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COMPILATION OF MECHANICAL PROPERTY DATA FOR IMPROPERLY QUENCHED (SOFT) ALUMINUM PLATES

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July 1981

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This technical report has been reviewed and is approved for publication.

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Data is summarized from a number of investigations that dealt with the overall issue of substrength aluminum plates. An improper heat-treatment resulted in localized areas of the plates with low mechanical properties. For these plates it is shown that: tensile, compression, and bearing strengths are significantly reduced; fatigue properties are reduced, particularly for 2000-series alloys; fatigue crack growth rates are faster in 2000-series alloys but may be slower in high strength 7000-series alloys; stress corrosion properties are not

DD FORM 1473, 1 JAN 73 EDITION OF 1 NOV 65 IS OBSOLETE reduced; toughness may increase; and the loss of strength can be reflected in electrical conductivity and hardness readings. The report also contains a statistical evaluation of tensile data from this study and other sources relating yield and ultimate tensile strength with electrical conductivity and hardness.

PREFACE

This report was prepared by the Materials Integrity Branch (AFWAL/MLSA), Systems Support Division, Materials Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio.

The work was conducted under Project 2481, "Metallic Structural Materials," Task 241807, "Systems Support for Metallic Materials Applications."

This report was submitted by the authors in January 1981.

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SECTION I

INTRODUCTION

A number of improper processing conditions can produce low tensile strength in wrought aluminum alloy products. One of these is an improper heat treatment which could result in substrength properties existing throughout a plate, forging, or extrusion, or, depending on the cause of the improper heat treatment, could result in localized areas of inferior strength. Recent events have shown that the latter of the two possibilities can occur and presents a significant threat to the structural integrity of aerospace systems.

If substrength areas (soft spots) exist in a plate, as opposed to a plate being completely soft, the possibility exists that the localized inferior material will not be detected during inspection for acceptance/rejection and the plate could ultimately be machined into a component and used in a structure. Although there is no proof that this has ever occurred, it is known that soft material has been found in components that were being prepared for fabrication into a structure.

Recent investigations, References 1 through 4, dealt with the problem of soft spots in high-strength structural aluminum plates that were caused by a defective quench system that was used at the end of the solution heat treatment. These studies were published as separate research efforts over a year's time, although each dealt with the same subject. In order to systematically organize the data and results and to consolidate the separate efforts, this report was prepared and is based on the cited references plus new data not previously documented. These new data are correlations between NDI measurements (hardness and conductivity) and strength properties.

The type of defect investigated was soft spots or local substrength regions that existed on one side of aluminum plates. The soft spots generally covered a small portion of the plate and had varying properties that consisted of very low tensile properties near the center of the spot which slowly increased going away from the center of the region until normal properties were again present. The same trend in properties existed through the thickness with the surface containing the spot possessing the lowest properties and the opposite side of the plate having normal properties. All of the anomalies came from one heat treating facility of a major aluminum supplier.

The discovery of these defects in plates that were in the inventories of aerospace manufacturers caused considerable concern in the DoD. As a result, it was mandated that all plates greater than one inch thick that came from the one supplier had to be inspected. This requirement encompassed all plates in the inventories and also uninstalled components machined from the plates.

SECTION II

OVERVIEW OF DATA

The data and results obtained in the reference works were intended to identify and quantify those properties that were affected by the substrength conditions and to develop an index of how the property losses could be inferred from nondestructive inspection (NDI) values. The first of the two tasks was addressed by performing a major test program on samples removed from substrength areas of aluminum plates. For every specimen that was removed from the soft side of a plate there was generally a companion specimen removed from the opposite (normal) side to serve as a baseline. All specimens were checked for hardness and electrical conductivity which were used to index the degree of softness and also to contribute to a data base of hardness and conductivity versus tensile properties. Additional data from industry were used in this latter effort in order to insure that the NDI/strength correlations that were developed were meaningful. Hardness and electrical conductivity measurements are extensively used throughout the aerospace industry to check for proper heat treatment and strength in aluminum alloys.

The properties that were investigated were those that could be expected to affect the flight safety of aerospace systems. In particular, those properties required for implementation of MIL-STD-1530, Aircraft Structural Integrity Program, Airplane Requirements, were catalogued. The majority of the material samples evaluated were tested for only their tensile properties; however, a sufficiently large data base was collected for other properties to develop indicators of how and to what degree they were influenced by the improper heat treatment.

Inasmuch as this report is intended to be a compilation of data, as opposed to a report on a specific test effort, items such as specimen configuration and testing procedures will not be identified. Only information necessary for an understanding and interpretation of the results will be defined and discussion will be limited to only the major findings of the various efforts.

Listed throughout the figures and tables are specification values which are generally values from MIL-HDBK-5, Metallic Materials and Elements for Aerospace Vehicle Structures. Hardness and conductivity values are recommended limits published by the Society of Automotive Engineers, Inc., in a draft of an Aerospace Materials Specification, AMS 26GB-1. Hardness is specified in terms of the Rockwell B scale, R_B, and electrical conductivity is defined as a percentage of the conductivity of the International Annealed Copper Standard, %IACS.

In the text, tables, and figures, the specimens from the improperly quenched areas of the plates are referred to as soft, substrength, and affected while the specimens removed from the properly quenched side are identified as normal and baseline.

SECTION III

MECHANICAL PROPERTIES

The format of the presentation will be by test types and then by individual plates. The one plate that was tested most extensively is a plate of 2124-T851, which received a thorough evaluation of all significant properties.

1. TENSILE

a. 2124-T851, 5-1/2 inch thick.

Tensile specimens were removed from this plate in the longitudinal and transverse direction. In addition, a stack of samples with longitudinal orientation was removed at selected distances through-the-thickness of the plate to obtain a profile of how the strength varied from the affected (soft) to the normal (baseline) side. Tables 1, 2, and 3 and Figure 1 show the results of these tests where it can be seen that the strength is significantly reduced in the soft area and that the electrical conductivity and hardness both reflect the change in strength. The maximum loss in yield strength relative to the specification values is on the order of 40 percent. In Figure 1, the trend lines through the conductivity and hardness data have the same shape as the lines representing the tensile data (electrical conductivity is inversely related to strength) showing the applicability of these methods for ascertaining strength.

b. 2124-T851, 2-3/4 inch thick.

Three tensile specimens were removed from each side of the plate and the results are shown in Table 4, where it can be seen that two of the three specimens from the soft side possessed properties that were below the specification values. Note that conductivity was within recommended limits for these two specimens, indicating a review of the recommended limits or additional criteria are needed.

c. 2124-T851, normal thick plate.

Two plates of 2124-T851 which had been properly produced were used to obtain typical data reflecting normal through-the-thickness strength, hardness, and conductivity variation in such products. The results are presented in Table 5 and Figure 2 which were obtained from a stack of specimens, with longitudinal orientation, removed from each plate. It can be seen that the strength is lowest in the center and increases toward the surfaces of the plate, and, again, the two NDI measurements follow this trend. This indicates that parts machined from normal thick plates will have inherent through-the-thickness variations in these properties.

d. 2024-T351, 2 inch thick.

Longitudinal tensile specimens were removed from the two surfaces of this plate plus from the mid-thickness. All data (Table 6) except for some of the conductivity values were within recommended specifications. The fact that this plate was suspect may have been caused by a very shallow soft spot which is possibly indicated by the rather large variations in conductivity readings for the specimens removed from the suspected soft side.

e. 7075-T651, 1-1/4 inch thick.

This plate had a set of specimens removed and tested after which it was observed that the possibility existed that there were soft areas on both sides of the plate. Additional specimens were then removed from the plate to confirm this suspicion. Table 7 and 8 present the results from the first series of tests and Table 9 presents the data from the second group of specimens. It can be observed that the soft spots did exist on both sides of the plate even though the conductivity readings were all within recommended specifications, again pointing out the need for additional criteria for this property.

f. 7075-T7351, 4 inch thick.

Longitudinal (Table 10), transverse (Table 11), and a stack of longitudinal specimens (Table 12), were removed from this plate. All tensile values were very close to or above specification minimums for 2.5 - 3" material (no specification values are available for 4 inch thick material although the trend is for the specification values to decrease with increasing thickness). Much of the conductivity data is below the recommended range while the hardness readings are generally above the minimums. The conductivity criteria again becomes suspect.

g. Summary of Tensile Results.

Improperly quenched aluminum plates can have tensile properties that are signficantly below minimum values. Substrength properties can exist to a significant depth into a plate that experienced a localized improper quench on one side. One of the major quality control (QC) nondestructive inspection methods for examining aluminum plates for proper strength (electrical conductivity) has been shown to be in need of additional acceptance criteria. The data in this report, coupled with other data from other sources, was used to devise such a criterion for use by the DoD. Present requirements state that in addition to electrical conductivity readings being within the range for an alloy-heat treatment combination, all readings from one side of a plate cannot vary by more than two percent IACS.

2. COMPRESSION

Only one plate was evaluated for its compression properties, namely the 5-1/2 inch thick sample of 2124-T851. The results, shown in Table 13, indicate a significant strength reduction occurs in compression; at least as great as the reduction that can occur in tension.

3. BEARING

Bearing specimens with E/D = 2 were removed from the 5-1/2 inch thick 2124-T851 plate. Table 14 presents the results obtained with these specimens, which display significant reductions in load carrying capability for the soft material. These results reflect the loss of tensile and compression strength reported in the foregoing.

4. TOUGHNESS

Four inch wide compact type specimens were used to obtain the crack growth resistance curves for the 5-1/2 inch thick 2124-T851 plate as shown in Figure 3. The trend lines indicate there is not a loss in crack growth resistance and there might be some increase in the resistance curve for the soft material in this alloy and temper.

5. CONSTANT AMPLITUDE FATIGUE

a. 2124-T851, 5-1/2 inch thick.

The 5-1/2 inch thick 2124-T851 plate was checked for its constant amplitude fatigue properties. The results for smooth and notched tests are shown in Figures 4 and 5, respectively. The smooth data indicates there is little or no effect of softness on the unnotched fatigue life and the literature data scatter band confirms this. The notched results indicate there may be some influence on the fatigue life. To confirm this observation, the notched data in Figure 5 are replotted in Figures 6 and 7 as electrical conductivity and hardness versus cycles to failure where it can be readily observed that a strong correlation exists between NDI measurements and life, particulary at the higher stress. It can be concluded that fatigue properties of 2124-T851, at least in the notched condition, are affected by an improper quench.

b. 7075-T651, 4-1/2 inch thick.

Two plates of 7075-T651 were used for notched constant amplitude fatigue testing with the results shown in Figure 8 as conventional S-N data and re-plotted in Figures 9 and 10 as conductivity and hardness, respectively, versus cycles. A much steeper slope for the data fit can be seen for these data compared to that for the 2124-T851 indicating less of an effect of softness on 7075 notched fatigue properties.

6. SPECTRUM FATIGUE

a. 2124-T851, 5-1/2 inch thick.

Notched spectrum fatigue specimens with transverse orientation were machined from the broken halves of the R-curve specimens. The results in Figures 11 and 12 are presented as NDI measurements versus flights to failure. The spectrum used was a standardized spectrum which was developed by several European countries using flight recordings from a number of aircraft. It is known as FALSTAFF, Fighter Aircraft Loading STAndard For Fatigue. It can be seen in the figures that a strong dependence exists between flights to failure and the NDI measurements (which are indicators of strength) which, of course, substantiate the findings from the notched constant amplitude tests.

b. 7075-T651, 4-1/2 and 2 inch thick.

