (A2) for F_{wt}, one obtains

$$F_{wt} = \frac{F \cos \phi - F_{wd} \sin \theta_d}{\sin \theta_t} \qquad (A3)$$

Substituting eq (A3) into eq (A1) and solving for F_{wd}, one obtains eq (1):

$$F_{wd} = F \left(\frac{\cos \phi \; \text{ctn} \; \theta_t - \sin \phi}{\sin \theta_d \; \text{ctn} \; \theta_t + \cos \theta_d} \right)$$

$$= F \frac{\cos (\theta_t + \phi)}{\sin (\theta_d + \theta_t)} . \qquad (1)$$

Substituting eq (A4) into eq (A2) and solving for F_{wt}, one obtains eq (2):

$$F_{wt} = F \frac{\cos (\theta_d - \phi)}{\sin (\theta_t + \phi_d)} . \qquad (2)$$

To obtain eqs (4) and (5) one must make use of the following relations:

$$\sin \theta_d = \frac{(h+H)}{\left[(h+H)^2 + [(1-\epsilon)d]^2\right]^{\frac{1}{2}}}$$

$$\cos \theta_d = \frac{(1-\epsilon)d}{\left[(h+H)^2 + [(1-\epsilon)d]^2\right]^{\frac{1}{2}}} \qquad (A4)$$

$$\sin \theta_t = \frac{h}{\left[h^2 + (\epsilon d)^2\right]^{\frac{1}{2}}}$$

$$\cos \theta_t = \frac{\epsilon d}{\left[h^2 + (\epsilon d)^2\right]^{\frac{1}{2}}}$$
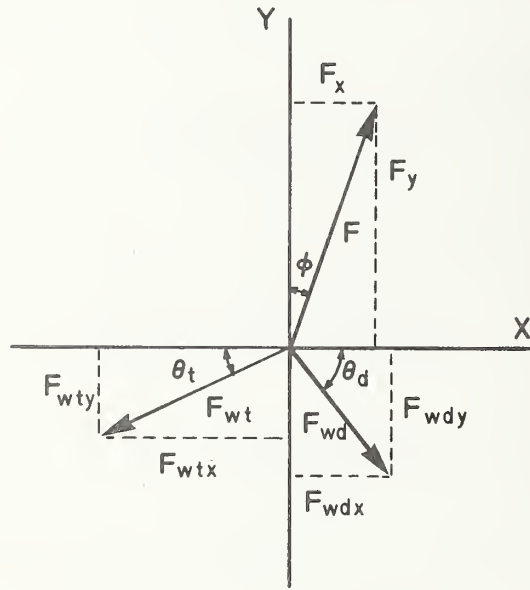
Figure A1. Vector diagram for resolution-of-forces operative in bonded system during application of pulling force. (The following relations are used in obtaining Eqs. (A1) and (A2).)

$F_x = F \sin \phi$ $\qquad\qquad$ $F_y = F \cos \phi$

$F_{wtx} = F_{wt} \cos \theta_t$ $\qquad$ $F_{wty} = F_{wt} \sin \theta_t$

$F_{wdx} = F_{wd} \cos \theta_d$ $\qquad$ $F_{wdy} = F_{wd} \sin \theta_d$

Appendix B

Programs Used for Resolution-of-Forces Calculation

This appendix contains several programs which may be used to calculate F_{wt} and F_{wd} from the resolution-of-forces calculation (See eqs (4) and (5)). These programs are in HP-65 language, Basic, and Fortran.

With the HP-65 program, the key entries of table B1 are entered into the calculator and put on magnetic cards according to the instructions given in the owner's manual. The program is then permanently entered on the magnetic cards.

To perform the calculation the following instructions are to be used.

Enter the program. Clear the memory registers if they are full. Then, enter each of the six variables in the memory indicated below. (There is no need to clear the stack after each entry.)

<u>Key Entry</u>	<u>Stored Variables</u>
STO 1	h
STO 2	H
STO 3	d
STO 4	ε
STO 5	F
STO 6	φ

If any variable is zero, simply ignore that particular memory. Then press either A or B to obtain the desired result (either F_{wt} or F_{wd}).

Any or all of the variables may be changed by simply entering the new values in the appropriate memories.

