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EVALUATION OF NONDESTRUCTIVE TENSILE TESTING

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16. Abstract

This report presents the results of a series of experiments performed in the evaluation of nondestructive tensile testing of chip and wire bonds. Semiconductor devices were subjected to time-temperature excursions, static-load life testing and multiple pre-stressing loads to determine the feasibility of a nondestructive tensile testing approach. The report emphasizes the importance of the breaking angle in determining the ultimate tensile strength of a wire bond, a factor not generally recognized nor implemented in such determinations.

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EVALUATION OF NONDESTRUCTIVE TENSILE TESTING

1.0 INTRODUCTION

The realization of the concept of 100 percent nondestructive testing of wire bonds has eluded semiconductor manufacturers since thermocompression wire bonding and ultrasonic wire bonding were first used to connect transistor chips to the outside world. The qualitative, self-defeating air-pressure test for checking bonds was set aside when it became apparent that not only were "good" bonds being weakened, but the only inferior bonds being detected were those in which the wire was not bonded to the pad but merely sat on the surface.

Manufacturers then took to verifying the quality of bonds by tensile testing to destruction a sampling of bonds. What the quality of the bonds was before, during and after the samples were evaluated is anybody's guess. There are almost as many approaches to destructive tensile testing of wire bonds as there are semiconductor manufacturers. Indeed, a meaningful standard for tensile testing of wire bonds is still lacking in the industry*. The differences in angles formed by the wire and the chip and the wire and the posts; the breaking angles α and β; the rate of pull and its constancy and repeatability, and the direction of pull and the breaking load are some of the factors which must be considered in determining the quality of chip and wire bonds.

2.0 DISCUSSION

In the experiments performed in our laboratory, we were somewhat limited by the fact that we had to take whatever devices

*See Appendix III

were available from the manufacturer at the time. Instead of one type of microcircuit with tightly controlled bonding, we had to choose our samples from several types with varied geometries and loosely controlled bonding techniques evident. However, the most severe handicap was the time lost due to the equipment manufacturer's failure to provide in the early stages of this program both a workable nondestructive tensile tester and a microtensile wire/bond tester.

In order to evaluate the equipment under investigation, we required a tensile tester which would measure the breaking load of the wire/bonds in a repeatable, well-controlled manner. A commercial Microtensile Wire/Bond Tester, was purchased and found to be deficient in many regards. We used an in-house designed tensile tester and restricted the evaluation to the concurrent pull-testing of wire bond pairs.

We purchased a commercial Microbond Nondestructive Pull-Tester and found that it did not function in a manner which would be acceptable to in-line manufacturing requirements. The company representative attempted to correct the inadequacy of the machine but failed to do so. The difficulty centered on the extreme amount of force required to maneuver the device under test to its correct location under the hook. The machine was subsequently replaced by the company and the replacement was found to be mechanically acceptable.

It was our intention to study the Microbond Nondestructive Pull-Tester in depth, by performing the series of experiments listed below. However, due to the limitations of time, equipment, and material, some of the tests were not carried out and others had to be limited in scope.

2.1 TESTS

2.1.1 Establish Failure Strength Minimum

(A) Concurrent pull-test to destruction of bond pairs*

(B) Pull to destruction of chip bond only:
  (1) At 90°
  (2) At 45°

(C) Pull test to destruction of post bond only:
  (1) At 90°
  (2) At 45°

(D) Plot strength frequency distribution of A, B, C
  (1) From the above data, established the Failure Strength Minimum (FSM) to be used as the pre-stress load for the nondestructive pull tester.

2.1.2 Static Load Life Test

(A) Devices as received
  (1) Concurrent pull test to destruction after 1000 hour load at FSM.

(B) Pre-stressed devices
  (1) Concurrent pull test to destruction after 1000 hour load at FSM.

2.1.3 Multiple Pre-Stress Test

(A) Extensive pre-stresses at FSM before test to destruction

(B) Limited pre-stresses at FSM before test to destruction

(C) Plot strength frequency distribution of B, noting fallout below FSM and compare with 2.11 (D) above.

---

*See Figure 1

2.1.4 Time-Temperature Storage

(A) Devices as received

(1) Store devices @150°C in N_2 ambient

(a) Concurrent test to destruction all bond pairs after 250 hours.

(b) Concurrent test to destruction all bond pairs after 500 hours.

(c) Concurrent test to destruction all bond pairs after 1000 hours.

(2) Store devices @200°C in N_2 ambient

(a) Repeat (1) (a), (b) and (c) above

(3) Store devices @250°C in N_2 ambient

(a) Repeat (1) (a), (b) and (c) above

(4) Store devices @300°C in N_2 ambient

(a) Repeat (1) (a), (b) and (c) above

(B) Pre-stressed devices

(1) Repeat (A)(1), (2), (3) and (4) for an equal number of devices in which each bond pair has been pre-stressed once at the established FSM.

NOTE

As in previous tests: direction of pull shall be 90° to substrate; failure strength and mode shall be noted and recorded; breaking angles α and β shall be translated to the corrective factors (F_α) and (F_β) in order to relate the hook load to $T.S._\alpha$ and $T.S._\beta$; and the strength frequency distribution shall be plotted.

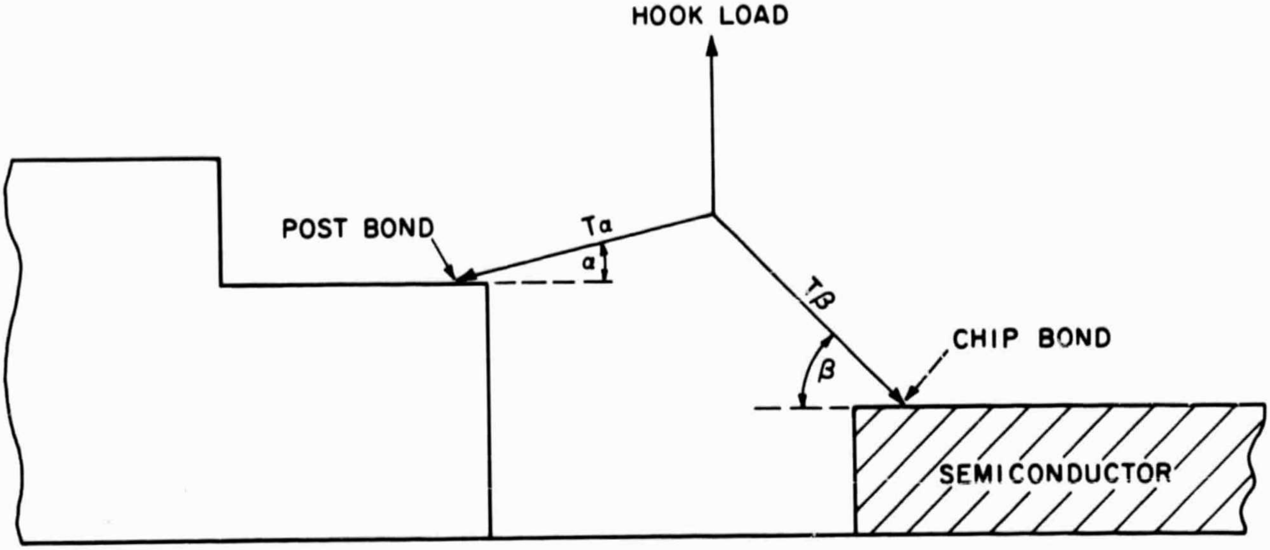


Figure 1. Concurrent pull test of bond pairs

when $\alpha \neq \beta$

$$T.S._{\alpha} = \frac{L}{\sin\alpha + \cos\alpha \tan\beta} = (F_{\alpha})\, L \qquad T.S._{\beta} = \frac{L}{\sin\beta + \cos\beta \tan\alpha} = (F_{\beta})\, L$$

$$T.S._{\alpha} = (T.S._{\beta})\, \frac{\cos\beta}{\cos\alpha} \qquad T.S._{\beta} = (T.S._{\alpha})\, \frac{\cos\alpha}{\cos\beta}$$

when $\alpha = \beta$

$$T.S._{\alpha} = T.S._{\beta} = \frac{L}{2\sin\alpha} = \frac{L}{2\sin\beta}$$

L = Hook Load at moment of fracture
α = Breaking angle between wire and post
β = Breaking angle between wire and chip
$T.S._{\alpha}$ = Tensile Strength of post bond
$T.S._{\beta}$ = Tensile Strength of chip bond
F_{α} = Corrective factor for post bond
F_{β} = Corrective factor for chip bond

Figure 1.- Concurrent pull test of bond pair

2.1.5 Mechanical Evaluation of Visual Rejects

(A) Concurrent pull-test to destruction of bond pairs

(1) Inspect devices for visual bond rejects and code for traceability.

(2) Pull-test to destruction.

(3) Compare number of visual rejects with those failing FSM.

It cannot be emphasized too strongly that in reporting the strength of wire bonds, unless due consideration is given to the breaking angles, the data are of little value. The breaking angle is a function not only of the inherent tensile strength of the bond, but is also dependent on whether each bond pair is made with an extended loop or a tight loop. The breaking angle can also be influenced by the position of the bonding pad on the chip relative to the post. Thus, merely reporting the hook load at the moment of bond failure says little about the strength of the wire bond.

All devices used in these experiments were from one manufacturer. The devices consisted of uncapped silicon microcircuits with aluminum metallization. The bonding wire was 0.001" diameter aluminum, ultrasonically bonded from post (first bond) to chip (second bond). We separated the devices into types according to chip size, geometry, and bonding pad layout. The samples were restricted to three of the different types. Figures 2 and 3 are Scanning Electron Microscope photographs of typical bonds.

2.2 TEST RESULTS

2.2.1 Failure Strength Minimum

In order to establish the FSM, a sample of 18 devices was taken, made up of 4 devices from Type 1, 6 devices from Type 2, and 8 devices from Type 3. Since each device has 14 leads, a total of 252 bond pairs or 504 bonds was involved in the test.

Each bond pair was concurrently pull-tested to destruction. The rate of travel of the hook load was 0.178 inches/minute. The direction of travel was 90° to the substrate.

In order to determine the breaking angles (α and β) for the computation of the bond strengths ($T.S._{\alpha}$ and $T.S._{\beta}$), the devices were coded and the leads were numbered for bond traceability. Each bond pair from one unit of each type of device was carefully photographed and the angles measured. See Figures 4 and 5. From these measurements, corrective factors (F_{α}) and (F_{β}) were computed for each post and chip bond.