Specimens from these plates were subjected to the same spectrum as discussed in the foregoing and the results are shown in Figures 13 and 14. Correlations between the NDI measurements and flights to failure are not as strong for these data. The trend lines are much steeper, demonstrating less of an effect of the softness than for the 2124. This is the same as was concluded for the constant amplitude data; soft 7075-T651 experiences less of a loss of fatigue life than 2124-T851.

7. CONSTANT AMPLITUDE FATIGUE CRACK GROWTH

Compact type specimens removed from a 5-1/2 inch thick plate of 2124-T851 were tested at a stress ratio, R, of 0.1 to obtain the results shown in Figures 15 and 16. There is a slightly faster growth rate for the affected specimens at the lower stress intensities and almost no difference at the higher stress intensities. The maximum difference is about a 50 percent faster growth rate near the lower end of the data sets.

8. SPECTRUM FATIGUE CRACK GROWTH

a. 2124-T851, 5-1/2 inch thick.

A spectrum representing a location on a fighter aircraft was used to test center cracked panels made from a 5-1/2 inch thick plate of 2124-T851. The spectrum represented 1000 hours of flight (one hour is approximately equal to one flight) and one time through the spectrum was called a pass. Figure 17 presents the results in terms of total crack length versus passes through the spectrum. The same data are replotted in Figure 18 as crack growth per pass versus the maximum stress intensity during a pass (which occurs one time during each pass). It can be seen that the affected specimen had an approximately 40 percent faster growth rate throughout the range of the data. This is about the same as the maximum difference in the constant amplitude data.

b. 2024-T351, 4 inch thick.

Four inch wide center cracked panels of 2024-T351 were subjected to a cargo/transport spectrum known as TWIST, Transport WIng STandard. This spectrum is much less severe than a fighter aircraft type spectrum and is composed of 4000 flights which vary in intensity from stormy to tranquil. The results of the tests are shown in Figure 19, where it can be seen that the soft specimen that underwent a normal test had a significantly shorter life than the baseline specimen. The large jumps in the data for the baseline specimen occur at places in the spectrum where major peak load excursions occur. These results for the 2024 are similar to the results for the 2124 presented previously; soft material has less resistance to spectrum fatigue crack growth than normal material.

c. 7075-T651, 1-3/4 inch thick.

The TWIST spectrum was used to test 7075-T651 center cracked panels at two different maximum spectrum stress levels as noted in Figures 20 and 21. The results are completely reversed from those obtained for the 2000-series alloys shown previously. That is, the soft 7075-T651 had longer lives and slower growth rates. It is apparent from these results, coupled with the fatigue results presented previously, that soft 7075-T651 presents less of a threat than 2024 or 2124 to structural integrity in fatigue applications.

9. STRESS CORROSION

Round corrosion specimens were removed from the 5-1/2 inch thick plate of 2124-T851 and tested in a 3.5 percent NaCl solution which was alternately applied; 10 minutes in the solution then 50 minutes in air. The results in Table 15 show that at 75 percent of the yield strength the specimens lasted 600 hours without failure which indicates there is no corrosion problem associated with soft aluminum in this alloy/temper.

10. STRESS CORROSION CRACKING

Precracked compact type stress corrosion cracking specimens again using the 2124-T851 material were tested in a 3.5 percent NaCl solution with the results shown in Table 16. These results indicated, as did the previous results from smooth specimens, there is no corrosion problem with the soft material in this alloy/temper.

11. OTHER PROPERTIES AND FINDINGS

Two other types of tests were performed which used single lap shear specimens of 2124-T851 in which the lap was held together with four fasteners in a rectangular configuration. Tensile testing of this simulated structure specimen showed that the joint had reduced load carrying capacity, as would be expected from the tensile and compression data. Fatigue tests, which were performed on the same configuration of specimen, did not show a degradation of life, but it can be concluded from other findings, notably the fatigue data, that life will be reduced.

Chemical analysis did not reveal any difference in the constituents in the soft material while a microstructural evaluation revealed a difference in precipitate size and spacing.

SECTION IV

CORRELATION OF PROPERTIES

A comprehensive data accumulation and analysis effort was performed on available mechanical property and supporting data (i.e. hardness and electrical conductivity) from many aerospace contractors and also the material supplier and government laboratories. Three basic needs were served by the results of the analysis:

1. Developed an initial "quick look" to determine if the levels of hardness and conductivity set by the draft AMS specification on aluminum alloys 26GB-1 were applicable for the material screening effort.

2. Provided documented guidance to the Aeronautical Systems Division on the maximum level of degradation to be anticipated in the various structural alloys evaluated. Various flight critical parts and locations in the aircraft were then evaluated to see if this level of degradation would cause a safety-of-flight problem or if it would involve any mission curtailment.

3. Supplied data for comparison to the current material acceptance criteria to determine if the specifications needed to be changed to preclude purchase of unacceptable material. Present military specifications for aluminum alloys require a tensile test on each lot of material and widely spaced electrical conductivity tests on the ends and centerline of the master plate.

While the full range of aerospace structural alloys was surveyed for this analysis effort only four alloys had sufficient data available to use a statistical interpretation. These alloys were 2124-T851, 2024-T351, 7075-T651, and 7075-T7351, which covers the range of strength levels currently used in airframe structures.

One of the immediate concerns of this analysis effort was to evaluate the "sorting" capability of the electrical conductivity and hardness tests. The initial task after the soft aluminum problem was defined was to examine all warehoused plates and uninstalled parts made from plate, using electrical conductivity as the primary screening technique. It was discovered that due to equipment variances, alloy chemistry variances, and even processing variables, that simply specifying an allowable range for conductivity was not sufficient for detecting soft spots. Therefore, the inspection criteria were modified by ASD to include an additional criterion that all readings on one side of a plate could not vary by more than two units of measurement, i.e., 2% IACS. The maximum conductivity limits that were used during this period generally conformed to the AMS draft specification 26GB-1.

As the data accumulation effort continued, periodic releases of the information were made to give interested government and contractor personnel the most up-to-date information for their evaluation efforts. The data presented in this report is the final update on these data sets. The data will be presented in the following order for each alloy: ultimate strength versus electrical conductivity, yield strength versus electrical conductivity, ultimate strength versus hardness, and yield strength versus hardness.

On each of the Figures 22-37, a mean line has been determined by using a second order polynomial curve fitting procedure. A one sided 90 percent confidence line about that mean is also displayed. The 90 percentile level was chosen to be relatively conservative and have the same statistical significance as MIL-HDBK-5 "B" values.

The data as presented do not represent the full range of strength to condutivity or hardness comparisons. All of the data inputs were from plates with soft areas and represent the correlations generally obtained by through the thickness scans from the soft areas to the unaffected areas. Inclusion of a large bulk of "normal" material data could alter the upper end of the comparison curves and a larger data set from soft aluminum could affect the shape of the whole curve. However, the data in the figures provided a basis for the inspection of plate already manufactured and will also be used to guide modifications of material purchase specifications and set realistic inspection criteria for future procurements.

A method of presenting the through the thickness degradation is shown in Figures 38 and 39. A lower bound line on the data was used for worst case structural analyses by ASD personnel. The percent thickness curves are displayed for the 5-1/2" to 6" thick 2124-T851 alloy only. Many thicknesses were involved in each alloy and each range required a separate evaluation. The thick plate 2124 had the most input data and was typical of the types of summary plots furnished to ASD. Some late arriving data can be seen to fall below the Design Check Curves, but the overall effect of these additional data did not justify making changes to these curves.

It should be noted that the purchase specification strength levels are based on MIL-HDBK-5 "A" values which are set at a 99 percent reliability with a 95 percent confidence level. Therefore, on a graph which shows a specification strength level, normally, less than one percent of tested materials would have strengths less than this value.

SECTION V

CONCLUSIONS

Based on a review of the information presented in References 1 through 5, the following general conclusions can be drawn about the mechanical properties of wrought aluminum alloy products that experience a localized or full surface slow quench following the solution heat treatment:

1. Strength properties, tension, compression, and bearing can be significantly reduced.

2. Fatigue lives can be shortened and it appears that 2000-series alloys experience a greater loss of fatigue life than 7000-series alloys.

3. Fatigue crack growth rates in soft 2124-T851 and 2024-T351 are faster while soft 7075-T651 has better resistance to fatigue crack growth.

4. Stress corrosion properties are not affected.

5. Toughness appears to increase.

6. The loss of strength can be tracked very accurately for a given plate of material by both electrical conductivity and hardness. However, when a large amount of such data is plotted together there is significant scatter in the results.

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TABLE 1

LONGITUDINAL TENSILE DATA,
2124-T851 5.50" PLATE

	SPEC. NO.	UTS, KSI	YIELD, KSI	ELONG, %	RA, %	HARDNESS, R_B	EC, % IACS*
SOFT SIDE, LONGITUDINAL	TL-1A	44.5	32.8	8.7	20.6	40/36	46/46
	TL-2A	44.8	33.6	9.1	18.9	48/39	46/46
	TL-3A	44.9	32.7	8.3	23.3	39/36	46/46
	TL-4A	48.9	37.5	7.7	24.6	50/47	45/45
	TL-5A	50.5	38.5	8.5	24.9	48/58	45/44
	TL-6A	49.1	37.4	8.6	19.6	49/47	45/45
	TL-7A	48.4	36.2	8.4	27.2	47/47	45/45
	TL-8A	49.6	37.6	8.5	22.3	47/48	45/45
	TL-9A	49.3	37.1	8.8	24.5	47/49	45/45
	TL-10A	50.9	39.2	8.3	25.2	47/54	45/45
	AVERAGE	48.1	36.3	8.5	23.1	46.2	45.2
	σ n-1	2.43	2.37	0.37	2.70	5.59	0.54
SPECIFICATION		63	54	5	--	74	35.0-42.5
NORMAL SIDE, LONGITUDINAL	TL-1B	69.1	61.3	7.4	20.4	77/74	41/41
	TL-2B	69.6	61.8	7.2	17.7	78/77	41/41
	TL-3B	69.5	61.3	7.7	18.0	75/74	41/41
	TL-4B	68.8	60.8	7.4	12.5	75/74	41/41
	TL-5B	69.6	62.0	7.2	13.1	77/79	41/41
	TL-6B	69.8	61.9	7.1	20.8	79/80	41/41
	TL-7B	69.7	61.8	8.4	17.4	79/80	41/41
	TL-8B	69.5	61.4	6.6	15.6	80/80	41/41
	TL-9B	70.1	62.2	8.1	17.4	80/80	41/41
	TL-10B	70.3	62.1	7.6	18.0	79/79	41/41
	AVERAGE	69.6	61.7	7.5	17.1	77.8	41.0
	σ n-1	0.43	0.44	0.51	2.71	2.26	0.00
SPECIFICATION		63	54	5	--	74	35.0-42.5