In the case of the angle φ, which is normally expressed in degrees, this may be entered as either positive or negative depending upon the actual physical situation.

The values of h, H, and d may be entered in either English or metric units so long as they are consistent.

The value of F may be any set of units and need not be consistent with the units of h, H, and d. The forces F_{wt} and F_{wd} will, of course, have the units of F.[†]

The remaining programs which may be used to calculate F_{wt} and F_{wd} are given in Basic and Fortran. The programs have all the necessary information to allow for rapid computation. It should be noted that step 990 of the Basic program and the corresponding step of the Fortran V program convert the pull angle φ from degrees to radians. This is required by the fact that both Basic and Fortran read angles in radians. However, the readout of the angle is given in degrees. If a particular machine reads angles in degrees, simply set A2=A1.[††]

[†]This program was written by G. G. Harman. The program was written for the HP-65 since it was the only programmable pocket calculator available at the time. Other programmable pocket calculation may also be used for the computation.

[††]The Basic program, written with the assistance of W. J. Keery, is an adaptation of one used by A. H. Sher to perform the sensitivity calculation (ref 15). The Fortran program was written with the assistance of T. F. Leedy.

HP-65 Program for Resolution-of-Forces Calculation

SWITCH TO W/PRGM PRESS [f] [PRGM] TO CLEAR MEMORY.

KEY ENTRY	CODE SHOWN	COMMENTS	KEY ENTRY	CODE SHOWN	COMMENTS	REGISTERS	
LBL	23		÷	81		R_1	h
A	11		RCL 5	34 05			
f	31		x	71			
STK	42		RTN	24		R_2	H
RCL 1	34 01		LBL	23			
RCL 2	34 02		B	12			
+	61		f	31		R_3	d
RCL 3	34 03		STK	42			
÷	81		RCL 6	34 06			
RCL 6	34 06		f	31		R_4	ε
f	31		COS	05			
SIN	04		RCL 4	34 04			
x	71		x	71		R_5	F
RCL 6	34 06		RCL 6	34 06			
f	31		f	31			
COS	05		SIN	04		R_6	φ
1	01		RCL 1	34 01			
↑	41		RCL 3	34 03			
RCL 4	34 04		÷	81		R_7 used for
−	51		x	71		inter-
x	71		−	51		mediate
+	61		RCL 2	34 02		R_8 storage
STO 7	33 07		RCL 1	34 01			
CL x	44		÷	81			
RCL 4	34 04		1	01		R_9	
RCL 3	34 03		+	61			
x	71		x	71			
RCL 1	34 01		STO 7	33 07		LABELS	
÷	81		CL x	44		A	x
f^{-1}	32		RCL 3	34 03		B	x
√x̄	09		1	01		C	
1	01		RCL 4	34 04		D	
+	61		−	51		E	
f	31		x	71		0	
√x̄	09		RCL 1	34 01		1	
RCL 7	34 07		RCL 2	34 02		2	
x	71		+	61		3	
STO 7	33 07		÷	81		4	
CL x	44		f^{-1}	32		5	
LBL	23		√x̄	09		6	
8	08	step 40 to 54	1	01		7	
RCL 2	34 02	is a subroutine	+	61		8	x
RCL 4	34 04	used in both	f	31		9	
x	71	$F_{wt} + F_{wd}$	√x̄	09			
RCL 1	34 01		RCL 7	34 07		FLAGS	
÷	81		x	71		1	
1	01		STO 7	33 07			
+	61		CL x	44		2	
RCL 7	34 07		g+0	22			
g x↔y	35 07		8	08			