$\underline{T.S._{\alpha} = (F_{\alpha})L}$

Type 1: $F_{\alpha} = 0.56$ to 1.3; Ave $T.S._{\alpha} = (0.86)L = 5.6$ gm

Type 2: $F_{\alpha} = 0.77$ to 1.2; Ave $T.S._{\alpha} = (0.99)L = 5.4$ gm

Type 3: $F_{\alpha} = 1.1$ to 1.3; Ave $T.S._{\alpha} = (1.1)L = 5.5$ gm

$\underline{T.S._{\beta} = (F_{\beta})L}$

Type 1: $F_{\beta} = 0.52$ to 1.5; Ave $T.S._{\beta} = (1.0)L = 6.5$ gm

Type 2: $F_{\beta} = 0.92$ to 1.5; Ave $T.S._{\beta} = (1.2)L = 6.6$ gm

Type 3: $F_{\beta} = 0.79$ to 1.8; Ave $T.S._{\beta} = (1.3)L = 6.5$ gm

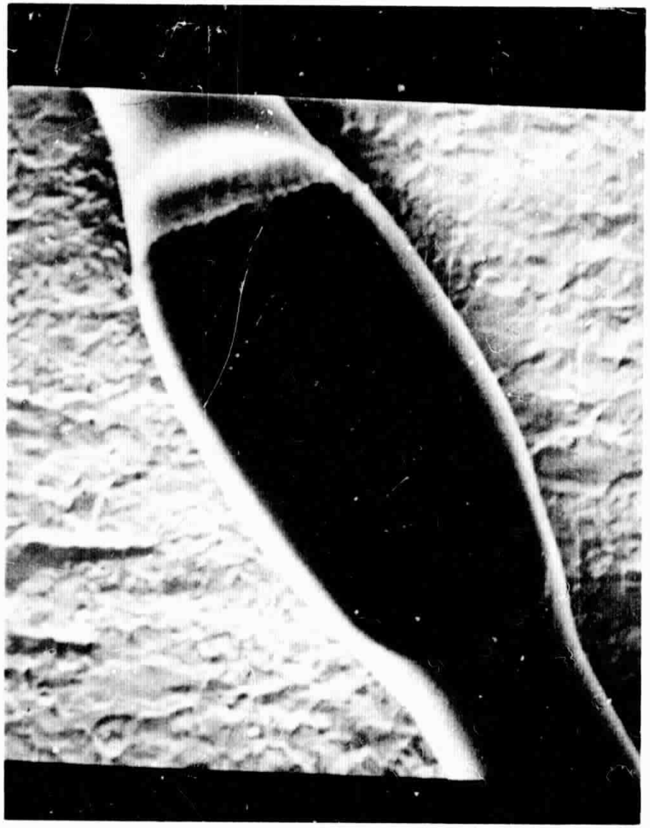


Figure 2
SEM Photograph of Typical Post Bonds
(1200X)

Figure 3
SEM Photograph of Typical Post Bonds
(600X)

Figure 4

$L = 4.7$ gms

$\alpha = 11°$ $\beta = 30°$

$F_{\alpha} = 1.3$ $F_{\beta} = 1.4$

$T.S._{\alpha} = 6.1$ gm $T.S._{\beta} = 6.6$ gm

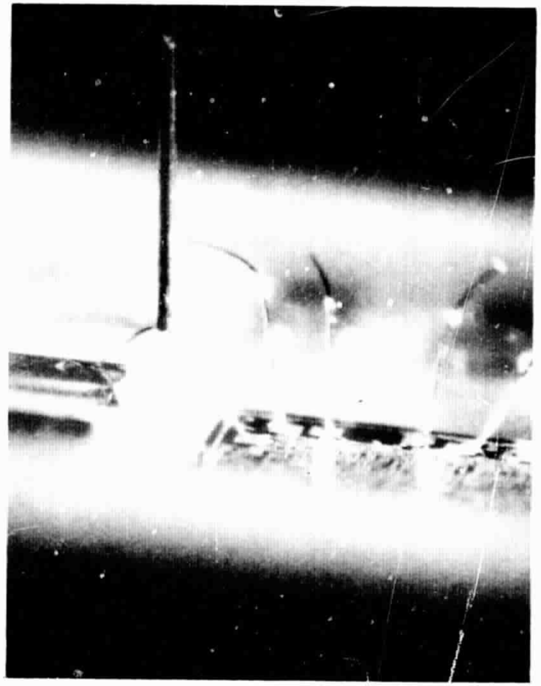


Figure 5

$L = 8.2$ gms

$\alpha = 38°$ $\beta = 56°$

$F_{\alpha} = 0.56$ $F_{\beta} = 0.79$

$T.S._{\alpha} = 4.6$ gm $T.S._{\beta} = 6.5$ gm

It is clear, that due to the differences in the angles α and β, a 2.0 gm load applied concurrently to the types of devices under consideration will result in unequal stresses to each bond of any given bond pair. For example, a 2.0 gm load on a Type 1 device would result in the following stresses for the bond pair indicated:

Bond Pair	T_α	T_β
#4	2.0 gm	2.4 gm
7	1.1	1.6
9	1.7	1.0
13	2.6	3.0

Using a FSM of 2.0 gm, then:

4/18 = 22% devices failed

12/252 = 4.8% bond pairs failed

24/504 = 4.8% bonds failed

Parts (B) and (C) of Test 2.1.1 were not carried out since we did not have the equipment to pull to destruction any single-ended bonds to the chip or to the post.

2.2.2 -STATIC LOAD

This test consists of loading 2.0-gm weights on six bond pairs. It was difficult to load the wire without rupturing the bond. After several unsuccessful attempts, we did manage to hang weights on three bond pairs which were pre-stressed and three bond pairs which were not. The devices have survived over 700 hours with the 2.0-gm static load.

2.2.3 - MULTIPLE PRE-STRESS

Part (A) of this test involved pre-stressing one device up to 100 times per bond pair with the FSM load of 2.0 gms. It was intended to pull each bond pair to destruction following the pre-stressing in order to compare the data with unstressed bonds pulled to destruction. However, since only two bond pairs out of 13 survived, there was no point in carrying out the test further. The data below would appear to indicate that multiple stresses of wire bonds may be causing the wire to undergo detrimental metallurgical changes in the bonds. This would be an area for further investigation.

Bond #	Number Pre-Stresses Before Failure
1	4
2	12
3	26
4	Omit (damaged bond)
5	5
6	18
7	31
8	76
9	99
10	100
11	29
12	100
13	58
14	38

Part (B) of the multiple pre-stress experiments involved 18 devices in which each bond pair was stressed five times with the FSM load of 2.0 gm. Two devices which failed on the fifth loading were replaced by two others which survived all five loadings.

After pre-stressing each bond pair five times, the bond pairs were concurrently pull-tested to destruction and the failure mode and breaking load were noted in each case. The correction factors F_α and F_β determined in Test 2.1.1 were applied to the data with the result that 3/504 or 0.6% of the bonds failed. If the corrective factors were ignored, as was the apparent case in the original data presented by the equipment manufacturer, then our data would also reflect no bond pair failures after pre-stress, since the minimum fracture load in each case equaled or exceeded 2.0 gms.

2.2.4 - TIME-TEMPERATURE STORAGE

This experiment was performed to determine the effect of extended storage at elevated temperatures on devices which were pre-stressed vs devices which were not pre-stressed. Although one sample set was stored for 500 hours, only the 250-hour storage test can be reported on at this time.

The sample consisted of 10 devices stored at 150°C; 10 devices stored at 200°C, and 10 devices stored at 250°C in a nitrogen ambient. Half of the devices were pre-stressed once with a 2.0-gm load. At the end of the 250-hour period, each bond pair was pull-tested to destruction and the tensile strength of each bond was computed from the previously determined corrective factors.

A statistical analysis of the data at the 95% confidence level reflects no significant differences in the bond strengths of the control sample and the pre-stressed sample.

Both the pre-stressed and control samples had nearly the same number of bond failures with the former having 12.7% failures and the latter 12.2% failures for all three temperature excursions.

The number of failures for bonds stored at temperature was about 4-1/2 times the number which saw no temperature excursion.

3.0 STATISTICAL ANALYSES

3.1 INTRODUCTION

A portion of the effort was spent on statistical evaluation of the problem in setting up the experiments and in statistical evaluation of the data derived from the experiments.

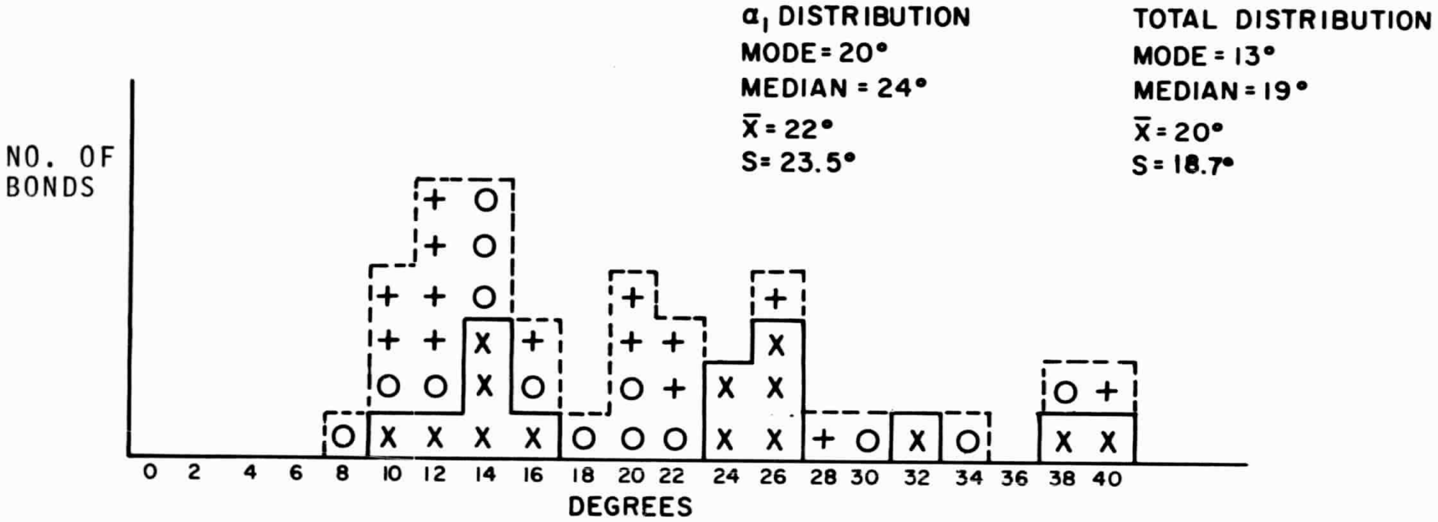
The integrated circuits purchased for these experiments were primarily of three configurations, but each had 14 bonded wires (i.e., 14 chip bonds and 14 post bonds) and were similar in most respects.

3.2 CONSIDERATION OF MEASUREMENTS OF ANGLES

It was required initially to determine whether the three kinds of circuit could be considered to have been drawn from the same population as far as bonds were concerned. A physical measurement such as the angle of the wire at the post and at the chip bond was considered an appropriate and significant measurement toward such a determination. The further role of the angle in testing bonds is also of prime importance, as is discussed above. As elsewhere in this report, the angle α is the breaking angle of the post bond, and the angle β is the breaking angle of the chip bond (See Figure 1). Histographs of the distribution of the measured angles of units numbered 1, 5, and 11 are shown in Figures 6-12. Data for α and β are given in Figure 13. Although there is a certain amount of right skewness to the distributions of α_1, α_2, α_3 and β_1, β_2, β_3, and of left skewness to the distribution of the weighted averages, the amount is not sufficient to invalidate the use of the mean $\overline{X}$. Indeed, the median is very close to the $\overline{X}$ value of these distributions as shown in Figure 14. The mode is not as close in value to the average $\overline{X}$ but is still sufficiently close to warrant the use of $\overline{X}$ as a significant measure of the central tendency of the distributions. The comparison of the mode with the $\overline{X}$ value is shown in Figure 15. In evaluation of the variances of the different means, the fact that the standard deviation of these distributions is large (close to 20°) is significant. The values of the standard deviations (s) of the samples are shown in Figure 16.