* IACS: International Annealed Copper Standard

TABLE 2

TRANSVERSE TENSILE DATA,
2124-T851 5.50" PLATE

	SPEC. NO.	UTS, KSI	YIELD, KSI	ELONG., %	RA, %	HARDNESS, R_B	EC, % IACS
AFFECTED SIDE, SOFT, TRANSVERSE	TT-1A	47.2	31.1	8.2	13.7	53/42	45/45
	TT-2A	44.5	27.3	9.6	20.3	39/38	46/46
	TT-3A	46.3	29.2	9.5	15.3	53/40	45/45
	AVERAGE	46.0	29.2	9.1	16.4	44.2	45.3
SPECIFICATION		63	54	4	--	74	35.0-42.5
NORMAL SIDE, TRANSVERSE	TT-1B	69.3	61.6	6.9	9.3	77/79	41/41
	TT-2B	69.4	61.7	5.4	8.8	79/78	41/41
	TT-3B	69.1	60.5	7.7	10.1	79/79	41/41
	AVERAGE	69.3	61.3	6.7	9.4	78.5	41.0
SPECIFICATION		63	54	4	--	74	35.0-42.5

TABLE 3

TENSILE TRAVERSE THROUGH THE THICKNESS,
LONGITUDINAL, 2124-T851, 5.50" PLATE

DEPTH FROM SOFT SIDE (")	SPEC NO.	UTS, KSI	YIELD, KSI	HARD., R_B	EC, % IACS
1/8	TL-2-A	44.8	33.6	48/39	45.8
3/4	TL-2-1	44.9	33.8	44/38	45.3
1-1/4	TL-2-2	56.9	48.0	60/64	42.5
1-3/4	TL-2-3	58.5	49.8	65.5	42.4
2-1/4	TL-2-4	59.7	51.4	68.5	42.2
2-3/4	TL-2-5	59.8	51.9	69	42.2
3-1/4	TL-2-6	60.4	50.3	68.5	42.2
3-3/4	TL-2-7	62.4	52.4	70	42.1
4-1/4	TL-2-8	64.6	55.1	74	41.8
4-3/4	TL-2-9	67.8	59.3	77	41.2
5-3/8	TL-2-B	69.6	61.8	77.5	41.0
SPECIFICATION		63	54	74	35.0 - 42.5

TABLE 4

LONGITUDINAL TENSILE DATA,
2124-T851 PLATE 2-3/4" THICK

	SPEC. NO.	UTS, PSI	YIELD, PSI	ELONG, %	RA, %	HARD., R_B	EC, % IACS
SOFT	2	59,870	52,750	6	12.6	73	40.9
SOFT	5	56,770	47,097	7.7	11.3	74	41.4
SOFT	6	64,012	57,324	8.9	17.2	75	39.8
	AVG	60,217	52,390	7.5	13.7	74	40.7
NORMAL	1	72,020	66,284	8.9	14.9	82	38.5
NORMAL	3	70,063	66,242	9.6	17.2	84	38.6
NORMAL	4	70,512	66,506	8.9	13.3	82	38.6
	AVG	70,865	66,344	9.1	15.1	82.7	38.6
	SPEC	65,000	57,000	6	--	74	35.0-42.5

TABLE 5

LONGITUDINAL TENSILE DATA FROM NORMAL (NOT SOFT) 5-1/2" AND 5" PLATES OF 2124-T851

PLATE THICK.	SPECIMEN DEPTH FROM SURFACE, INCH	SPEC NO.	ULT, KSI	YIELD, KSI	ELONG., %	RA, %	E.C., %IACS	HARDNESS, R_B
5-1/2"	1/8	A5B	73.0	68.0	6.0	24.5	41.5	83-84
	1 7/16	A2	69.1	62.0	7.4	16.7	41.7	80-79
	2 3/4	A3	69.0	61.1	7.3	16.6	42.0	78-79
	4 1/16	A4	68.9	61.8	7.1	17.4	42.0	80-79
	5 3/8	A1T	72.9	68.9	8.5	21.2	41.0	84-84
5"	1/8	K-1T	70.8	65.5	7.8	24.6	41.0-41.0	81.6-79.6
	7/8	K-2	65.5	58.0	7.3	21.6	41.8-41.6	73.4-72.4
	1 3/4	K-3	64.8	56.7	6.5	16.4	41.8-41.9	70.6-69.5
	2 1/2	K-4	64.0	56.6	6.7	14.1	42.0-42.0	73.6-70.9
	3 1/4	K-5	65.1	57.1	7.0	17.2	41.9-41.9	73.0-72.1
	4 1/8	K-6	66.1	58.8	7.7	20.8	41.5-41.6	75.8-76.3
	4 7/8	K-7B	72.2	66.4	7.9	23.9	41.0-40.5	73.8-78.8
	SPECIFICATION		63	54	5		35.0-42.5	74

TABLE 6

LONGITUDINAL TENSILE DATA,
2024-T351 PLATE 2" THICK

SPEC. NO.		UTS, KSI	YIELD, KSI	ELONG, %	RED. AREA, %	HARD., R_B	E.C. % IACS
Base	Y-1B	69.9	53.0	13.0	23.6	77-78	30.0-30.4
	Y-2B	69.7	53.8	17.7	24.4	77-78	30.1-30.3
	Y-3B	69.7	54.1	19.8	24.4	78-79	30.0-30.4
AVG.		69.8	53.6	16.8	24.1		
Middle	Y-1M	73.3	57.4	15.5	19.9	77-76	31.0-30.8
	Y-2M	73.3	57.0	13.6	16.2	78-77	31.0-31.0
	Y-3M	72.9	57.7	13.0	15.3	78-77	31.0-31.0
AVG.		73.2	57.4	14.0	17.3		
Affected	Y-1T	65.6	52.1	13.9	23.0	76-73	30.8-33.9
	Y-2T	65.7	52.6	12.1	21.2	76-77	30.6-34.0
	Y-3T	65.3	52.1	13.0	19.8	72-73	31.0-33.8
AVG.		65.5	52.3	13.0	31.3		
SPECIFICATION		62	47	6	--	63	28.5-32.5

TABLE 7

LONGITUDINAL TENSILE DATA, 7075-T651
1-1/4" IMPROPERLY QUENCHED ALUMINUM PLATE

	SPEC. NO.	UTS, KSI	YIELD, KSI	ELONG., %	RA, %	HARD., R_B	EC, % IACS
SOFT SIDE, LONGITUDINAL	L-1A	70.0	58.6	10.0	15.9	78.0	34.2
	L-2A	70.0	60.0	8.6	18.8	81.0	34.1
	L-3A	69.8	58.3	11.0	18.5	82.7	33.9
	L-4A	68.8	56.6	10.4	20.2	81.7	34.1
	L-5A	68.6	55.8	11.3	21.1	81.0	34.2
	L-6A	69.1	58.2	10.5	18.8	83.7	33.7
	L-7A	70.7	61.5	7.5	18.6	83.5	33.5
	L-8A	70.7	59.7	10.2	19.4	82.5	33.8
	L-9A	70.2	58.2	11.1	21.6	81.7	34.1
	L-10A	70.3	58.4	11.5	18.4	78.5	33.7
	AVERAGE	69.8	58.5	10.2	19.3	81.4	33.9
	σ n-1	.74	1.62	1.26	1.60	1.92	.25
MID THICKNESS LONGITUDINAL	L-4M	81.0	71.9	10.3	12.2	83.5	33
	L-5M	80.2	71.0	9.3	12.6	82.7	33
	L-6M	80.4	70.6	10.3	14.7	83.0	33
	AVERAGE	80.5	71.2	10.0	13.2	83.1	33
NORMAL SIDE, LONGITUDINAL	L-1B	74.8	64.9	18.1	10.6	82.5	32.5
	L-2B	77.1	70.2	8.6	22.6	84.2	32.2
	L-3B	76.9	67.5	9.3	19.0	84.7	32.0
	L-4B	78.1	69.2	11.5	21.3	85.5	31.9
	L-5B	78.7	69.8	11.6	20.0	85.2	31.5
	L-6B	79.1	70.5	11.6	20.6	85.5	31.8
	L-7B	78.1	68.4	12.6	19.7	86.0	32.0
	L-8B	77.7	68.6	13.2	17.3	86.2	31.9
	L-9B	79.5	70.9	13.4	23.1	88.2	31.3
	L-10B	81.8	75.8	7.2	17.9	85.5	31.1
	AVERAGE	78.2	69.6	11.1	19.2	85.3	31.8
	σ n-1	1.84	2.80	3.03	3.55	1.46	.42
SPECIFICATION		76	69	6	--	84	30.5 - 36

TABLE 8

TRANSVERSE TENSILE DATA,
7075-T651 1-1/4" IMPROPERLY QUENCHED ALUMINUM PLATE

	SPEC. NO.	UTS, KSI	YIELD, KSI	ELONG., %	RA, %	HARD., R_B	EC, % IACS
SOFT SIDE	X-1A	71.2	56.8	10.0	17.8	79.0	34
	X-2A	69.9	54.7	9.2	16.5	77.5	34
	X-3A	69.9	54.2	10.6	15.2	79.9	34
	AVERAGE	70.3	55.2	9.9	16.5	78.8	34
NORMAL SIDE	X-1B	79.6	66.5	9.7	16.1	87.5	31.9
	X-2B	80.2	67.7	9.9	14.6	86.0	32.0
	X-3B	79.8	66.1	9.6	15.7	86.5	31.7
	AVERAGE	79.9	66.8	9.7	15.5	86.7	31.9
SPECIFICATION		75	65	6	--	84	30.5-36

TABLE 9

LONGITUDINAL TENSILE DATA, 7075-T651 1-1/4" THICK PLATE

	SPEC. NO.	UTS, KSI	YIELD, KSI	ELONG., %	R.A., %	HARD., R_B	E.C., % IACS
SOFT SIDE	L-11T	67.3	55.4	10.8	22	81	34.1
	L-12T	72.1	63.0	9.3	20	87	34.1
	L-13T	73.3	63.8	10.0	23	86	32.5
	L-14T	73.2	63.6	12.2	24	85	32.9
	AVERAGE	71.5	61.5	10.6	22	85	33.4
NORMAL SIDE	L-11B	73.4	64.2	7.0	23	83	33.5
	L-12B	72.8	64.7	9.2	20	85	32.5
	L-13B	73.4	64.3	10.4	23	87	32.2
	L-14B	71.2	60.4	11.7	24	85	32.4
	AVERAGE	72.7	63.4	9.6	22	85	32.6
SPECIFICATION		76	69	6	--	84	30.5-36

TABLE 10

LONGITUDINAL TENSILE DATA, 7075-T7351 4" PLATE

	SPEC. NO.	UTS, KSI	YIELD, KSI	ELONG., %	RA, %	HARDNESS, R_B	E.C., % IACS
SOFT SIDE LONGITUDINAL	P-1-A	71.7	60.7	7.9	15.9	78/81	39.2/40.9
	P-2A	70.8	59.5	7.4	15.1	81/79.5	39.2/40.8
	P-3A	70.4	58.6	6.7	11.6	80.5/81.5	39.2/40.2
	P-4A	71.6	60.7	8.4	14.4	81/79	38.8/40.8
	P-5-A	71.2	60.2	8.0	14.9	76/81	39/41.3
	P-6-A	71.9	60.6	7.4	16.6	76/81	39/39.8
	P-7-A	71.7	60.4	7.1	16.0	82/83	38.8/39.3
	P-8-A	71.9	60.5	7.9	13.3	82.5/82.5	38.7/39.8
	P-9-A	71.2	59.6	8.0	14.3	82/82	38.6/40.0
	P-10-A	70.5	58.6	8.4	16.9	80/81	38.8/41.2
	AVERAGE	71.3	59.9	7.7	14.9	80.5	39.6
	σ n-1	0.56	0.82	0.55	2.11	1.97	0.94
SPECIFICATION		*63	*49	--	--	78	40-43