Table B2

Basic Program for Resolution-of-Forces Calculation

```
10 PRINT "DO YOU WANT ALL THE INTRODUCTORY COMMENTS? (YES=1, NO=2)"
20 INPUT N
30 ON N GO TO 40,380
40 PRINT
50 PRINT "* * * * * * RESOLUTION OF FORCES CALCULATION * * * * * * *"
60 PRINT "* * * * * * *  DESTRUCTIVE BOND PULL TEST  * * * * * * * *"
70 PRINT
80 PRINT "THIS PROGRAM CALCULATES THE FORCES ON THE WIRE AT THE"
90 PRINT "TERMINAL AND AT THE DIE FROM THE BOND GEOMETRY AND THE"
100 PRINT "PULL STRENGTH"
110 PRINT
120 PRINT "B IS THE HEIGHT, AT RUPTURE, OF THE WIRE SPAN (AT THE "
130 PRINT "  POINT OF PULL) ABOVE THE TERMINAL"
140 PRINT
150 PRINT "H IS THE HEIGHT OF THE TERMINAL RELATIVE TO THE DIE SURFACE"
160 PRINT
170 PRINT "D IS THE BOND-TO-BOND SPACING"
180 PRINT
190 PRINT "E IS THE DIMENSIONLESS FRACTIONAL HORIZONTAL DISTANCE BETWEEN"
200 PRINT "  THE TERMINAL BOND AND THE POINT OF APPLICATION OF THE "
210 PRINT "  FORCE"
220 PRINT
230 PRINT "F IS THE PULL STRENGTH"
240 PRINT
250 PRINT "A IS THE PULL ANGLE AND IS EXPRESSED IN UNITS OF DEGREES"
260 PRINT
270 PRINT "T1 IS THE FORCE ON THE WIRE AT THE TERMINAL, FWT"
280 PRINT
290 PRINT "T2 IS THE FORCE ON THE WIRE AT THE DIE, FWD"
300 PRINT
310 PRINT "THE VALUES OF B, H, AND D MAY BE EXPRESSED IN EITHER"
320 PRINT "ENGLISH OR METRIC SO LONG AS THEY ARE CONSISTENT"
330 PRINT
340 PRINT "THE VALUE OF F MAY BE IN ANY SET OF UNITS AND NEED NOT BE"
350 PRINT "CONSISTENT WITH THE UNITS OF B, H, AND D"
360 PRINT
370 PRINT "THE FORCES T1 AND T2 WILL, OF COURSE, HAVE THE UNITS OF F"
380 PRINT
390 PRINT
400 PRINT "ENTER B, H, D, E, F,A"
410 INPUT B,H,D,E,F,A
420 PRINT
430 PRINT "SPECIFY PARAMETER TO BE VARIED"
440 INPUT Q$
450 B1=B
460 H1=H
470 D1=D
480 E1=E
490 F1=F
500 A1=A
510 IF E1>1.0 GO TO 1110
520 IF A1>45.0 GO TO 1130