The following hypothesis was then tested: "The sample distribution of measured angles α_1 comes from the same population as the total population."

In order to test this hypothesis statistically, the $\overline{X}$ and S of the total population are taken as the measures (particularly valid in view of the homoscedasticity of the distributions). Thus M = 19 degrees and α = 18.7 degrees, so that $T_{\overline{X}} \simeq 5$ degrees.



$X = \alpha_1$
$O = \alpha_5$
$+ = \alpha_{11}$

Figure 6 - Distribution of Total Population (α) and of α_1

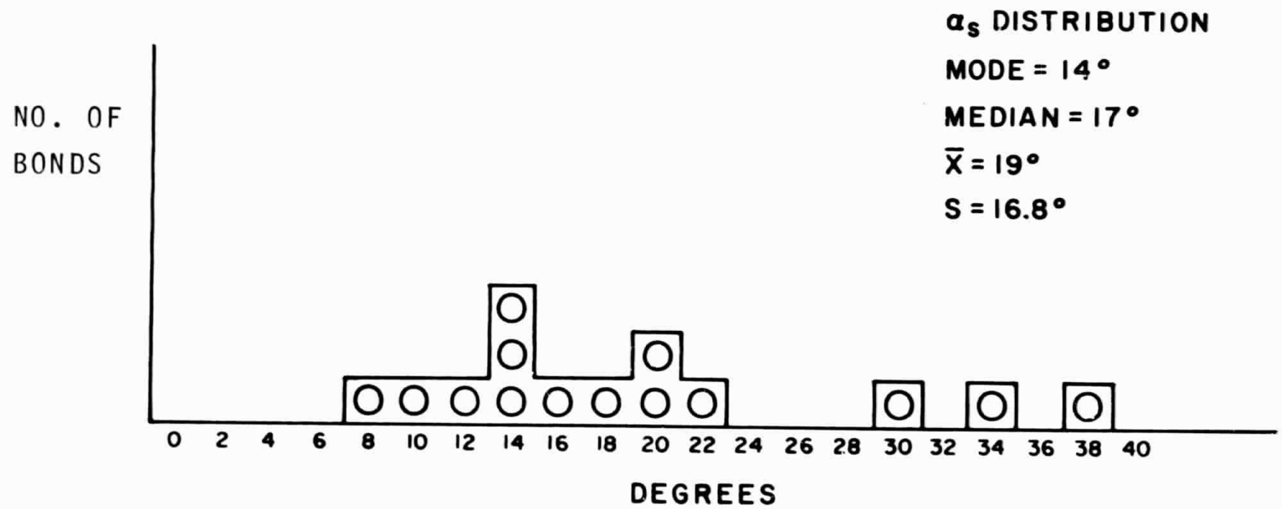


Figure 7 - Distribution of α_5

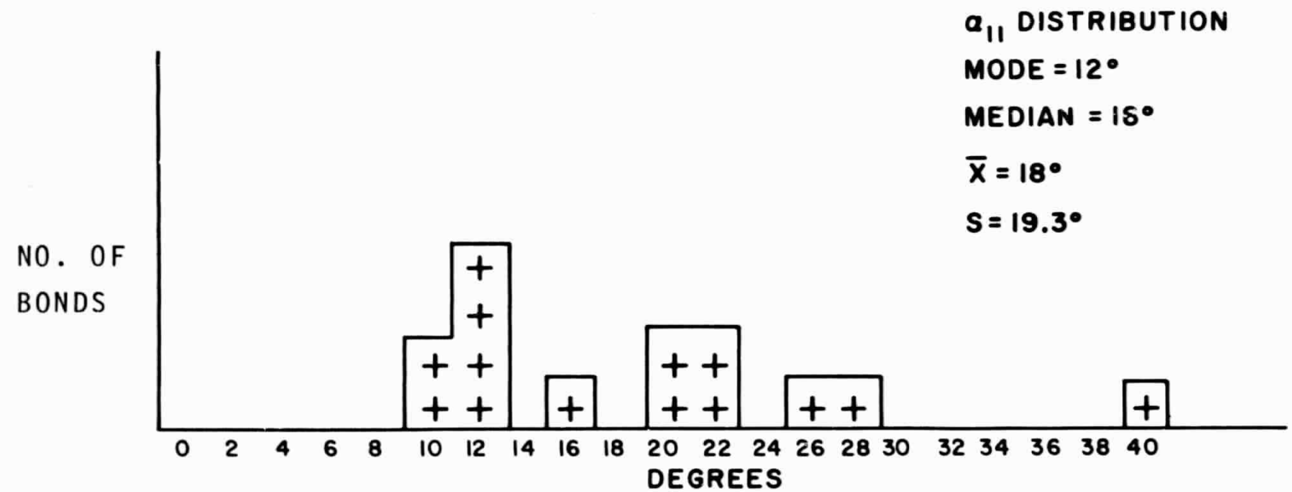


Figure 8 - Distribution of α_{11}

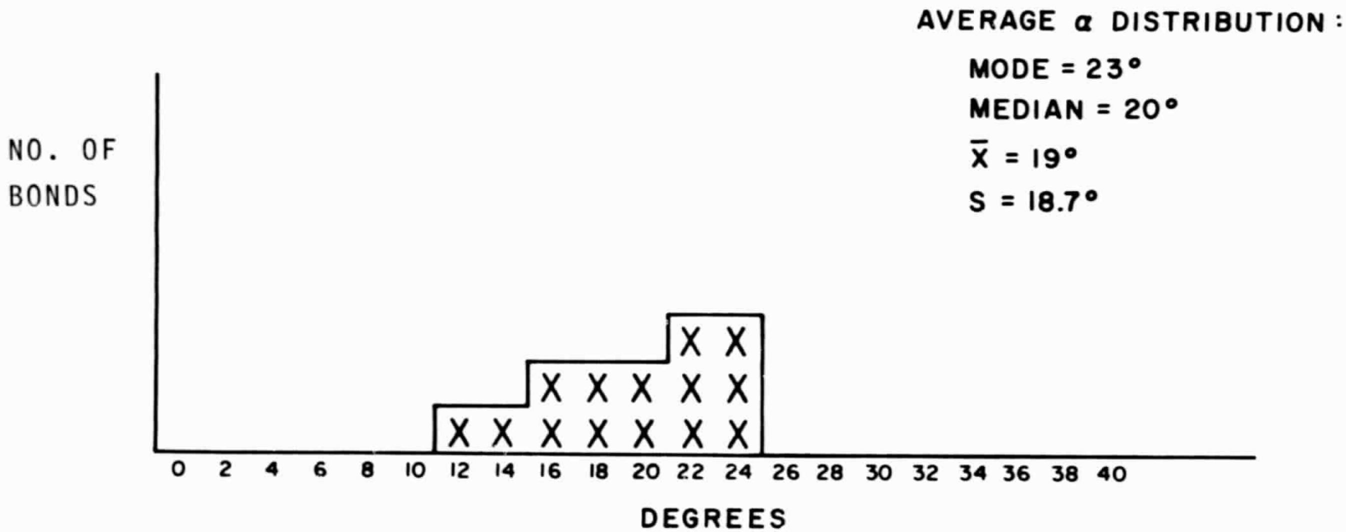


Figure 9 - Distribution of α (Weighted Average)