	SPEC. NO.	UTS, KSI	YIELD, KSI	ELONG., %	RA, %	HARDNESS, R_B	E.C., % IACS
NORMAL SIDE LONGITUDINAL	P-1-B	73.9	63.3	9.3	13.6	82.5/82	38.7/39.4
	P-2B	73.6	62.8	7.3	14.5	82/83	38.7/39
	P-3-B	73.3	62.3	7.3	16.4	82.5/82	38.7/39.2
	P-4-B	73.5	62.6	8.4	15.6	82/78	38.7/38.8
	P-5-B	73.4	63.1	7.8	14.5	80/83	38.5/38.8
	P-6-B	73.1	62.3	7.4	14.0	79/82	38.7/39
	P-7-B	72.3	61.7	6.9	14.8	82/83	38.7/39
	P-8-B	72.8	61.6	7.0	12.0	82/83	38.7/39
	P-9-B	72.7	62.3	7.4	13.4	82.5/82	38.5/38.9
	P-10-B	72.5	61.3	7.6	16.6	84/83.5	38.5/38.9
	AVERAGE	73.1	62.3	7.6	14.5	82.0	38.8
	σ n-1	0.52	0.65	0.72	1.41	1.45	0.23
SPECIFICATION		*63	*49	--	--	78	40-43

*MIL-HDBK-5 "A" Value for 2.5"-3.0" Plate.

TABLE 11

TRANSVERSE TENSILE DATA, 7075-T7351 4" PLATE

	SPEC. NO.	UTS, KSI.	YIELD, KSI.	ELONG, %	RA, %	HARDNESS, R_B	E.C., % IACS
SOFT SIDE TRANSVERSE	G-1-A	69.7	59.0	7.5	17.0	82/83	39/41.4
	G-2-A	71.1	60.3	9.2	17.7	81/81	39/40
	G-3-A	69.8	58.3	9.2	19.1	81/80	39.1/39.5
	G-4-A	69.4	58.6	8.3	18.3	80/80	39.2/39.7
	AVERAGE	70.0	59.1	8.6	18.0	81.0	39.6
	σ n-1	0.75	0.88	0.82	0.89	1.07	0.71
SPECIFICATION		*64	*49	6	--	78	40-43
NORMAL SIDE TRANSVERSE	G-1-B	72.1	61.7	9.5	19.7	82/83	38.8/39.3
	G-2-B	71.5	61.1	9.0	20.0	83/83	38.7/38.8
	G-3-B	72.0	62.1	9.5	18.0	83/83	38.7/38.9
	G-4-B	72.1	61.8	9.1	26.3	83/83.5	38.7/39.3
	AVERAGE	71.9	61.7	9.3	21.0	82.9	38.8
	σ n-1	0.29	0.42	0.26	3.64	0.42	0.33
SPECIFICATION		*64	*49	6	--	78	40-43

* MIL-HDBK-5 "A" Value for 2.5"-3.0" Plate.

TABLE 12

TENSILE TRAVERSE THROUGH-THE-THICKNESS, 7075-T7351 4" PLATE, LONGITUDINAL

	SPEC. NO.	UTS, KSI	YIELD, KSI	ELONG, %	RA, %	HARDNESS, R_B	E.C., % IACS
SOFT SIDE	P-5-A	71.2	60.2	8.0	14.9	76/81	39/41.3
	P-5-1	62.0	48.1	8.0	14.5	72/74	40.0/40.5
	P-5-2	61.6	48.2	7.6	11.8	70/70.5	40.3/40.6
	P-5-3	64.4	52.6	6.3	11.4	74/73	40.3/40.3
	P-5-4	63.7	53.2	6.4	10.0	74/74.5	40.1/40.3
	P-5-5	63.7	50.3	6.6	10.9	74/74	40.0/40.1
NORMAL SIDE	P-5-6	68.4	56.1	7.6	11.4	77/77.5	39.1/39.5
	P-5-B	73.4	63.1	7.8	14.5	80/83	38.5/38.8
SPECIFICATION		*63	*49	--	--	78	40-43

* MIL-HDBK-5 "A" Value for 2.5"-3.0" Plate.

TABLE 13

COMPRESSION STRENGTH DATA,
2124-T851 5-1/2" ALUMINUM PLATE

	SPEC NO.	YIELD, KSI	HARDNESS, R_B	EC, % IACS
SOFT SIDE	C-1A	24.7	39.2	45.5
	C-2A	26.0	51.0	45.4
	C-3A	32.1	62.5	44.2
	AVERAGE	27.6	50.9	45.0
NORMAL SIDE	C-1B	62.9	80.0	40.5
	C-2B	62.3	80.5	40.8
	C-3B	62.0	80.5	40.6
	AVERAGE	62.4	80.3	40.6
SPECIFICATION		51	74	35.0-42.5

TABLE 14

BEARING STRENGTH DATA (E/D=2.0),
2124-T851 5-1/2" ALUMINUM PLATE

	SPEC NO.	YIELD, KSI	ULT, KSI	HARD., R_B	EC, % IACS
SOFT SIDE	BE-1A	71.6	103.0	59-60	43.8
	BE-2A	66.3	102.0	56-56	43.7
	BE-3A	67.0	98.0	55-55	44.2
	AVERAGE	68.3	101.0	56.8	43.9
NORMAL SIDE	BE-1B	99.6	132.0	76-77	40.7
	BE-2B	97.0	129.0	77-77	40.6
	BE-3B	98.7	131.0	78-77	40.9
	AVERAGE	98.4	130.7	77.0	40.7
SPECIFICATION		93.0	121.0	74	35.0-42.5

TABLE 15

STRESS CORROSION TEST RESULTS FOR 2124-T851 5-1/2" THICK PLATE, CONSTANT STRESS, ALTERNATE IMMERSION

SPEC NO.	ORIENTATION	STRESS (KSI)	STRESS/ YIELD* X 100, %	EXPOSURE TIME, HRS	FAIL YES/NO
S-1A	Longitudinal	45	83	317	YES
S-1B	Longitudinal	45	83	677	NO
S-4A	Short Trans.	45	88	547	YES
S-5B	Short Trans.	45	88	625	YES
S-6A	Short Trans.	45	88	386	YES
S-6B	Short Trans.	45	88	593	YES
S-5A	Short Trans.	38.2	75	600	NO
S-4B	Short Trans.	38.2	75	600	NO

*Yield Strength per MIL-HDBK-5: Longitudinal=54 KSI: Short transverse=51KSI

TABLE 16

STRESS CORROSION TEST RESULTS FROM COMPACT TYPE SPECIMENS,
2124-T851 5-1/2" THICK PLATE,
L-T ORIENTATION, CONTINUOUS IMMERSION

SPEC. NO.	$K_{Initial}$, KSI $\sqrt{in.}$	TIME HR	FAIL/ NO FAIL	HARD., R_B	E.C., %IACS
K-1A	22*	2000 +	No Fail	42	45.6
K-2A				52	45.2
K-1B	22*	2000 +	No Fail	79.5	40.6
K-2B				79.5	40.8