530 IF A1<-45.0 GO TO 1150
540 IF Q$="B" GO TO 640
550 IF Q$="H" GO TO 680
560 IF Q$="D" GO TO 720
570 IF Q$="E" GO TO 760
```

```
 580 IF Q$="F" GO TO 810
 590 IF Q$="A" GO TO 850
 600 PRINT
 610 PRINT "!!!! INVALID PARAMETER ENTERED !!!!"
 620 PRINT
 630 GO TO 430
 640 FOR B1=0.1*B TO 2.0*B STEP  0.1*B
 650 GO SUB 950
 660 NEXT B1
 670 GO TO 1170
 680 FOR H1=0.1*H TO 2.0*H STEP 0.1*H
 690 GO SUB 950
 700 NEXT H1
 710 GO TO 1170
 720 FOR D1=0.1*D TO 2.0*D STEP 0.1*D
 730 GO SUB 950
 740 NEXT D1
 750 GO TO 1170
 760 FOR E1=0.1*E TO 2.0*E STEP 0.1*E
 770 IF E1>1.0 GO TO 1110
 780 GO SUB 950
 790 NEXT E1
 800 GO TO 1170
 810 FOR F1=0.5*F TO 5.0*F STEP 0.5
 820 GO SUB 950
 830 NEXT F1
 840 GO TO 1170
 850 IF 1.0*A,900,860,860
 860 FOR A1=0.0*A TO 45.0*A STEP 5.0
 870 IF A1>45.0 GO TO 1130
 880 GO SUB 950
 890 NEXT A1
 900 FOR A1=0.0*A TO 45.0*A STEP -5.0
 910 IF A1<-45.0 GO TO 1150
 920 GO SUB 950
 930 NEXT A1
 940 GO TO 1170
 950 B2=1.0+E1*H1/B1
 960 R1=E1*D1/B1
 970 R2=1.0+R1*R1
 980 R3=SQR(R2)
 990 A2=0.0174532925*A1
1000 R4=(1.0-E1)*COS(A2)+SIN(A2)*(B1+H1)/D1
1010 T1=F1*R3*R4/B2
1020 S1=(1.0-E1)*D1/(B1+H1)
1030 S2=1.0+S1*S1
1040 S3=SQR(S2)
1050 S4=1.0+H1/B1
1060 S5=E1*COS(A2)-SIN(A2)*B1/D1
1070 T2=F1*S3*S4*S5/B2
1080 PRINT B1,H1,D1,E1,F1,A1,T1,T2
1090 PRINT
1100 RETURN
1110 PRINT "E HAS EXCEEDED UNITY--THIS IS NON-PHYSICAL"
1120 GO TO 1170
1130 PRINT "ANGLE HAS EXCEEDED 45 DEGREES"
1140 GO TO 1170
1150 PRINT "ANGLE HAS EXCEEDED -45 DEGREES"
```

```
1160 GO TO 1170
1170 PRINT
1180 PRINT
1190 PRINT "DO YOU WANT TO RERUN PROGRAM? (YES=1,NO=2)"
1200 INPUT M
1210 ON M GO TO 1220,1250
1220 PRINT "DO YOU WANT TO VARY ONLY ONE PARAMETER? (YES=1,NO=2)"
1230 INPUT N
1240 ON N GO TO 430,400
1250 PRINT
1260 STOP
1270 END
```