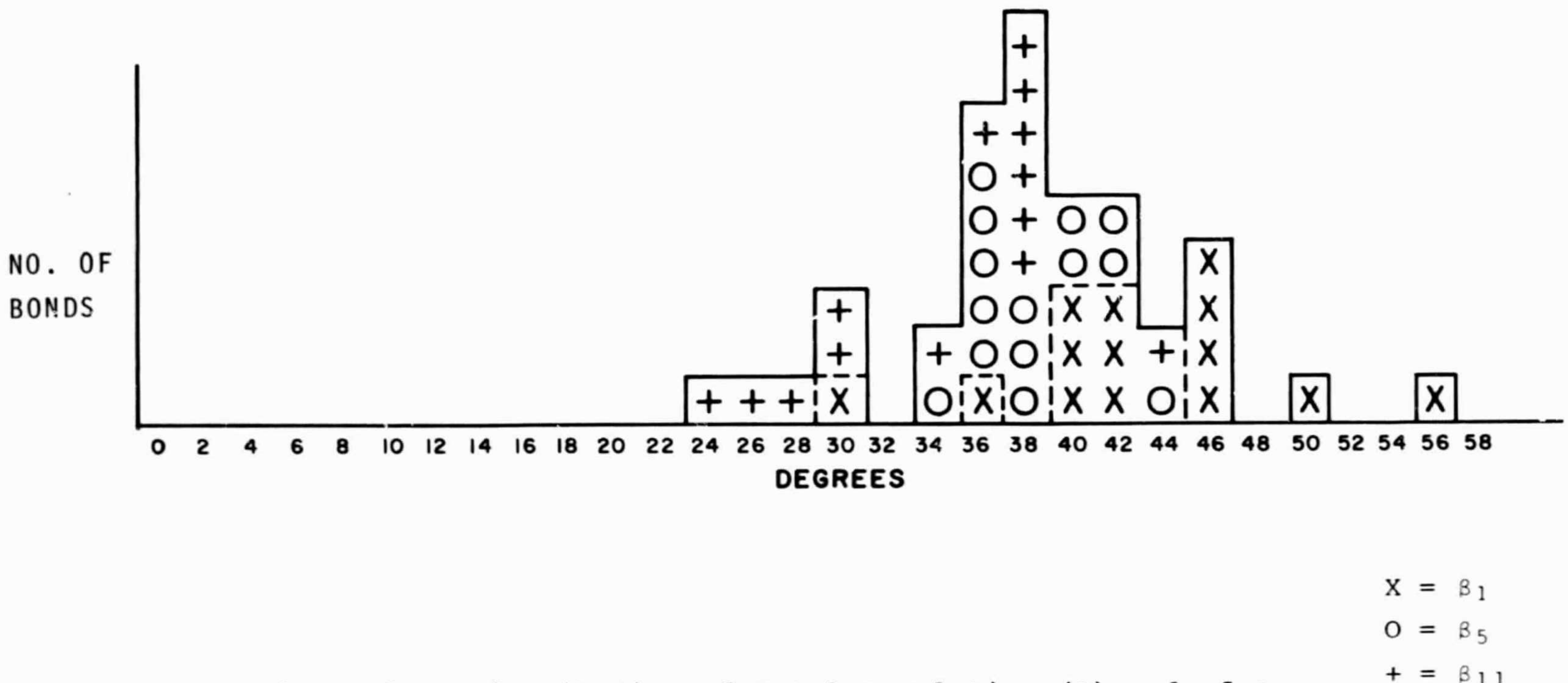


Figure 10 - Distribution of Total Population (β) and of β_1

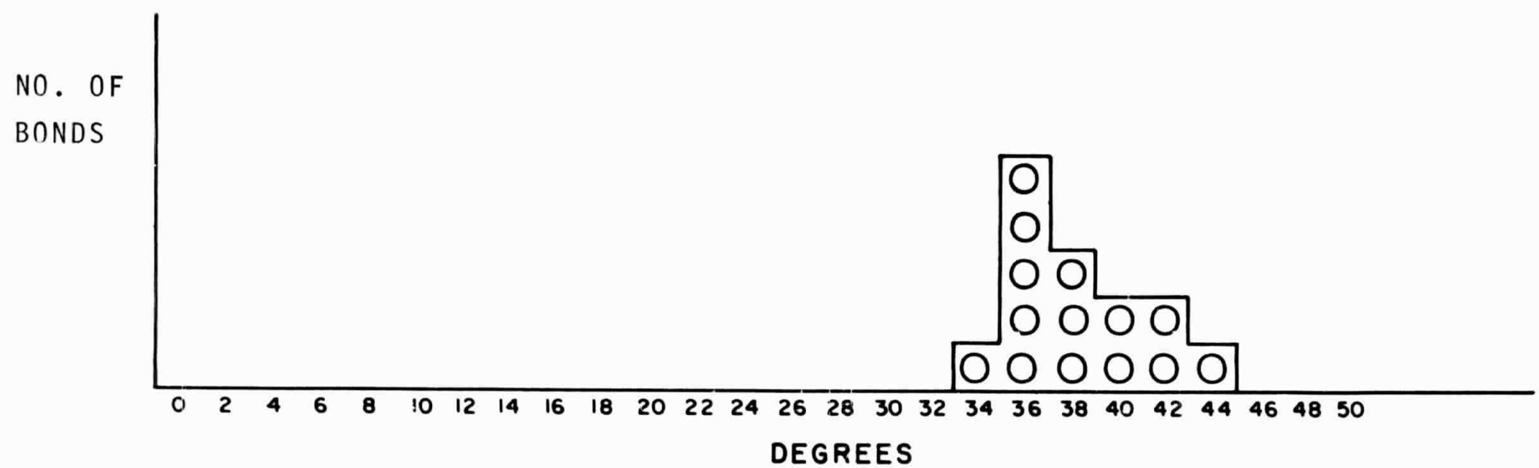


Figure 11 - Distribution of β_5

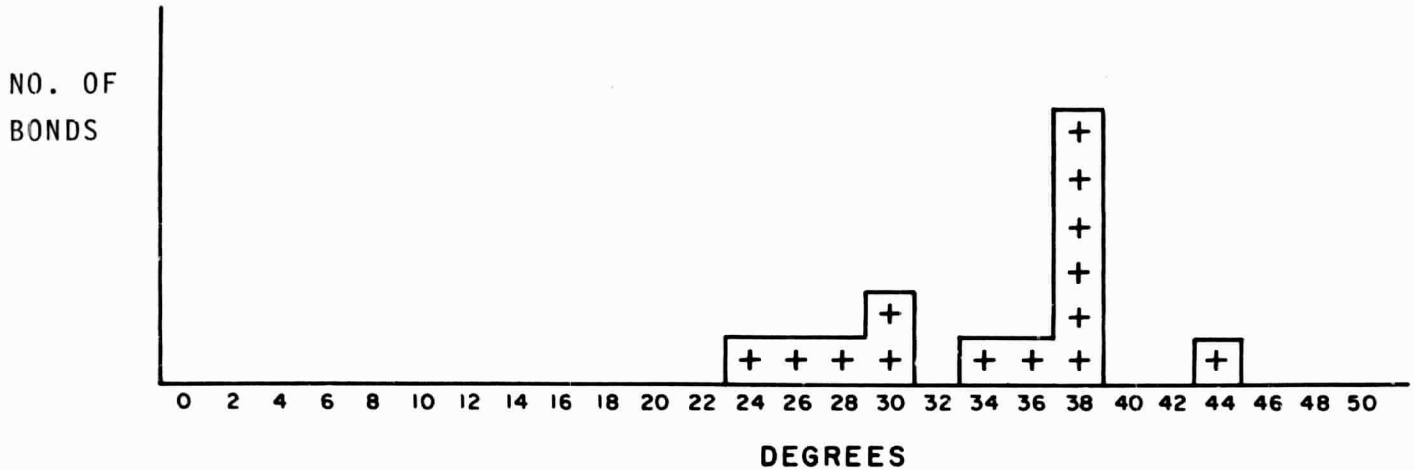


Figure 12 - Distribution of β_{11}

Bond #	α_1	α_5	α_{11}	Weighted Average $\alpha_{1,5,11}$
1	23°	19°	21°	21°
2	25	15	21	17
3	15	12	19	15
4	13	22	20	18
5	26	29	15	23
6	23	14	11	16
7	38	10	11	20
8	40	17	11	23
9	10	13	9	11
10	14	14	12	13
11	26	19	21	22
12	31	8	26	22
13	13	17	27	19
14	12	20	39	24
Ave.	22°	19°	18°	19°

Bond #	β_1	β_2	β_3	Weighted Average $\beta_{1,5,3}$
1	41°	40°	37°	39°
2	36	35	24	32
3	41	39	38	39
4	39	42	38	40
5	42	43	33	39
6	50	37	26	38
7	56	36	30	41
8	46	37	29	37
9	46	37	27	37
10	39	35	36	37
11	45	41	37	41
12	43	34	37	38
13	28	35	38	34
14	39	36	43	39
Ave.	42°	38°	34°	38°

Figure 13.- Measured angles α and β

	Median	$\overline{X}$	$- \lvert\Delta\rvert$
α_1	24 Degrees	22 Degrees	2 Degrees
α_5	17	19	2
α_{11}	18	18	0
α_{TOTAL}	24	22	2
$\alpha_{WEIGHTED}$	20	19	1

Figure 14.- Comparison of the median with the $\overline{X}$ value for measured angles α

	Mode	$\overline{X}$	$\lvert\Delta\rvert$
α_1	20 Degrees	22 Degrees	2 Degrees
α_5	14	19	5
α_{11}	12	18	6
α_{TOTAL}	13	22	9
$\alpha_{WEIGHTED}$	23	19	4

Figure 15.- Comparison of the mode with the $\overline{X}$ value of measured angles

---

	S
α_1	23.5 Degrees
α_5	16.8
α_{11}	19.3
α_{TOTAL}	
$\alpha_{WEIGHTED}$	18.7

Figure 16.- Values of standard deviations of samples of measured angles

The value of $\overline{X}$ for the α_1 sample is 22 degrees, and the corresponding value of the t parameter is 0.6. The probability (from a table of normal areas and ordinates) is 0.22575 of obtaining such a value or less.

If a significance factor of .05 (a confidence level of 95%) is used, the probability of error is less than 0.05 when one says that the value of $\overline{X}$ = 22 is not statistically significant and that the hypothesis is acceptable.

The details are presented in Appendix I.

A similar logical and statistical procedure was employed for the other angle parameters. It was established that the various samples could be considered to have been drawn statistically from the same population.

3.3 CONSIDERATION OF BREAKING STRENGTH DATA

The average $\overline{X}$ and the standard deviation σ of the breaking strength values as measured before any prestressing or non-destructive testing was calculated. Histographs of the distributions of $T.S._{\alpha}$ and $T.S._{\beta}$ are shown in Figures 17 and 18. It must be recalled that $T.S._{\alpha}$ and $T.S._{\beta}$ are the components of T.S., (the breaking force on the wire) at the post and chip respectively.

The average values of breaking strength for each of the three device types are:

Type 1	$_{1}\overline{X}_{T_{\alpha}}$	= 5.6 g
Type 2	$_{2}\overline{X}_{T_{\alpha}}$	= 5.4 g
Type 3	$_{3}\overline{X}_{T_{\alpha}}$	= 5.5 g

Overall Average (of classes Type 1, 2, 3) $_{\alpha}$ = 5.5 g

Overall Average (as individuals) $_{\alpha}$ = 5.5 g

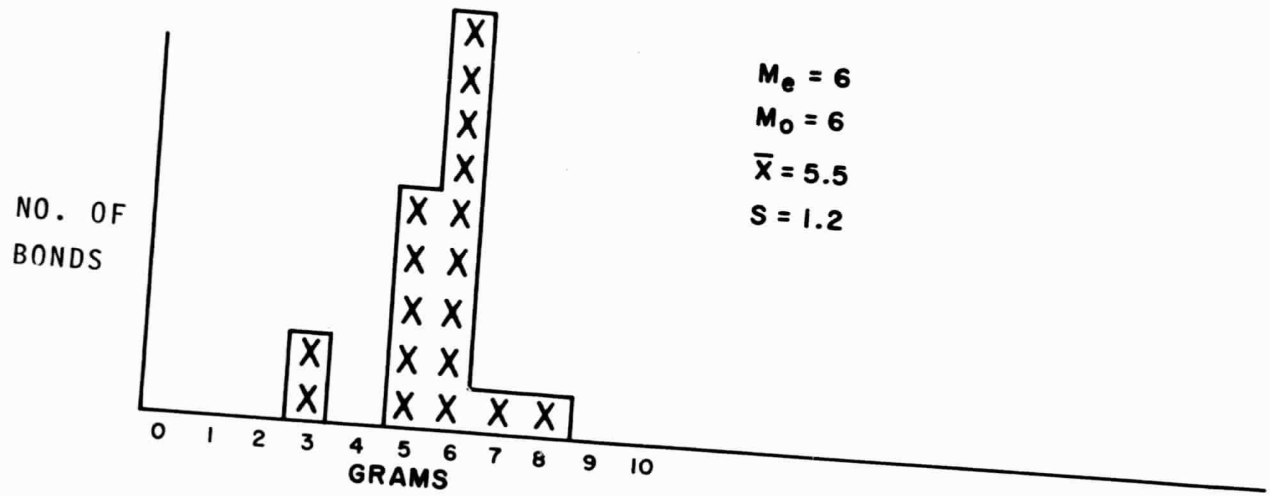


Figure 17 - Distribution of Bond Average Breaking Strength T_α

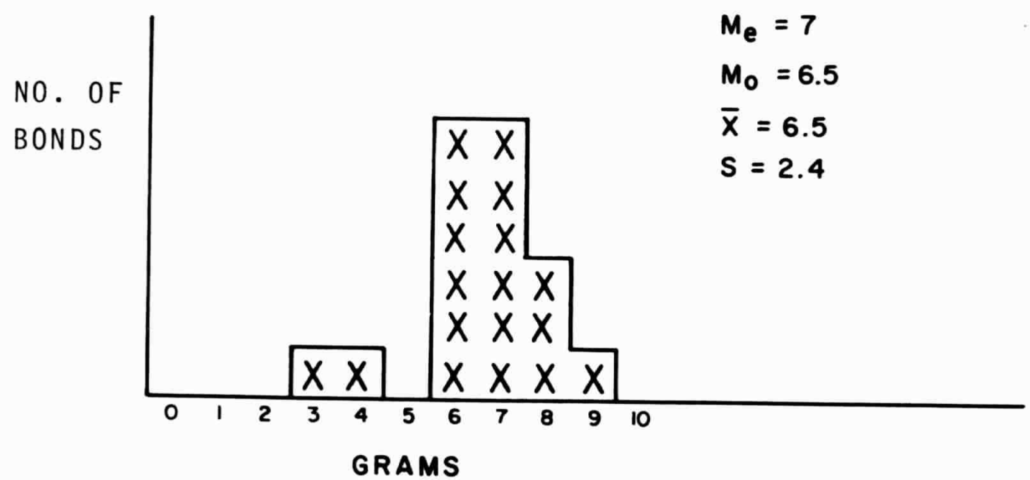


Figure 18 - Distribution of Bond Average Breaking Strength T_β

Similar values for the tension in the wire at the chip bond for the breaking force are:

Type 1	${}_1\overline{X}T_\beta$	= 6.5 g
Type 2	${}_2\overline{X}T_\beta$	= 6.6 g
Type 3	${}_3\overline{X}T_\beta$	= 6.5 g

Overall Average (of classes Type 1, 2, 3) $\overline{X}T_\beta$ = 6.5 g

Overall Average (as individuals) $\overline{X}T_\beta$ = 6.5 g

The calculation standard deviations for these distributions are as follows:

Overall $\overline{T}_\alpha$ = 5.5 $\quad \sigma_{T_\alpha}$ = 1.2 g

Overall $\overline{T}_\beta$ = 6.5 $\quad \sigma_{T_\beta}$ = 2.4 g

Since it has been assumed that the distributions are normal, and indeed it is seen that the distributions are in fact near normal, the $\overline{X}$ and the σ characterize the distributions.