*Based on crack length before test

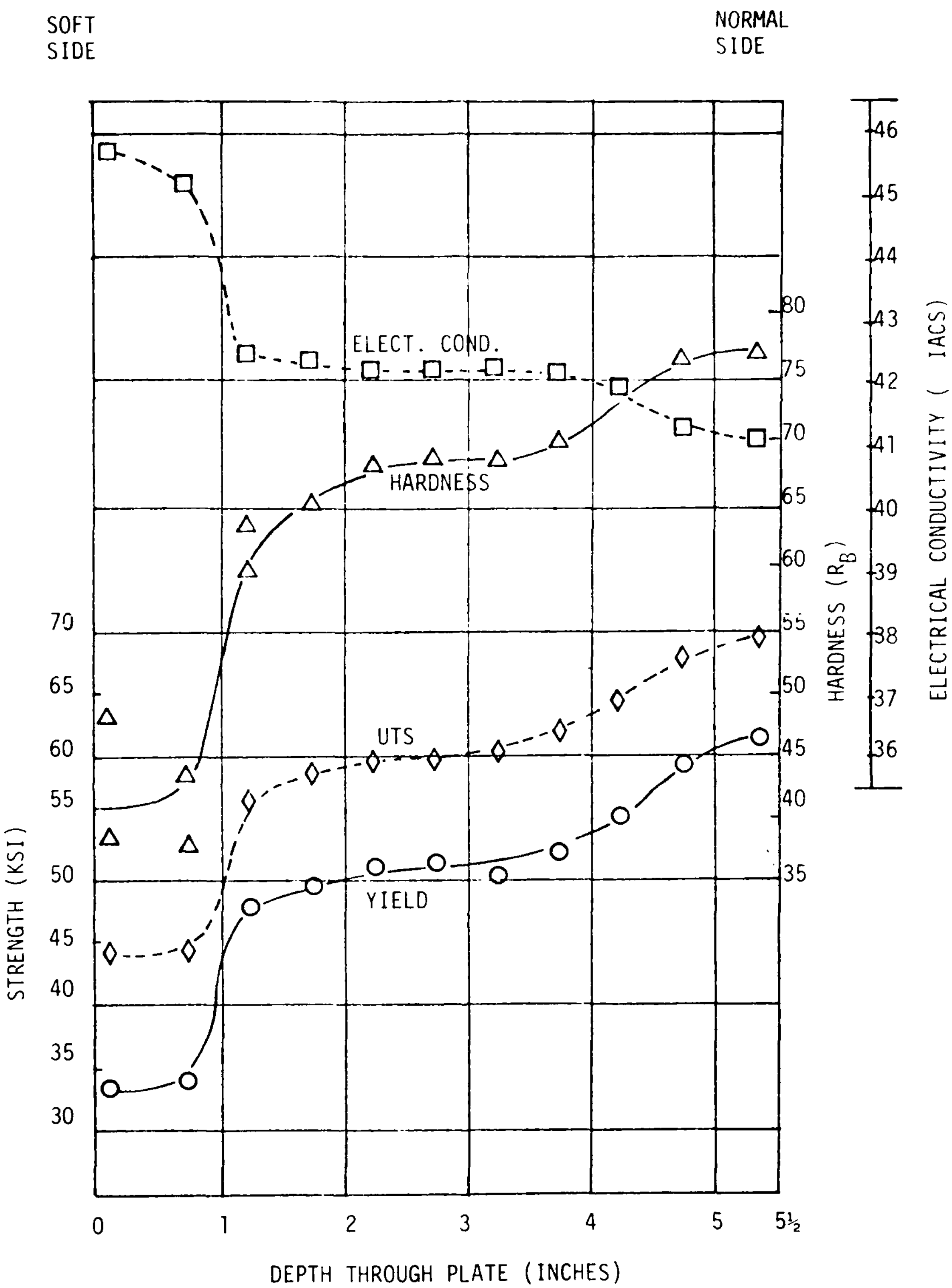

Figure 1. Test Data for 2124-T851 Aluminum Plate 5-½" Thick

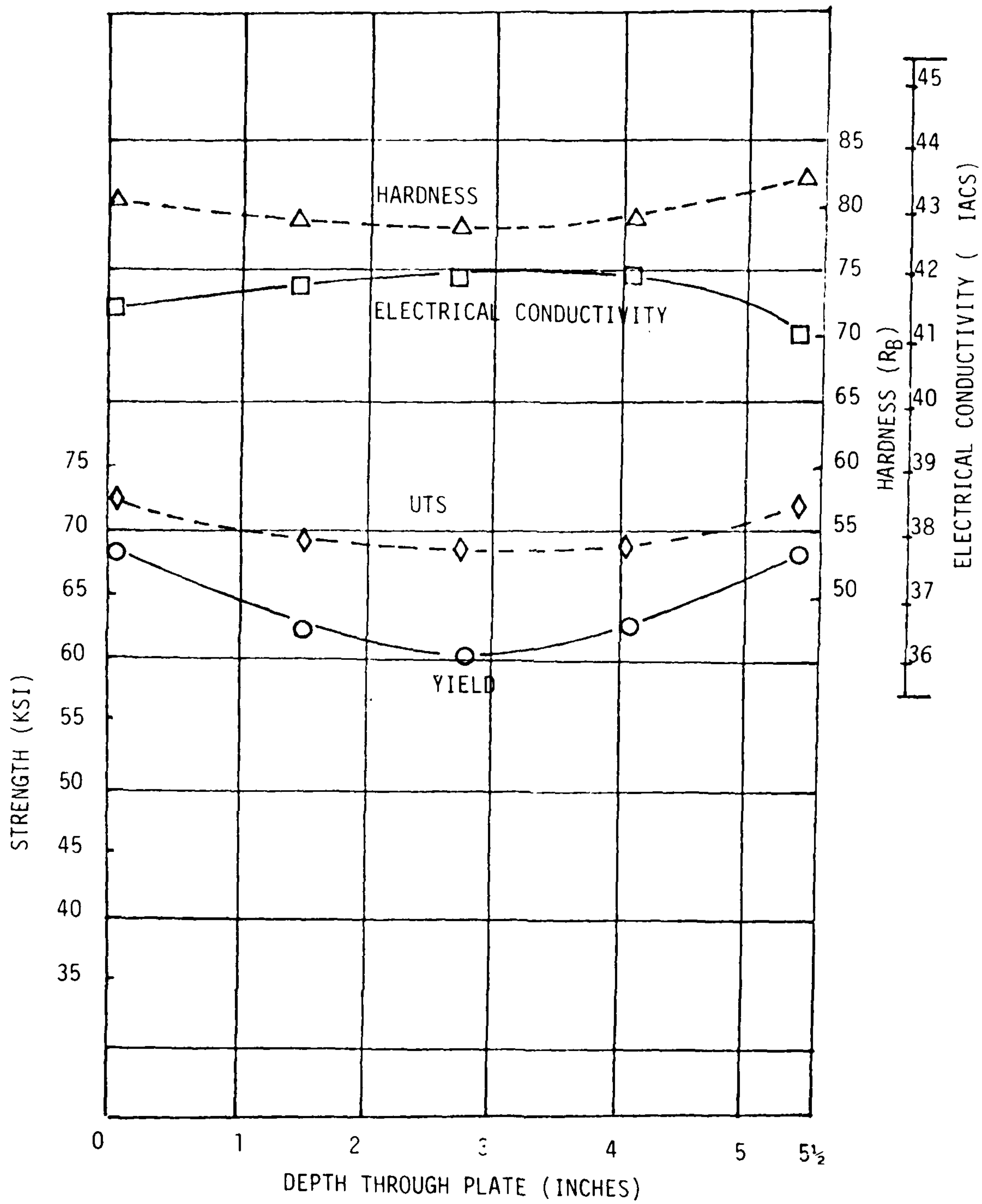

Figure 2. Test Data for Normal 2124-T851 Aluminum Plate 5-½" Thick

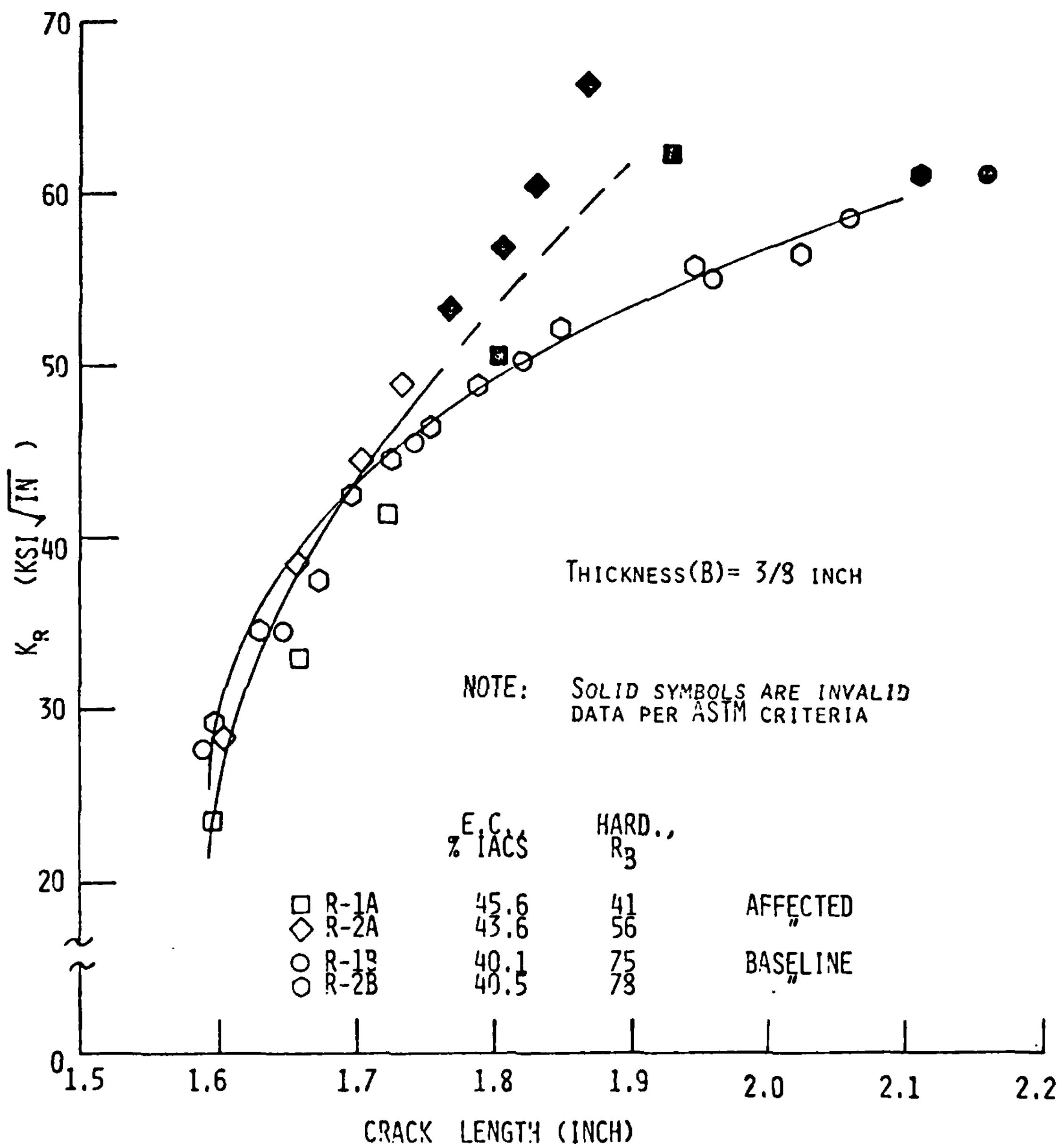

Figure 3. R-Curve Fracture Toughness Data, 2124-T851 5-1/2" Aluminum Plate

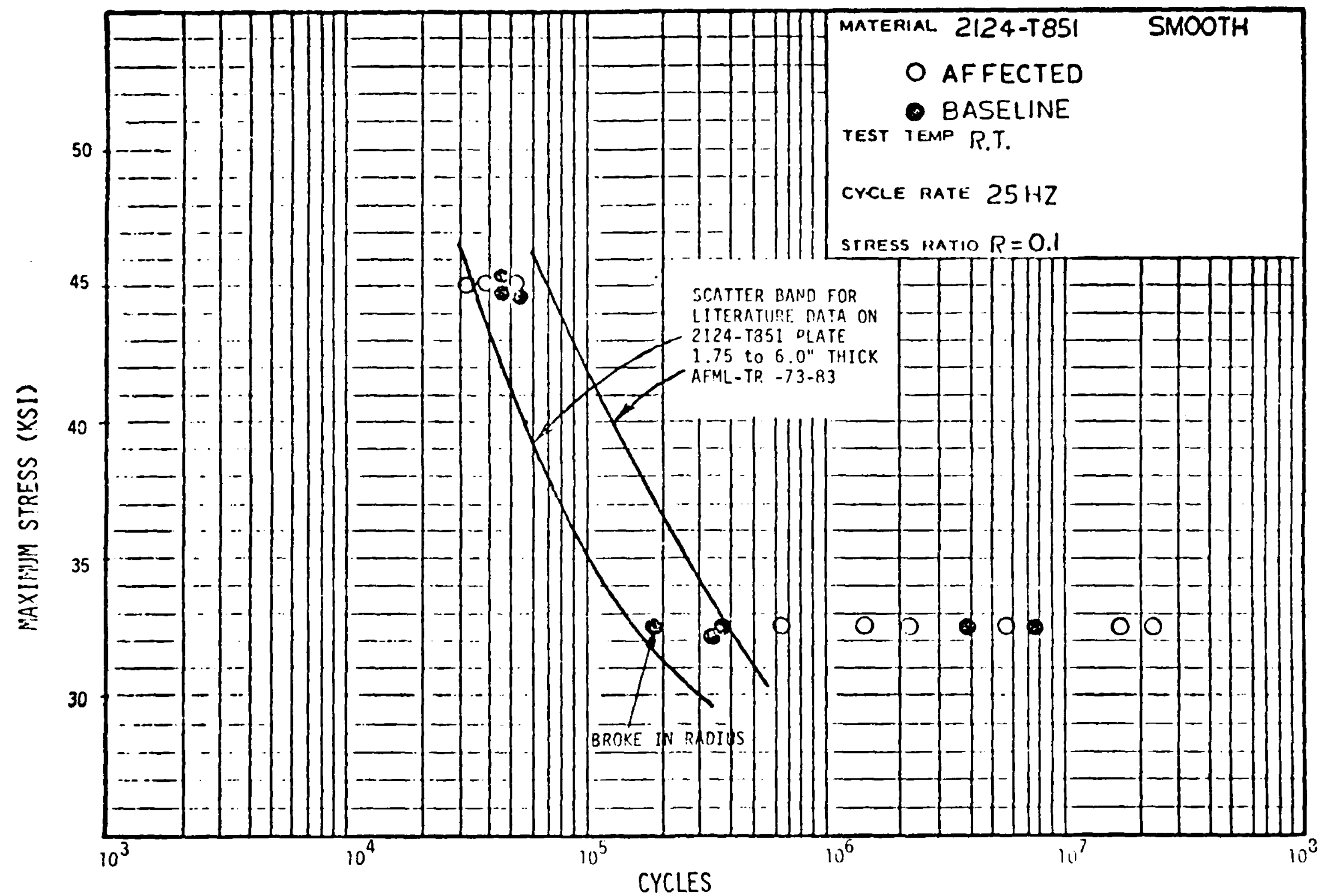

Figure 4. Smooth Fatigue Data for 2124-T851 5-1/2" Plate