Fortran Program for Resolution-of-Forces Calculation

```
      DIMENSION IN(6)
      DATA (IN(I),I=1,6) /1HB,1HH,1HD,1HE,1HF,1HA/
      WRITE (6,10)
10    FORMAT (1X,'* * * * * * * RESOLUTION OF FORCES CALCULATION * * *
     2* * * *',/,'* * * * * * * *   DESTRUCTIVE BOND PULL TEST  * * * *
     3* * * *',/1X,'THIS PROGRAM CALCULATES THE FORCES ON THE WIRE AT TH
     4E',1X,'TERMINAL AND THE DIE FROM THE BOND GEOMETRY AND THE',1X,
     5 'PULL STRENGTH.'/1X,'B IS THE HEIGHT, AT RUPTURE, OF THE WIRE SPA
     6N (AT THE',1X,'POINT OF PULL) ABOVE THE TERMINAL',/1X,
     7 'H IS THE HEIGHT OF THE TERMINAL RELATIVE TO THE DIE SURFACE',/1X
     8,'D IS THE BOND TO BOND SPACING')
      WRITE (6,20)
20    FORMAT (1X,'E IS THE DIMENSIONLESS FRACTIONAL DISTANCE ',/1X,
     2 'BETWEEN THE TERMINAL BOND AND THE POINT OF ')
      WRITE (6,30)
30    FORMAT (1X,'APPLICATION OF THE FORCE',/1X,'F IS THE PULL STRENGTH'
     2,/1X,'A IS THE PULL ANGLE AND IS  EXPRESSED IN UNITS OF DEGREES',/
     3 1X,'T1 IS THE FORCE ON THE WIRE AT THE TERMINAL, FWT',/1X,
     4 'T2 IS THE FORCE ON THE WIRE AT THE DIE, FWD',/1X,
     5 'THE VALUES OF B, H, AND D MAY BE EXPRESSED IN EITHER',/1X,
     6 'ENGLISH OR METRIC SO LONG AS THEY ARE CONSISTANT.',/1X,
     7 'THE FORCES  T1 AND T2 WILL, OF COURSE, HAVE ')
      WRITE (6,40)
40    FORMAT (1X,'UNITS OF F.  THE VALUE OF F MAY BE IN ',/1X,
     2 'ANY SET OF UNITS AND NEED NOT BE CONSISTANT WITH',/1X,
     3 'THE UNITS OF B, H, AND D')
50    WRITE (6,60)
60    FORMAT (1X,'ENTER B, H, D, E, F, A')
      READ (5,290) B,H,D,E,F,A
70    WRITE (6,300)
      READ (5,310) INQ
      B1=B
      H1=H
      D1=D
      E1=E
      F1=F
      A1=A
      IF (E1.GT.1.0) GO TO 160
      IF (A1.GT.45.) GO TO 210
      IF (A1.LT.-45.) GO TO 240
      DO 80 J=1,6
80        IF (INQ.EQ.IN(J)) GO TO (90,110,130,150,180,  200), J
      GO TO 70
90    DO 100 J=1,20
100       CALL PRINT (B*J*0.1,H1,D1,E1,F1,A1)
      GO TO 260
110   DO 120 J=1,20
120       CALL PRINT (B1,H*J*0.1,D1,E1,F1,A1)
      GO TO 260
130   DO 140 J=1,20
140       CALL PRINT (B1,H1,D*J*0.1,E1,F1,A1)
      GO TO 260
150   DO 170 J=1,20
          IF (E1*J*0.1.GT.1.0) GO TO 160
          GO TO 170
160       WRITE (6,320)
          GO TO 260
```

```
170          CALL PRINT (B1,H1,D1,E*J*0.1,F1,A1)
         GO TO 260
180      DO 190 J=1,20
190          CALL PRINT (B1,H1,D1,E1,F*J*0.1,A1)
         GO TO 260
200      IF (A) 230,,
         DO 220 J=0,9
             IF (A1*J*5.GT.45.) GO TO 210
             GO TO 220
210          WRITE (6,330)
             GO TO 260
220          CALL PRINT (B1,H1,D1,E1,F1,A*J*5)
230      DO 250 J=0,9
             IF (A1*J*5.LT.-45.) GO TO 240
             GO TO 250
240          WRITE (6,340)
             GO TO 260
250          CALL PRINT (B1,H1,D1,L1,F1,A1*J*5)
         GO TO 260
260      WRITE (6,350)
         READ (5,360) M
         GO TO (270,280), M
270      WRITE (6,370)
         READ (5,380) N
         GO TO (70,50), N
280      STOP
290      FORMAT ()
300      FORMAT (1X,30HSPECIFY PARAMETER TO BE VARIED)
310      FORMAT (A1)
320      FORMAT (1X,46H E HAS EXCEEDED UNITY -- THIS IS NON-PHYSICAL.)
330      FORMAT (1X,30H ANGLE HAS EXCEEDED 45 DEGREES)
340      FORMAT (1X,30HANGLE HAS EXCEEDED -45 DEGREES)
350      FORMAT (1X,43HDO YOU WISH TO RERUN PROGRAM? (YES=1, NO=2))
360      FORMAT (I1)
370      FORMAT (1X,61HDO YOU WISH TO VARY ONLY ONE PARAMETER? (YES = 1
     2 , NO =2))
380      FORMAT (I1)
C
C        ****************************************************************
C
         SUBROUTINE PRINT (B1,H1,D1,E1,F1,A1)
C
C        ****************************************************************
C
         B2=1.0+E1*H1/B1
         R1=E1*D1/B1
         R2=1.0+R1*R1
         R3=SQRT(R2)
         A2=A1*0.0174532925
         R4=(1.0-E1)*COS(A2)+SIN(A2)*(B1+H1)/D1
         T1=F1*R3*R4/B2
         S1=(1.0-E1)*D1/(B1+H1)
         S2=1.0+S1*S1
         S3=SQRT(S2)
         S4=1.0+H1/B1
         S5=E1*COS(A2)-SIN(A2)*B1/D1
         T2=F1*S3*S4*S5/B2
         WRITE (6,10) B1,H1,D1,E1,F1,A1,T1,T2
         RETURN
10       FORMAT (8(1X,8G9.3))
         END
```