Statistical analyses were made of the data accumulated on various types of environmental and mechanical stress tests, with their controls.

In order to evaluate the significance of the "Nondestructive" aspect of bond testing, in respect to bond life, a series of experiments was performed in which samples as received were tested to failure, and other sets of samples were subjected to graded steps of ambient temperature (150°C, 200°C, 250°C) for 250 hours each.

The data for these experiments were compared. The $T.S._\alpha$ and $T.S._\beta$ averages of units placed at 150°C for 250 hours, as received and after prestressing, are shown in Figure 19.

The average values were calculated: $T.S._\alpha$ of all units as received is 3.8 g; the $T.S._\beta$ is 4.5 g. The standard deviations were calculated for these distributions:

$$S_\alpha = 3.3 \text{ g and } S_\beta = 4.1.$$

The average value of $T.S._\alpha$ of all prestressed units is 3.7 g and of $T.S._\beta$ 4.3 g. The corresponding standard deviations are $S_\alpha = 3.2$ g and $S_\beta = 2.8$ g.

The comparable data for $T.S._\alpha$ and $T.S._\beta$ as received and prestressed and placed at 200°C for 250 hours yield overall average values at:

200°C for 250 hours	$\overline{T.S.}_\alpha$	$\overline{T.S.}_\beta$
As Received	3.9	4.6
Prestressed	3.4	3.9

The data are shown in Figure 20.

Simularly, for the data shown in Figure 21, resulting from units placed, as received and after prestressing, at 250°C for 250 hours, the overall values are: As received, etc.: $\overline{T.S.}_\alpha = 2.8$, $\overline{T.S.}_\beta = 3.3$, $S_\alpha = 2.3$, $S_\beta = 2.8$; Prestressed: $\overline{T.S.}_\alpha = 3.3$, $\overline{T.S.}_\beta = 3.7$, $S_\alpha = 2.7$, $S_\beta = 3.3$

Statistical tests were performed evaluating the significance of the differences of the overall means, similar to those employed for the angular measurement data. The significances were evaluated at the 95% confidence level. The results of these tests showed that the differences of the means for the populations of

As Received	$\overline{T}_\alpha$	$\overline{T}_\beta$	Prestressed	$\overline{T}_\alpha$	$\overline{T}_\beta$
Unit 1	3.8	4.6	Unit 1	2.9	3.5
2	5.4	6.4	2	4.8	5.7
3	3.0	3.5	3	3.1	3.1
4	3.6	4.2	4	3.4	3.9
5	3.1	3.7	5	4.3	5.1

Figure 19.- Data for $\overline{T}_\alpha$ and $\overline{T}_\beta$ of devices (as received and prestressed) and placed at 150°C for 250 hours

As Received	$\overline{T}_\alpha$	$\overline{T}_\beta$	Prestressed	$\overline{T}_\alpha$	$\overline{T}_\beta$
Unit 1	4.2	4.9	Unit 1	3.6	4.1
2	3.1	3.7	2	3.0	3.6
3	4.4	5.2	3	2.2	2.6
4	3.5	4.5	4	4.6	5.5
5	——	——	5	3.5	4.0

Figure 20.- Data for $\overline{T}_\alpha$ and $\overline{T}_\beta$ of devices (as received and prestressed) and placed at 200°C for 250 hours

As Received	$\overline{T}_\alpha$	$\overline{T}_\beta$	Prestressed	$\overline{T}_\alpha$	$\overline{T}_\beta$
Unit 1	3.1	3.6	Unit 1	3.3	3.8
2	3.5	4.2	2	2.2	2.6
3	2.1	2.5	3	3.4	3.9
4	2.6	3.0	4	3.1	3.6
5	2.7	3.2	5	4.0	4.7

Figure 21.- Data for $\overline{T}_\alpha$ and $\overline{T}_\beta$ of units tested as received and after prestressing, for 250 hours at 250°C

the $T.S._\alpha$ of the devices subjected to 150°C for 250 hours as received and after prestressing are not significantly different statistically at this confidence level. For similar sets of data for 200°C, the overall means of the populations are not significantly different statistically. For similar data from devices at 250°C, other factors held constant the differences of the means of the $\overline{T.S.}_\alpha$ are not statistically different. It is noted that there is a statistically significant difference in the means of the populations of the devices as received and not subjected to further testing (those used to obtain the MFS) and the populations subjected to heat (as received and prestressed).

From these data and analyses, it must be concluded statistically that a single pull test does not significantly affect the failure strength of bonds of this type subject to temperatures up to 250°C for 250 hours, as far as average value of failure strength is concerned.

Statistical tests were next performed utilizing the chi squared (χ^2) and the F distributions to evaluate the significance of the differences of standard deviations. The differences of the variances (σ^2) were tested at the 95% confidence level. Considering the prestressed devices put at 150°C for 250 hours, as compared to the as-received devices subjected to similar time and temperature treatment, it was found that for the values of S of the prestressed bond data, the σ of the as-received device data could vary from 2.3 g to 8.3 g without significance at the 95% confidence level. The value S of the later data is 3.3 g, well within limits. Therefore, one can conclude that the two populations are statistically the same in regard to this parameter (and have that conclusion wrong is less than 5% of the cases). Putting this more practically for this application, in a useful over-simplification, one can conclude that the prestressing did not cause significant changes in the distribution of the bonding strengths. Coupled with the previous conclusions regarding the mean value, one can conclude that the bond strength showed no change due to bond testing as far as these tests were concerned.

Similar consideration of the data at 200°C and 250°C was taken. It can be concluded that neither the 200°C nor the 250°C testing revealed any significant changes in the bond strength distribution. Coupled with conclusions regarding the mean values and sigma values above, it can be concluded overall that the bond prestress testing did not significantly alter the bond strengths generally (as regards time and temperature testing).

A series of tests of multiple stressing was conducted using a second nondestructive bond tester.

The one, in which it was attempted to stress the bond with the hook of the instrument for a total of 100 times, showed that 11 out of 13 bonds so stressed failed before the test (of 100) was completed. Damage here is obvious.

The next, in which the bonds were stressed 5 times, yielded 16 (out of 18) survivors. The two losses were replaced, and failure strength tests were made on 18 bonds which had been pre-stressed five times each. The $T.S._{\alpha} = 5.8$ g and $T.S._{\beta} = 6.7$ g for these data. Again, it was shown that the difference of these means from those of the as-received data is statistically not significant at the 95% confidence level.

However, in testing the significance of the standard deviation for the 5 times stressed data, $S_{\alpha} = 29.16$ (for $n = 18$), compared to the value $S_{\alpha} = 1.44$ (for $n = 14$) for as-received bond strength data, it was found that the larger S_{α} is indeed significant, and alteration of the distribution occurred.

In view of the lack of significance of the differences of the mean strength, it may be considered that perhaps the 5 times stressing was not sufficiently controlled (reproducible) or that a large number of other quasi-random factors had influenced the result.

Histograms of the overall data are shown in Figures 22, 23, 24, and 25.

4.0 CONCLUSIONS AND RECOMMENDATIONS

4.1 STATISTICAL CONCLUSIONS

The statistical conclusion can be summed up as follows. In none of the populations analyzed was there a significant difference at the 95% confidence level between means or standard deviation with one exception. The standard deviations, but not the means, of the samples stressed five times, and those not stressed differed significantly, and the standard deviation of the stressed samples was the larger.

These conclusions may be translated into engineering, production, and reliability terms, based upon experience. Overall, the conclusion may be reached that under all the circumstances and controls of the experiments, (with the one exception) the nondestructive bond pulling was not significantly destructive. This conclusion of course is severely restricted; for example, the range of pull forces, the time and temperature excursions, and the type of bond were limited. It is highly indicative, however.

The one exception to the nondestructive quality of the test is, in a way, not surprising and may be considered from several view points. In general, metallurgically there is a significant difference between stressing a wire once and a number of times. Metallurgical phenomena occur: fatigue, work hardening, creep, etc., begin to influence results after a number of workings of a metal. The strength, generally weakened, may actually increase for a period. It is significant that 2/13 bond pairs lasted for 100 tests.