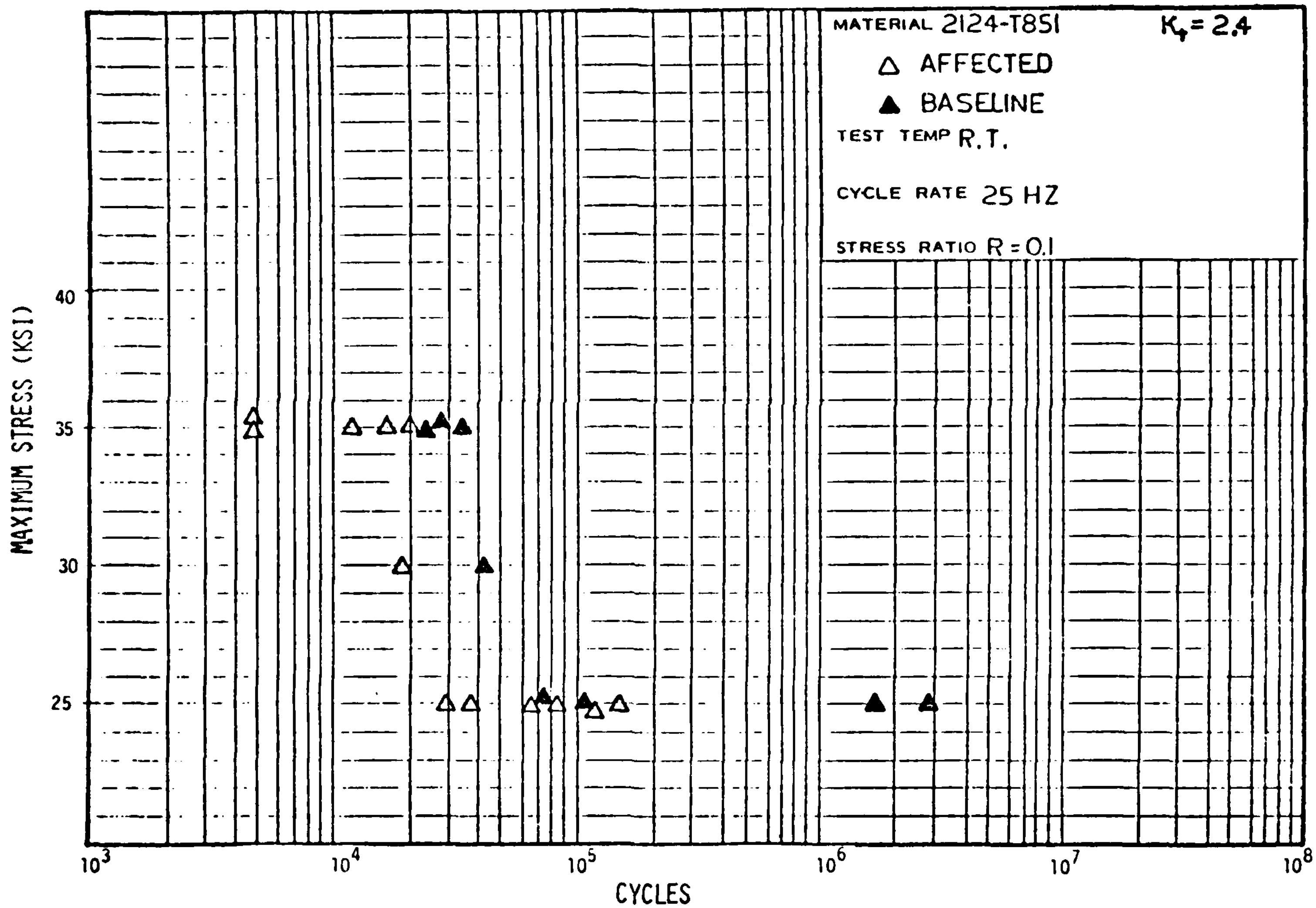

Figure 5. Notched Fatigue Data for 2124-T851 5-1/2" Plate

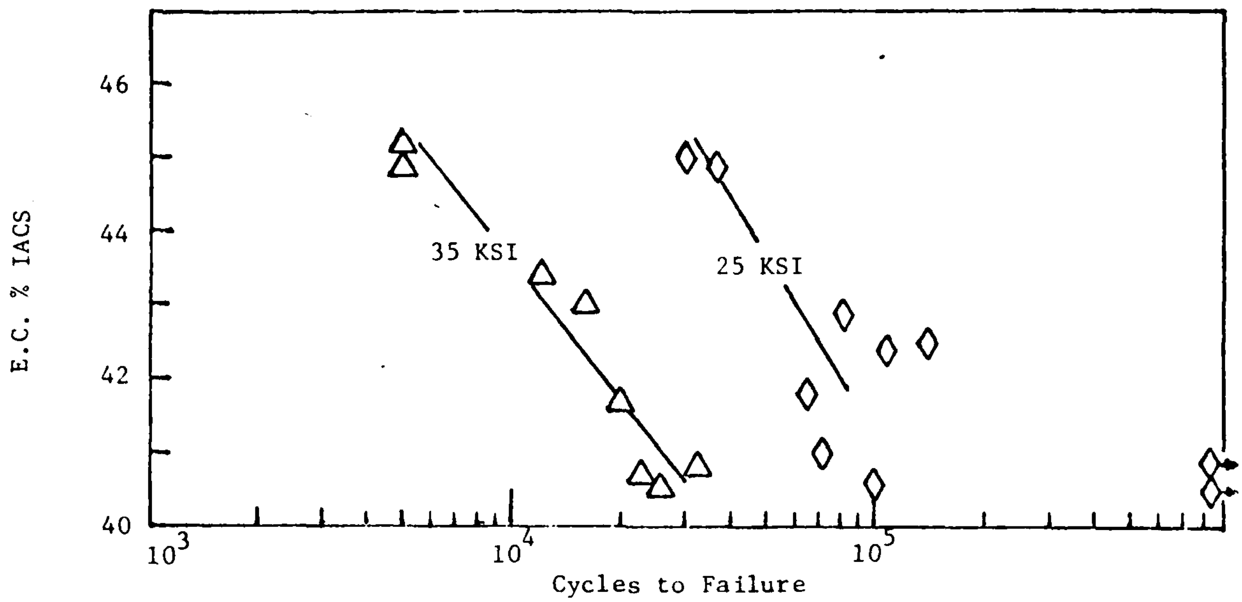

Figure 6. Notched Fatigue Data Showing Relationship Between Electrical Conductivity and Fatigue Life of 2124-T851 5-1/2" Plate

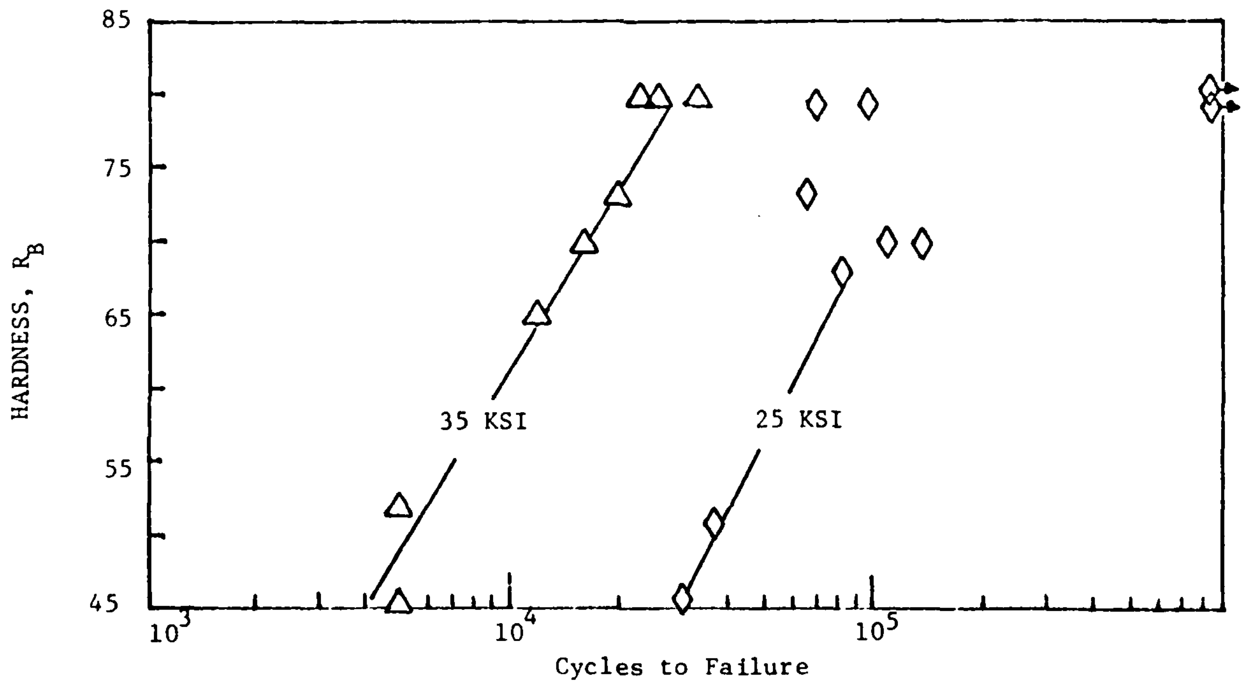

Figure 7. Notched Fatigue Data Showing Relationship Between Hardness and Fatigue Life of 2124-T851 5-1/2" Plate