Appendix C

Bond Pull Specifications for Large Diameter Wire

As was indicated in the Introduction, the better understanding of the pull test has led to further developments. One of these, a bond pull specification for large diameter wire, is included in this appendix.

At the request of the Defense Electronic Supply Center a bond-pull specification for the 5- to 20-mil (0.13- to 0.51-mm) diameter aluminum wire used in JAN-TXV power transistors was developed for proposed inclusion in appropriate slash sheets to MIL-S-19500, General Specification for Semiconductor Devices. This was a difficult problem because of the many wire sizes involved (at least 10), the wide range of geometrical configurations of the transistors, and the large variety of metallurgical properties of the available wire.

In order to establish the basis for a realistic specification that offered a meaningful level of quality control and was acceptable to both users and manufacturers, five semiconductor plants were visited to obtain pull test data and other information. Two other device manufacturers contributed additional data including mean-range charts for bond pull tests, and acceptance criteria were supplied by several users. Three major bonding wire companies supplied information on tensile strength, elongation, and other relevant metallurgical data. Additional bond-pull data were obtained in-house on a variety of wire sizes in a limited selection of device types.

The specification developed covers bonds made of aluminum wire, with or without alloying additives, ultrasonically bonded to the die and either ultrasonically bonded or electrical-discharge welded to the post. The test, which is primarily for use on uncapped devices being assembled at the manufacturer's plant, is performed by placing a rounded metal hook under the span of wire midway between the two bonds and pulling vertically to destruction with the device clamped. In some cases soldered clips of copper or other material are permitted. These may also be tested by this procedure, but in this case the hook is placed as close as possible to the soldered joint on the die. A bond failure is designated as any bond or wire which breaks at an applied stress less than that indicated in table C1. Procedures are included in the specification for both bond failures and die fracture.

It should be noted from figure C1 that, when plotted on log-log paper, the limits for large diameter wire in table join smoothly with the limits for small diameter aluminum wire. For completeness these small wire limits are also included in the table [16].

The results of this investigation have been incorporated in MIL-STD-19500 slash sheets for transistors.

Table C1 — Bond Pull Limits

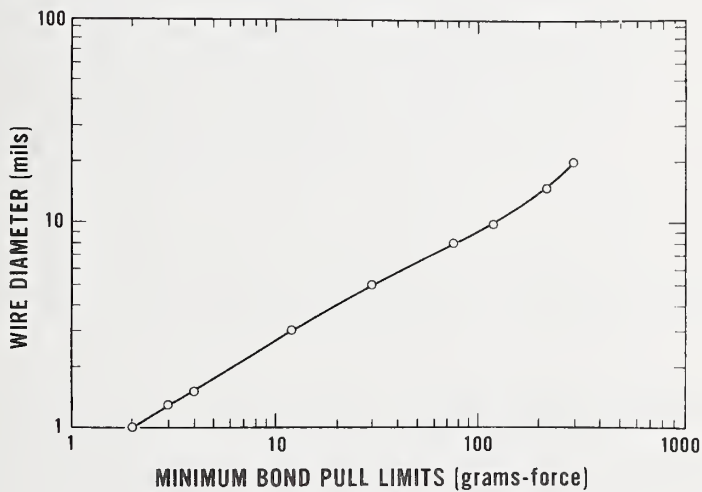| Wire diameter, mils (mm)	Minimum pull limit, gf (N)
1.0 (0.025)	2 (0.02)
1.3 (0.033)	3 (0.03)
1.5 (0.038)	4 (0.04)
3 (0.076)	12 (0.12)
5 (0.13)	30 (0.29)
8 (0.20)	75 (0.74)
10 (0.25)	120 (1.18)
15 (0.38)	220 (2.16)
20 (0.51)	300 (2.94)
solder clips	300 (2.94)

Figure C1. Minimum destructive bond-pull breaking-force vs wire diameter for aluminum wire bonds in semiconductor devices.

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Appendix D

Non-Destructive Wire Bond Pull Test

As the bond pull test is destructive to the bond, a non-destructive bond pull test has been introduced and used by the electronics industry. However, the stress level for which the test is truly non-destructive both in the short-term and long-term sense is purely a matter of trial and error for each individual case. The work done on and the understanding resulting from the destructive bond pull test as described in this report have led to certain criteria of general applicability for the force level to be safely used in the application of the non-destructive bond pull test. The results of this investigation for aluminum and gold wire are presented in this appendix.

In view of the fact that non-destructive bond pull (NDP) tests are often used in high-reliability production lines, the metallurgical and statistical rationales for the test developed, and maximum permissible NDP force limits applicable for a wide variety of wire sizes, both hard drawn and annealed were determined [17]. Previous work [18-21] on the subject has been restricted to small diameter wire having relatively low elongation under tensile stress.