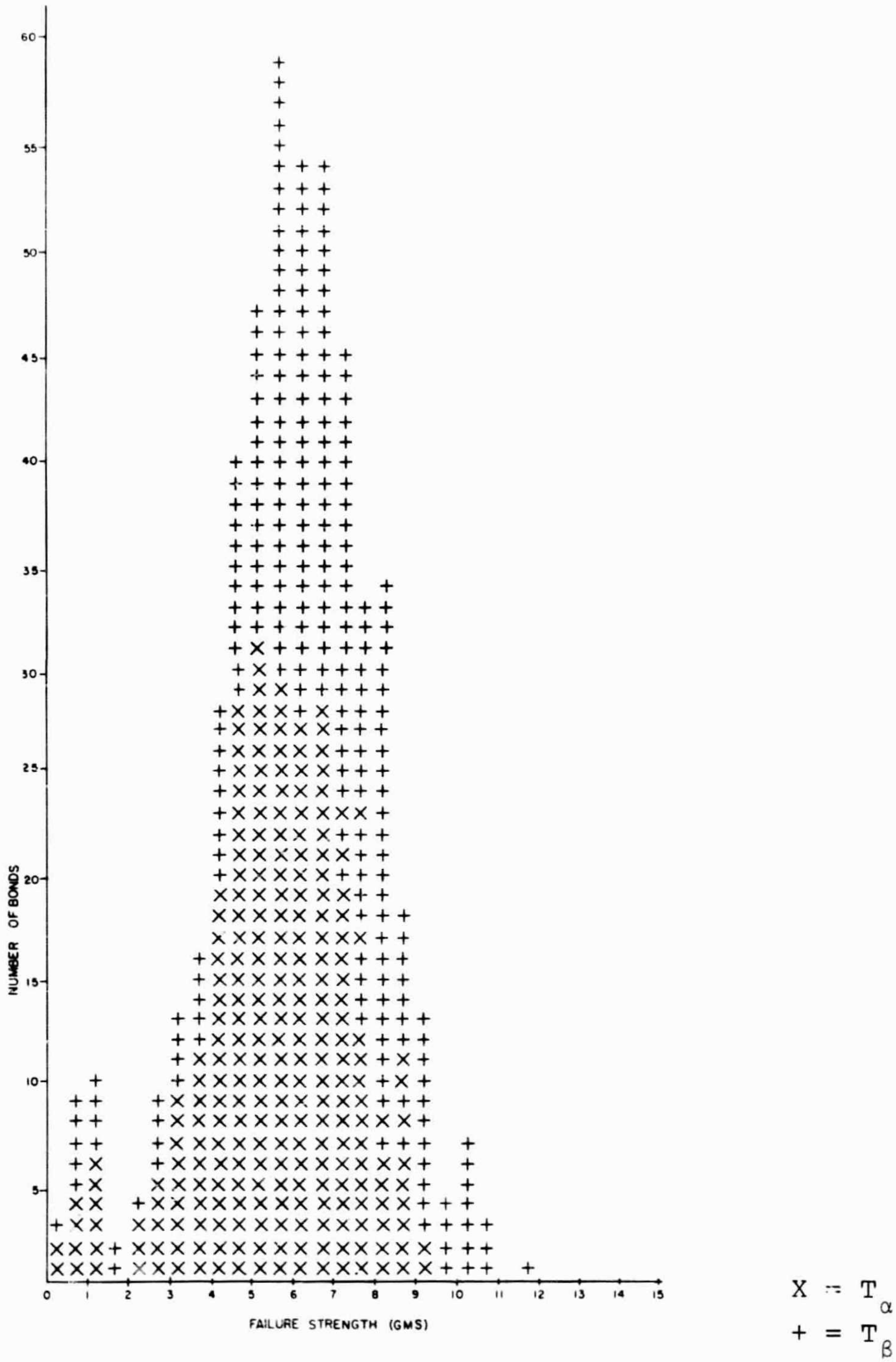


Figure 22. Histogram of Distribution of Failure Strengths of Devices as Received

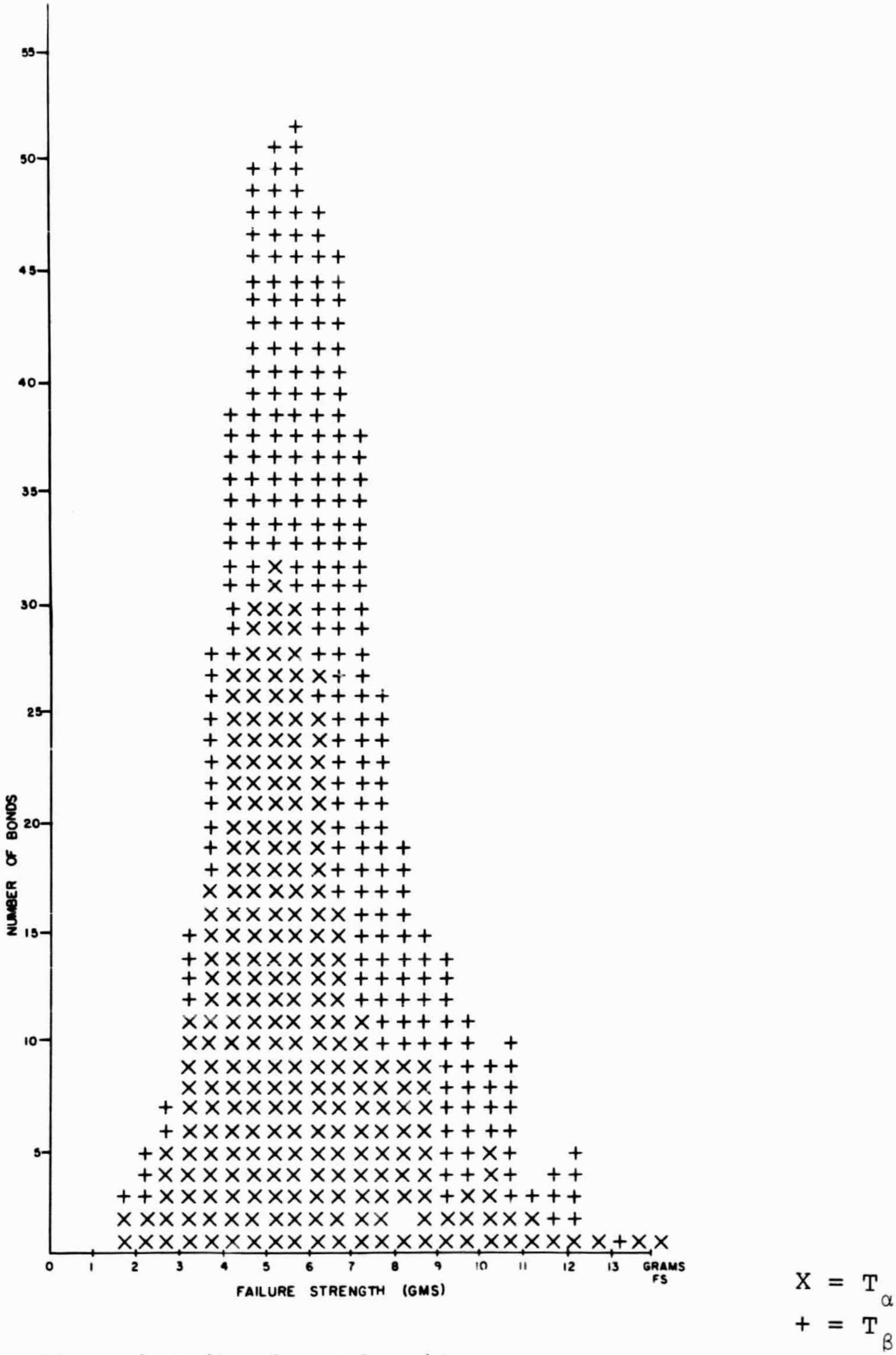


Figure 23. Distribution of Failure Strengths of Prestressed (5 times) Devices.

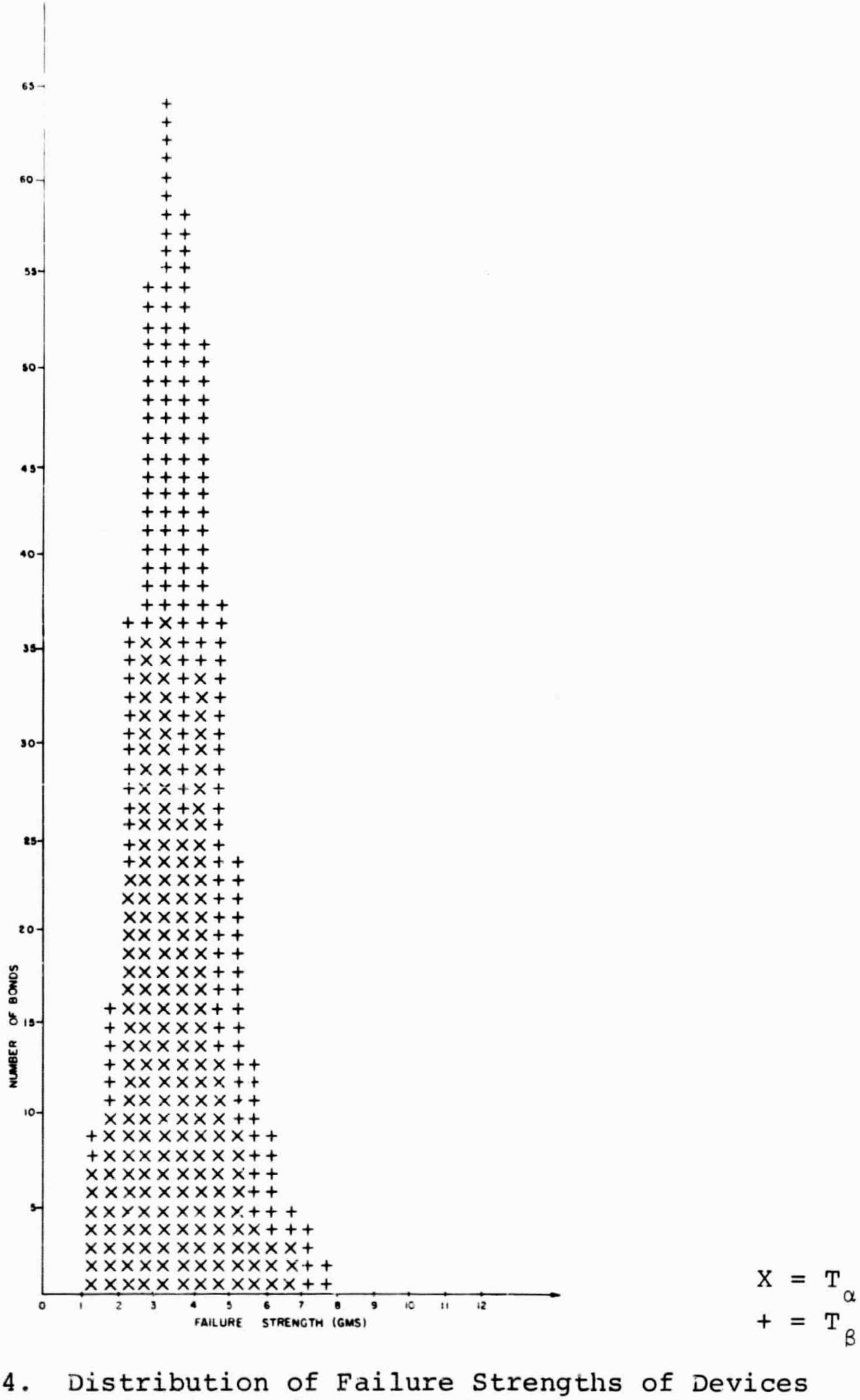


Figure 24. Distribution of Failure Strengths of Devices as Received after Time-Temp. Storage.