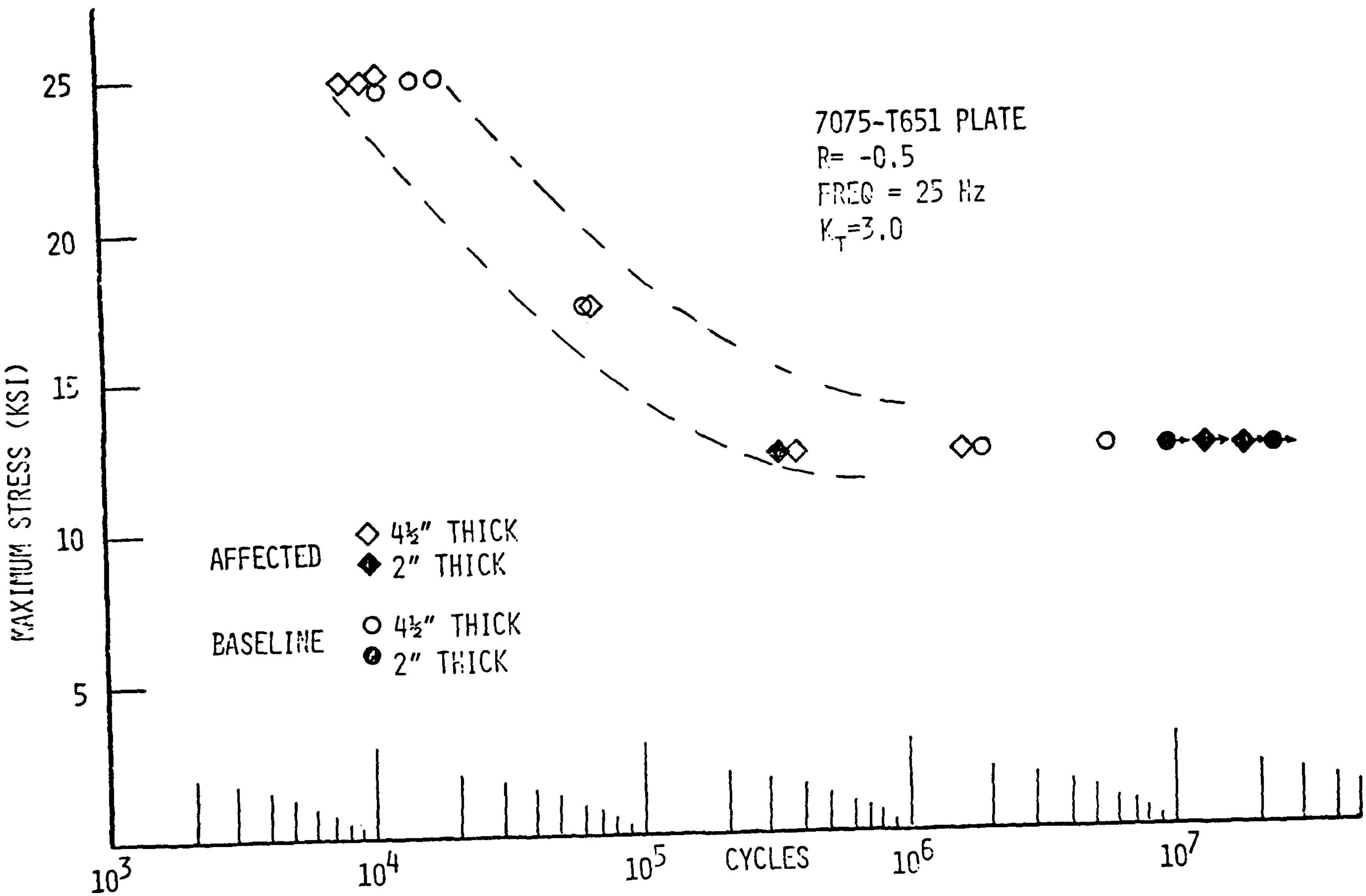

FIGURE 8. CONSTANT AMPLITUDE FATIGUE TEST RESULTS FOR NOTCHED 7075-T651

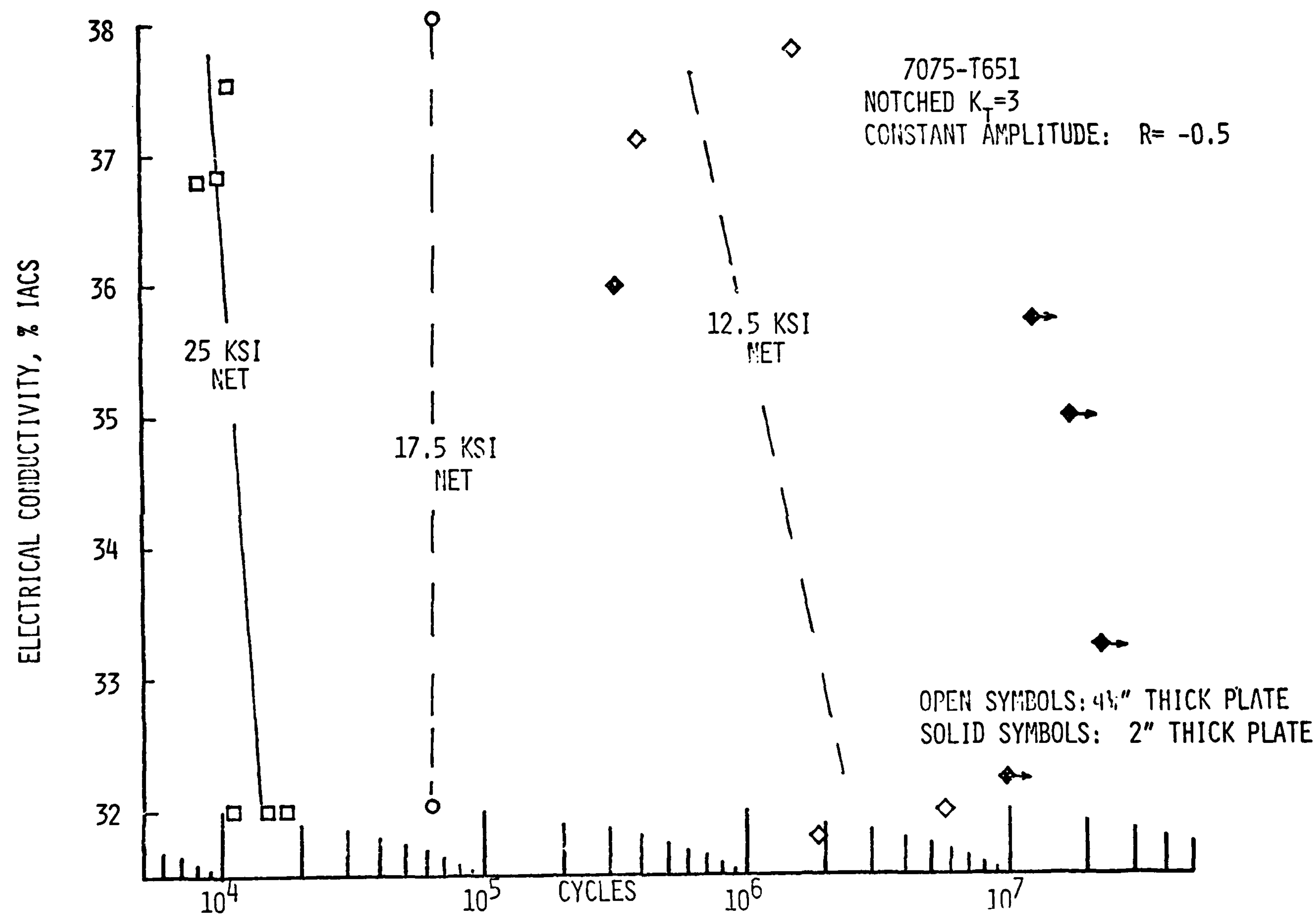

FIGURE 9. NOTCHED FATIGUE DATA SHOWING RELATIONSHIP BETWEEN ELECTRICAL CONDUCTIVITY AND CYCLES.

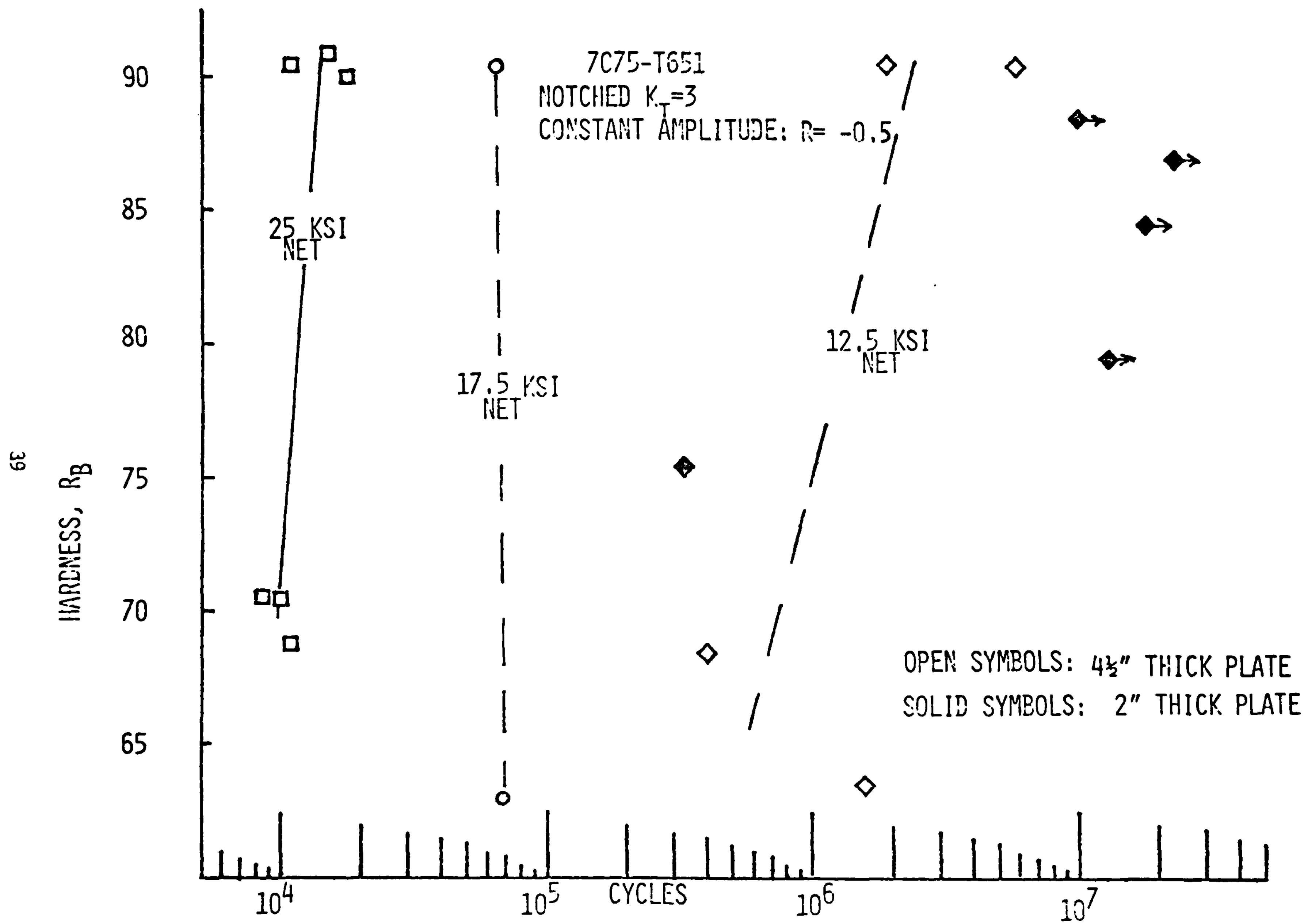

FIGURE 10. NOTCHED FATIGUE DATA SHOWING RELATIONSHIP BETWEEN HARDNESS AND CYCLES.