The NDP test consists of pulling bonds at force levels below those necessary to cause breakage of the bond loop system. In order for the NDP test to be truly non-destructive and hence avoid the introduction of metallurgical defects in the bond loop system, no part of the bond loop system should be subjected to stresses greater than the metallurgical elastic limits.

For the NDP test to be statistically meaningful, it must be carried out in conjunction with a destructive bond pull test. The results of both the destructive bond pull test and the NDP test depend upon the same variables, including wire metallurgical properties, bonding technique, bond geometry, and bond deformation. Hence the mean and the standard deviation of the destructive bond pull test are significant factors in developing criteria for the NDP test.

In relating the results of a destructive pull test to criteria for a non-destructive pull test the stress-strain relationship of the wire is a significant factor. The effect of the state of hardness on the stress-strain relation is exemplified in figure D1. In this figure stress-strain curves are shown for the same aluminum wire in two states of hardness. The annealed wire has a large elongation typical of large diameter aluminum wire used bonding power devices. Hard-drawn or stress-relieved wire has a small elongation and is typical of that of small-diameter aluminum wire used in bonding integrated circuits.

Bonds made with small diameter aluminum wire are typically ultrasonically welded which overworks the bond heel and causes it to be the weakest part of the bond-loop system. Hence, the strength of the heel determines the maximum safe NDP force. The heel strength depends upon the bond deformation which in turn depends upon the bonding schedule. Hence, a safe NDP force may be determined only if a destructive bond pull test is performed on bonds made under the same conditions. The results of a destructive bond pull test are assumed to follow a normal distribution for which $\bar{x}$ is the mean breaking force and s is the
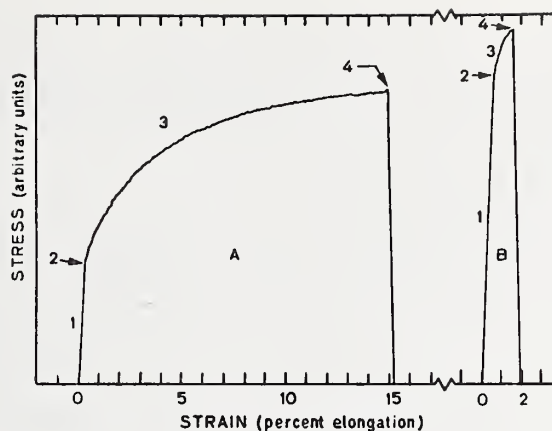
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Figure D1. Stress-strain curves for annealed (A) and hard-drawn or stress-relieved (B) aluminum wire. (This figure was made up from individual stress-strain charts reversed in direction for clarity of presentation. In order to display both curves on the same chart the stress axis was made relative, since the breaking load of the annealed wire was approximately one-half that of the hard-drawn wire. On both curves region 1 is the elastic region where the stress is proportional to the strain, point 2 is the proportional or elastic limit, region 3 is the region of inelastic or plastic deformation, and point 4 is the breaking load of the wire.)

Table D1 — Summary of NDP Force Recommendations

Type of Production Line	Wire Composition	Elongation	Relation Between $\bar{x}$ and s on the Bond Pull Test	Recommended Maximum Safe NDP Force
Normal	Aluminum	<3%	$0.15\bar{x}<s\leqslant0.25\bar{x}$	$0.9(\bar{x}-3s)$
High Rel	Aluminum	<3%	$s\leqslant0.15\bar{x}$	$0.9(\bar{x}-4s)$
All	Aluminum	$\sim$5 to 20%	$s\leqslant0.25\bar{x}$	$(\bar{x}-3s)/2$
	Aluminum	>20%	$s\leqslant0.25\bar{x}$	$(\bar{x}-3s)/3$
All	Gold	Any	$0.15\bar{x}<s\leqslant0.25\bar{x}$	$0.7(\bar{x}-3s)$
	Gold	Any	$s\leqslant0.15\bar{x}$	$0.7(\bar{x}-4s)$

sample standard deviation of the distribution. For normal assembly lines, where s can be expected to lie in the range $0.15 \bar{x}$ to $0.25 \bar{x}$ the recommended maximum safe NDP force is $0.9 (\bar{x} - 3s)$. For high-reliability lines, s may be equal to or less than $0.15 \bar{x}$. For this case, the recommended maximum safe NDP force is $0.9(\bar{x} - 4s)$. No NDP testing is recommended for cases where s is greater than $0.25 \bar{x}$ since this indicates that some aspect of the bonding procedure is out of control and either a low, meaningless NDP force would be used or too many bonds would be stressed beyond their elastic limits.