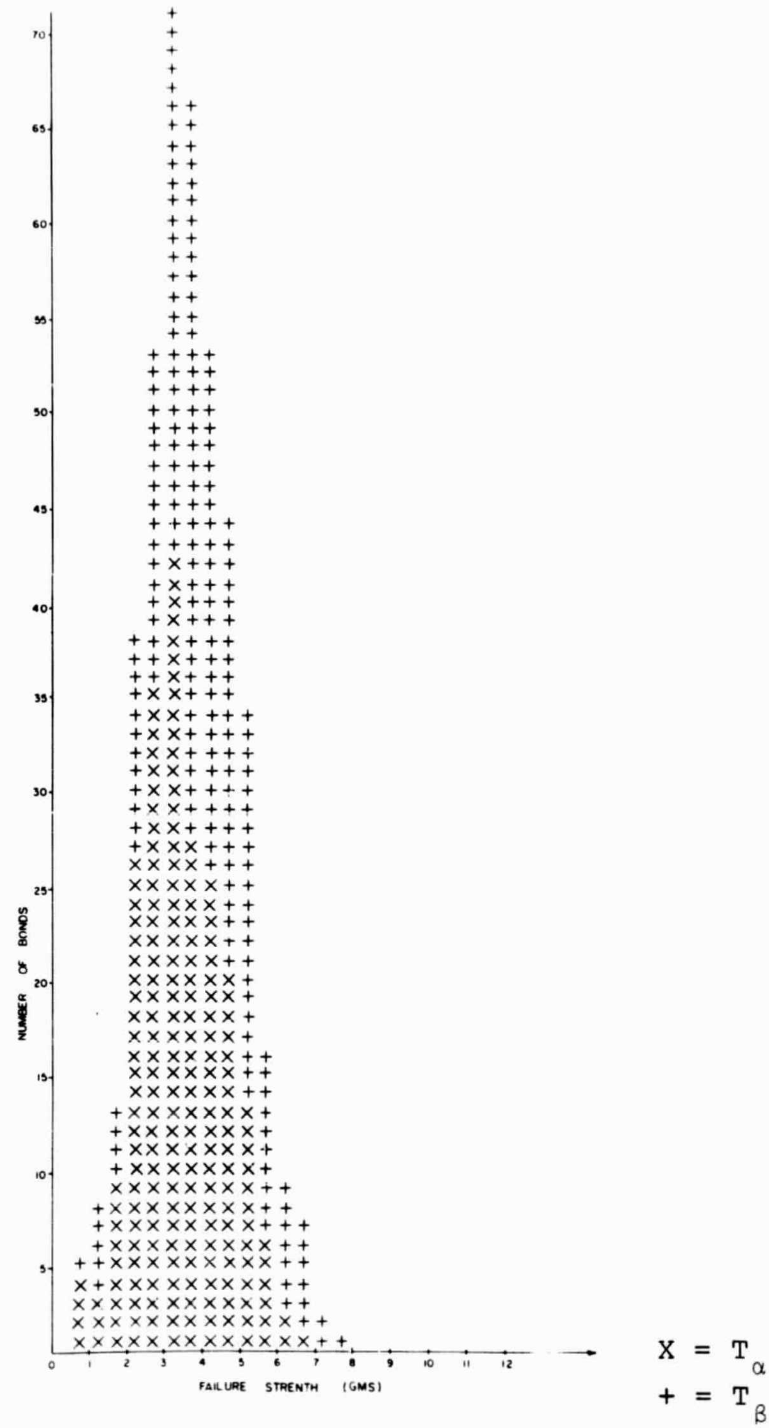


Figure 25. Distribution of Failure Strengths of Pre-stressed (once) Devices after Time-Temp Storage

The spreading of the data, as identified by the larger value of standard deviation, may be due to lack of control in the experiment, in the bond testing equipment itself, or may be due to a large number of factors of opposite trends, none sufficiently significant in itself. It is the latter that is considered operative in the one case of significance of different values.

4.2 PRACTICAL CONCLUSIONS

In view of the above, it has been shown that nondestructive bond testing was successfully accomplished in the course of this work. It can be stated that for the usual conditions found in the semiconductor industry (the limited conditions of these tests), nondestructive bond testing is not only possible but would be very valuable as a reliability tool, so long as precautions are taken as indicated below. Whether the success of nondestructive testing can be extrapolated to other conditions, can only be determined by further testing, as suggested below.

4.3 RECOMMENDATIONS

Certain outstanding precautions are in order. Nondestructive testing must be performed in such a manner as to maintain its nondestructive character. Operator control is essential. Proper maintenance, set-up, and functioning of the machine are a requisite. Frequent check ups are required to assure compliance with these conditions.

Other points are significant. It must be made certain that double testing of bonds of units to be used does not occur. This could happen for example in checking on an operators performance, on machine performance, in sampling or in inspection procedures.

Great care must be taken to determine properly the minimum failure strength of lots; awareness of the differences of technique in bonding, of differences of materials, and of geometry is essential.

A further recommendation is made. Control of bond loops is minimal and consequent control of breaking angles is almost nonexistent in the industry. It is important for more meaningful nondestructive testing of bonds (or for destructive testing of bonds for that matter) that specifications for control of these factors be drawn up, implemented, and adhered to.

The use of nondestructive testing of bonds could bring about improved reliability control, if properly handled, but could also open a Pandora's box of factors leading to poorer reliability if misused.

It is recommended that the following series of experiments be carried out to expand the evaluation of the nondestructive tensile tester to further limits:

(1) Perform the tensile testing and plot the strength frequency distribution of single bonds to the chip and to the post at 90° and 45°.

(2) Perform metallurgical examinations of bonds before and after 1,000 hour static load life test at FSM load.

(3) Perform metallurgical examinations of bonds before and after repeated stressing at FSM.

(4) Plot distribution of bond strengths after repeated stressing.

(5) Complete time-temperature storage tests.

(6) Relate visual rejects of bonds to mechanical testing at FSM.

(7) Perform functional electrical testing both before and after environmental testing such as constant acceleration and thermal shock.

APPENDIX 1

COMMONALITY OF THREE TYPES OF DEVICE

Consider the distribution of the weighted average of the α angular measurements as the population from which samples may be derived and the first moment,

$$\overline{X} = \frac{1}{n}\sum_{i=1}^{n} X_i f_i, \text{ or } m = 19°$$

and the root of second moment about the mean

$$m_2^{1/2} = \frac{1}{n}\sum_{i=1}^{h} \left(X_i - \overline{X}\right)^2 f_i, \text{ or } \sigma = 18.7°$$

degrees as the proper measures of central tendency and variation respectively of a normal population.

Considering for example the 14 measurements of α, as a sample, set up the hypothesis that this sample is indeed derived from the normal population defined above by M = 19 degrees and σ = 18.7 degrees.

In order to test the hypothesis, set up the $\overline{X}$ normal distribution with $M_{\overline{X}}$ = 19 degrees and $\sigma_{\overline{X}} = \frac{18.7°}{\sqrt{14}} \simeq 5°$. The $\overline{X}$ normal curve has approximately 1/4 the spread of the X normal curve. The value of $\overline{X}$ for the α_1 sample is 22°; the corresponding value of the statistical parameter $t = \frac{\overline{X}-m_{\overline{X}}}{\sigma_{\overline{X}}} = \frac{22-19}{5} = .6$. The probability (from a table of normal areas and ordinates) of obtaining a value of $t = \frac{\overline{X}-m_{\overline{X}}}{\sigma_{\overline{X}}}$ derived from the integral $\int_0^t \phi(t)dt$ is $P(t \leq .6) = .22575$. If a significant factor of .05 is used (corresponding to a 95% confidence level), it is clear that the probability of the value of t = .22575, and hence of $\overline{X} \leq 22$ is such that the difference in values is not statistically significant, and the hypothesis is acceptable.

The above is validated procedurally by the following considerations. The sample mean is:

$$\overline{X} = \frac{\sum_{1}^{n} X_n}{n}$$

In repeated samples, each X_i is a variable and in repeated samples $\overline{X}$ also is a variable. The moment generating function of $\overline{X}$ is:

$$M_X(\theta) = M_{[X_1 + \cdots + X_n]}(\theta) = M_{X_1 + \cdots X_n}\left(\frac{\theta}{n}\right)$$

The sampling is random so that the variables X_i are independent. Hence,

$$M_X(\theta) = M_{X_1}\left(\frac{\theta}{n}\right) M_{X_2}\left(\frac{\theta}{n}\right) \cdots\cdots M_{X_n}\left(\frac{\theta}{n}\right) M_{X_i}\left(\frac{\theta}{n}\right) .$$

Note that each term on the right is a moment generation function of the variable X. Thus,

$$M_X(\theta) = M_{\mathbf{x}}^{n}\left(\frac{\theta}{n}\right)$$

Now, for X normally distributed

$$M_{X-m}(\theta) = e^{\frac{\sigma^2 \theta^2}{2}}$$

and

$$M_X(\theta) = e^{m\theta + \frac{\sigma^2\theta^2}{2}}$$

Hence,

$$M_{\overline{X}}(\theta) = \left[e^{m\frac{\theta}{n} + \frac{\sigma^2}{2}\left(\frac{\theta}{n}\right)^2}\right]^n = e^{m\theta + \frac{\sigma^2}{n}\frac{\theta^2}{2}}$$

It is clear that if X is normally distributed with mean M and standard deviation σ and random samples of size N are drawn, the sample mean $\overline{X}$, will be normally distributed with mean M and standard deviation $\sigma/\sqrt{N}$.

APPENDIX 2

DISTRIBUTION OF AND CONFIDENCE LIMITS FOR σ^2

If X is normally distributed with zero mean and unit variances, the sum of the squares of N random samples has a χ^2 distribution with n degrees of freedom. This is shown by considering the χ^2 function

$$f\left(\chi^2\right) = \frac{1}{2^{\nu/2}\,\Gamma\left(\frac{\nu}{2}\right)}\left(\chi^2\right)^{\frac{\nu-2}{2}} e^{-\chi^{2}/2}$$

in which ν is the number of degrees of freedom (Γ is the well-known gamma function). By using the moment generating function for the X^2 distribution,

$$M_{\chi^2}(\theta) = (1 - 2\theta)^{-\nu/2}$$

in a manner similar to that of Appendix I, it can be seen that if X is normally distributed with variance σ^2 and S^2 is the sample variance based on a random sample of size N, then NS^2/σ has a χ^2 distribution with N-1 degrees of freedom.

From a table of the distribution values of χ^2, the confidence limits on σ^2 may be determined for a sample and population as defined above. For 95% confidence limits, two values of χ^2, χ_1^2 and χ_2^2 are found (for N-1 degrees of freedom) such that the probability is 0.975 that $X^2 > X_1^2$ and is 0.025 that $X^2 < X_2^2$. Thus, the probability is 0.95 that $\frac{NS^2}{2}$ is bounded by X_1^2 and X_2^2 or that the confidence limits is 95% that the σ^2 is bounded by the values $\frac{NS^2}{X_1^2}$ and $\frac{NS^2}{X_2^2}$.

A similar consideration in reference to the F distribution

$$f(F) = \frac{\sigma F^{\nu_1 - 2/2}}{(\nu_2 + \nu_1 F)^{\nu_1 + \nu_{2/2}}}$$

leads to the use of the F distribution to test the compatability of two variances.

APPENDIX 3

TENSILE TESTER

A meaningful technique for the tensile testing of wire bonds would be one utilizing a microtensile tester which would (1) allow the breaking angles α and β to be equalized before the breaking load is applied, (2) record the breaking force at the moment of wire fracture, (3) permit the measurement of the inherent tensile strength of the raw wire, and (2) perform the tensile testing at a constant and repeatable rate.

We have such a tensile tester in our laboratory and it was once hoped that it could be used to promulgate a standard technique for the meaningful evaluation of the quality of wire bonds.

Curves have been developed for the determination of tensile strengths, breaking loads and breaking angles when the breaking angles have been equalized, and these curves are included in this appendix as Figures 26, 27 and 28.

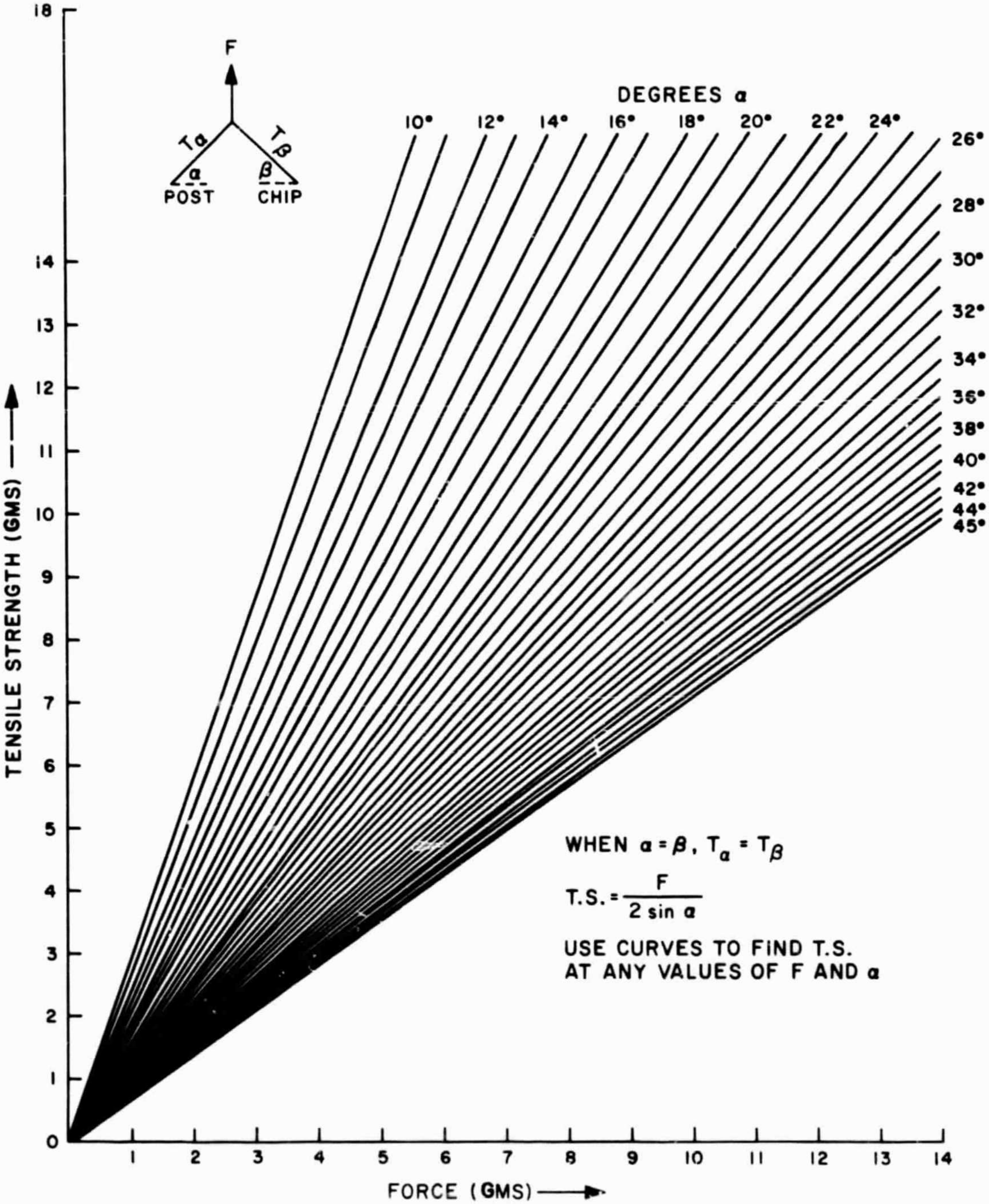


Figure 26. Curves to Find T.S. at any Value of F and α.

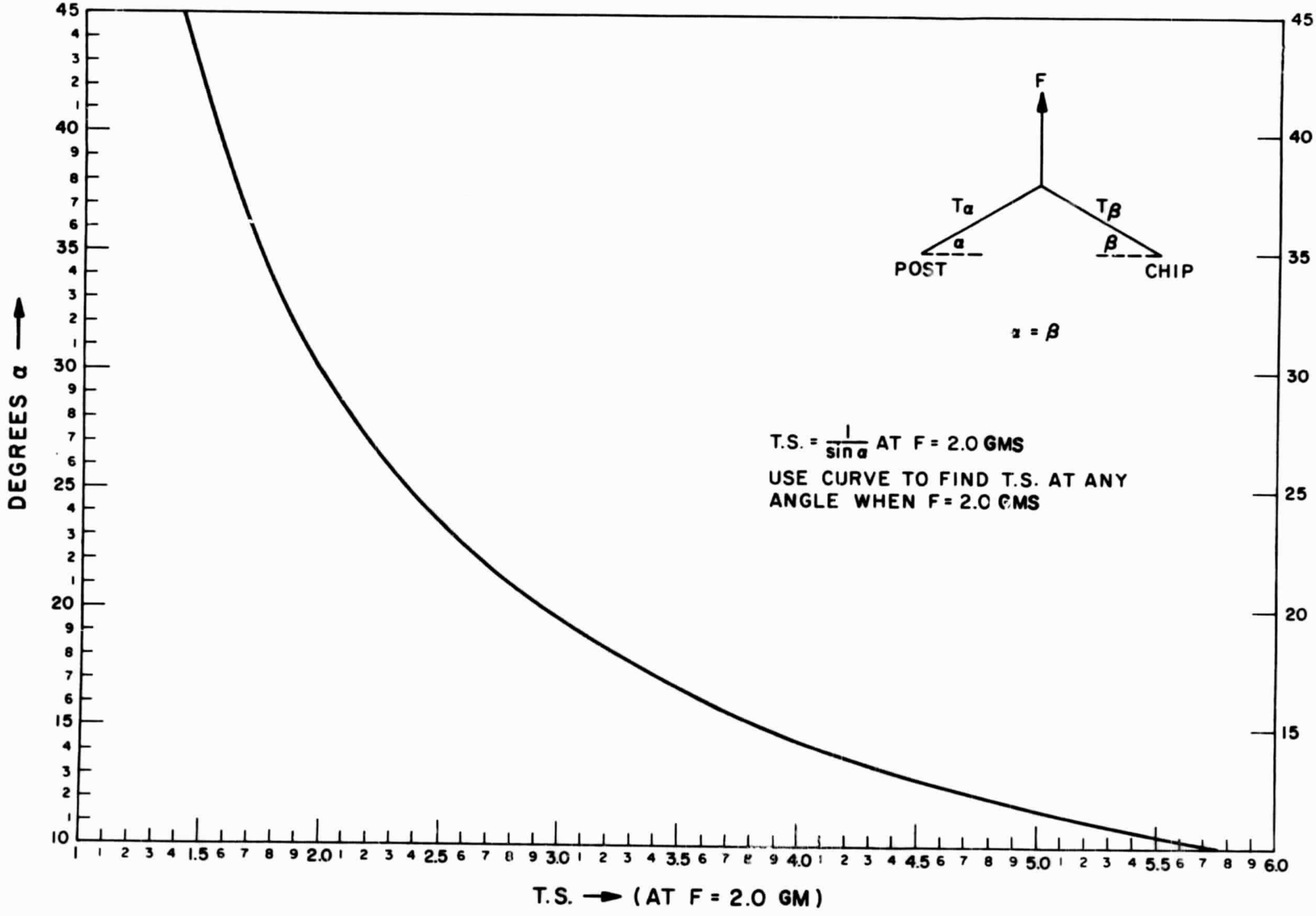


Figure 27. Curve to Find T.S. at any Angle when F = 2.0gms.

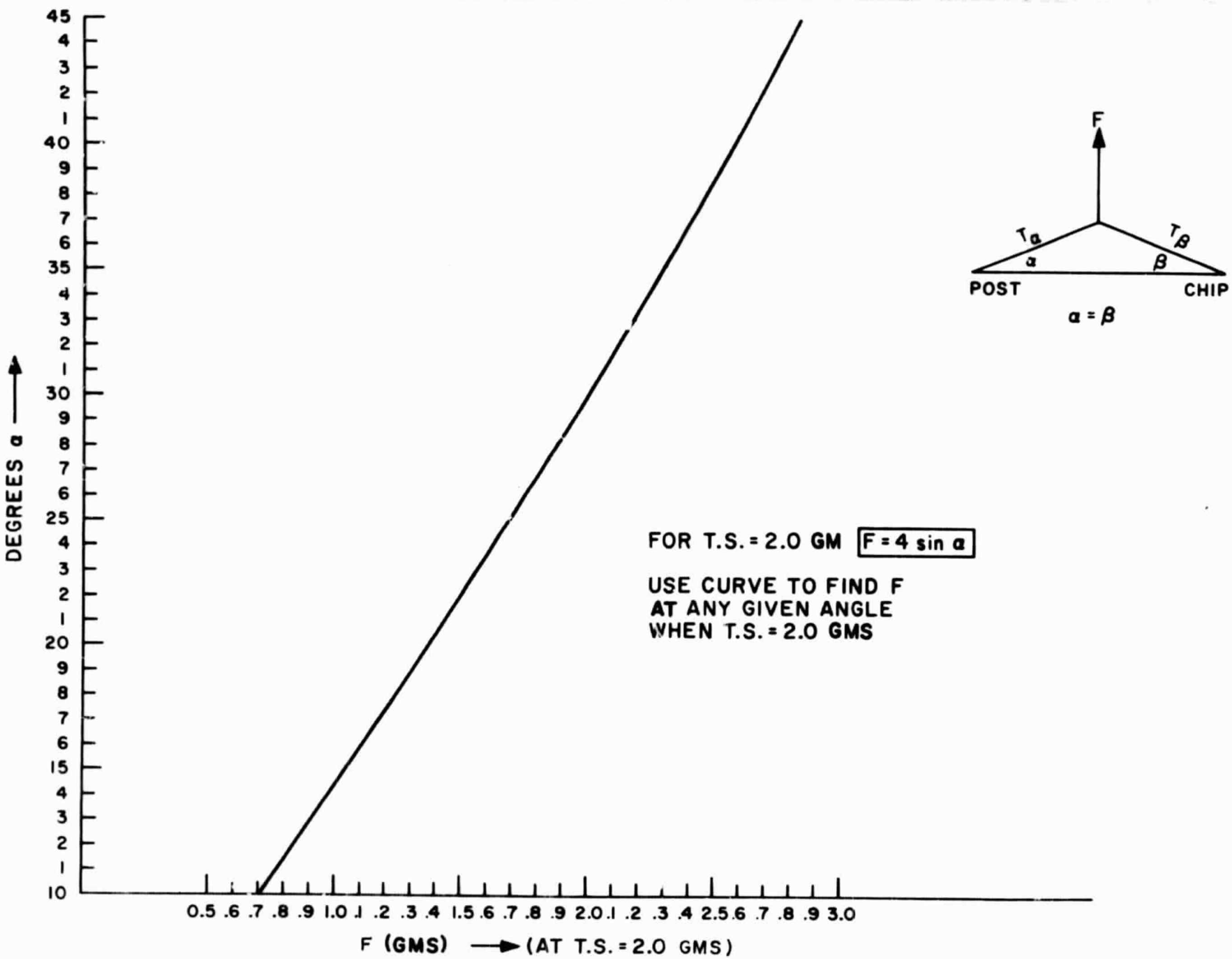


Figure 28. Curve to Find F at any given Angle when T.S. = 2.0 gms.