The large diameter aluminum wire used in power devices typically has an elongation up to 20 percent before breaking. Also, this wire is usually ultrasonically bonded with a grooved capillary-type tool which limits the maximum bond deformation and hence does not produce a weak bond heel. In this case, the stress-strain relation for the wire span determines the maximum safe NDP force. Due to the differences in the stress-strain relation from that of small diameter wire, a different NDP force is necessary. For a wire elongation up to 20 percent and an s of $0.25 \bar{x}$ or less the recommended maximum safe NDP force is $(\bar{x} - 3s)/2$. For an elongation greater than 20 percent, the maximum NDP force must be reduced to $(\bar{x} - 3s)/3$ in order to avoid significant inelastic wire elongation during the test.

Gold wire bonds formed by thermocompression or ultrasonic techniques do not have weak, overworked bond heels. Hence, the stress-strain relation for wire span determines the NDP force. These relations for small diameter grain-stabilized gold wire used in both ultrasonic and thermocompression bonding show that this type of gold wire typically experiences most of its elongation above 85 to 90 percent of its breaking load. However, some other gold wires may begin to elongate as low as 70 percent of their breaking load. Considering this and the high pull strength, even with large bond deformation, the recommended maximum safe NDP force control limit to include all small diameter gold wire is $0.7(\bar{x} - 3s)$ or $0.7(\bar{x} - 4s)$ for $0.15 \bar{x} \leq s \leq 0.25 \bar{x}$ or $s \leq 0.15 \bar{x}$, respectively.

Table D1 summarizes these recommendations. It must be noted that the NDP test ensures the reliability of a bond at the time of the test but does not prevent the later failure of the bond from intermetallic compound formation or post-production stresses [22].

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET	1. PUBLICATION OR REPORT NO. NBS Spec. Publ. 400-18	2. Gov't Accession No.	3. Recipient's Accession No.
4. TITLE AND SUBTITLE *Semiconductor Measurement Technology:* The Destructive Bond Pull Test		5. Publication Date February 1976	
		6. Performing Organization Code	
7. AUTHOR(S) John Albers, Editor		8. Performing Organ. Report No.	
9. PERFORMING ORGANIZATION NAME AND ADDRESS NATIONAL BUREAU OF STANDARDS DEPARTMENT OF COMMERCE WASHINGTON, D.C. 20234		10. Project/Task/Work Unit No.	
		11. Contract/Grant No.	
12. Sponsoring Organization Name and Complete Address (*Street, City, State, ZIP*) NBS - Washington, D. C. 20234 USNSSPO - NAD Crane, Ind. 47522 DNA - Washington, D.C. 20305		13. Type of Report & Period Covered Final	
		14. Sponsoring Agency Code SP 23	

15. SUPPLEMENTARY NOTES
Library of Congress Catalog Card Number: 75-619425

16. ABSTRACT (*A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.*)

This report summarizes the work done at NBS on the destructive bond pull test as applied to small-diameter (approximately 1 mil or 25 μm) ultrasonically bonded aluminum wire. This work was performed during the period from 1969 to 1974. The report begins with a brief summary of the calculation of the resolution-of-forces operative in the bond system during the application of the pulling force. Next, comparisons of the theoretical and experimental dependencies of the pull strength on the variables involved in the resolution-of-forces calculation are given. Some of the variables which are not directly involved in this calculation are then considered and their effects on the measured pull strength are presented. The report ends with a sensitivity calculation as to how well the variables must be controlled to maintain the variability of the pull strength to within given limits. Bond pull specifications for large-diameter wire as well as recommended force levels to be used in the application of the nondestructive bond pull test, both of which have resulted from the pull test work, are considered in the appendices.

17. KEY WORDS (*six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons*) Bond angle; bonding; bond pull test; bond-to-bond spacing; large wire; loop height; microelectronics; non-destructive bond pull test; position of hook; pull rate; pull strength; resolution-of-forces; semiconductor devices; ultrasonic bonding; wire bond.

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