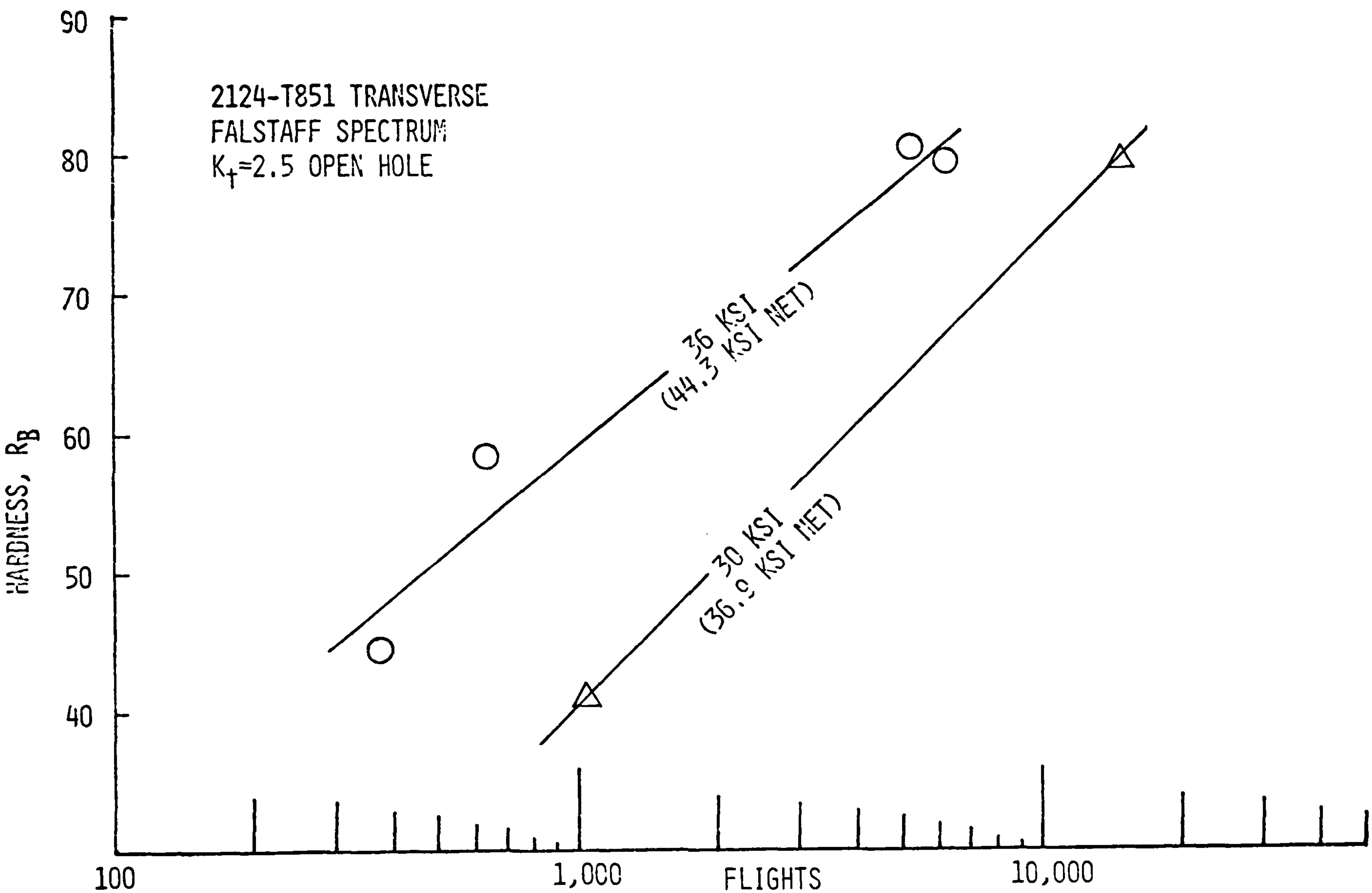

FIGURE 11. HARDNESS VERSUS FLIGHTS TO FAILURE

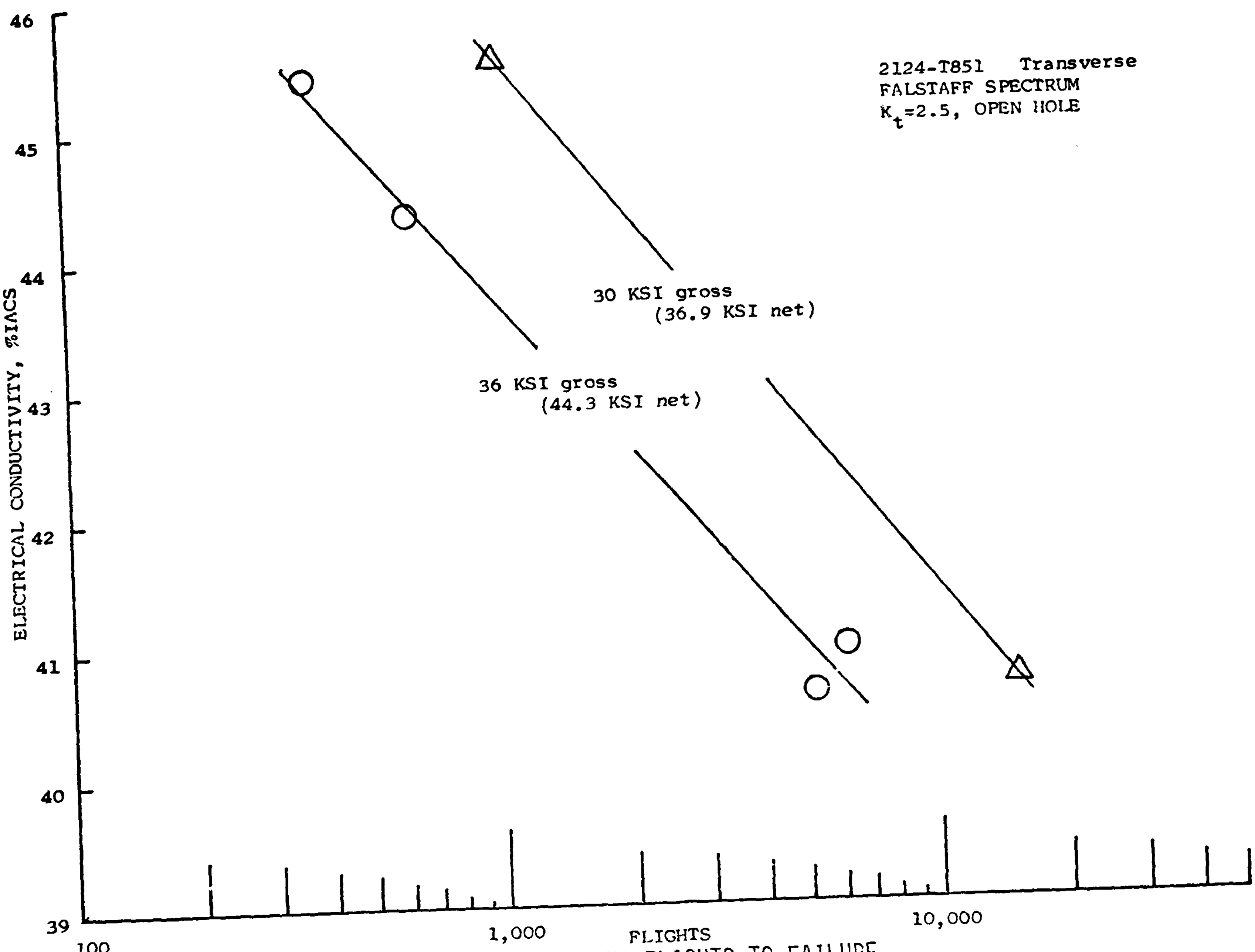

FIGURE 12. ELECTRICAL CONDUCTIVITY VERSUS FLIGHTS TO FAILURE

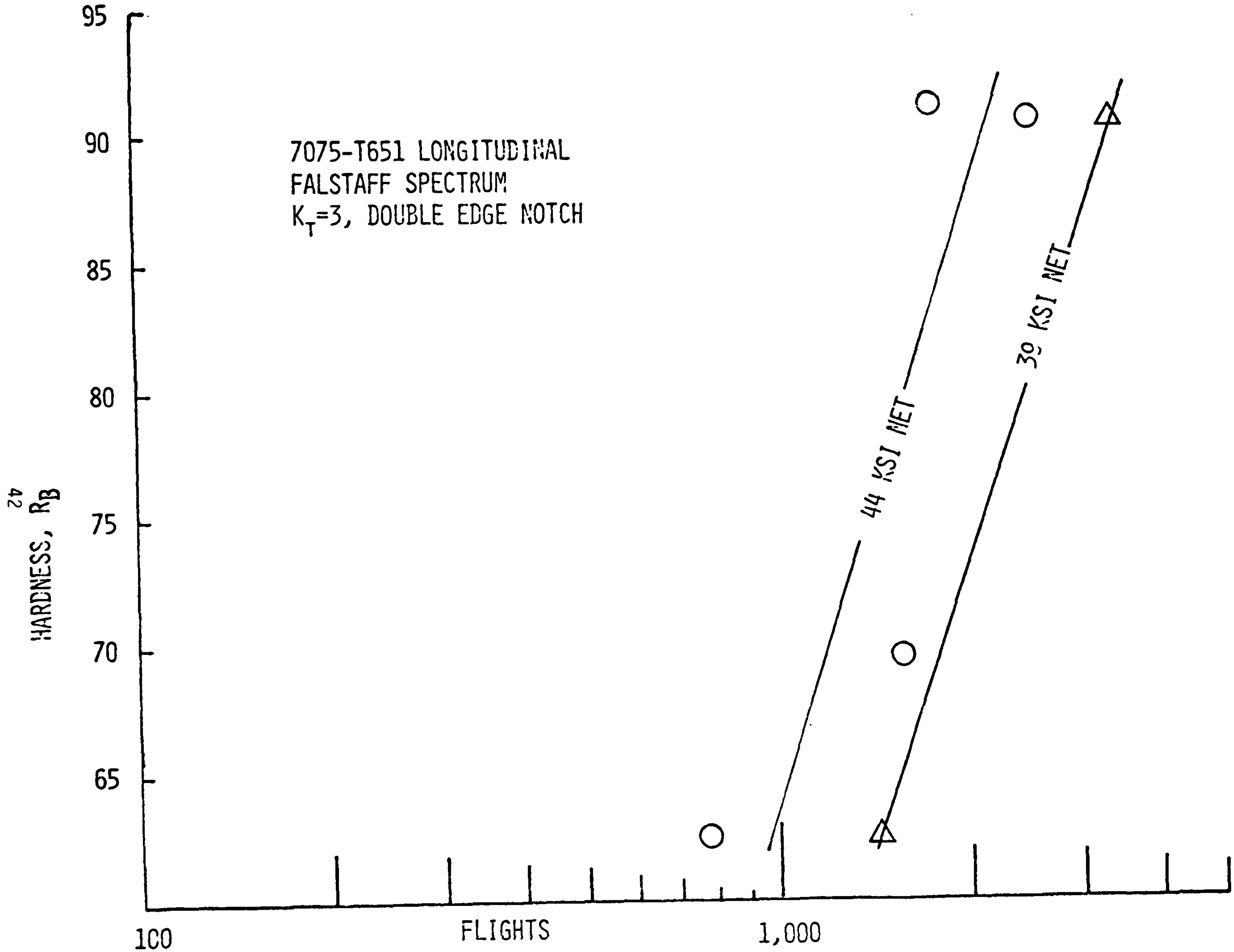

FIGURE 13. HARDNESS VERSUS FLIGHTS TO FAILURE

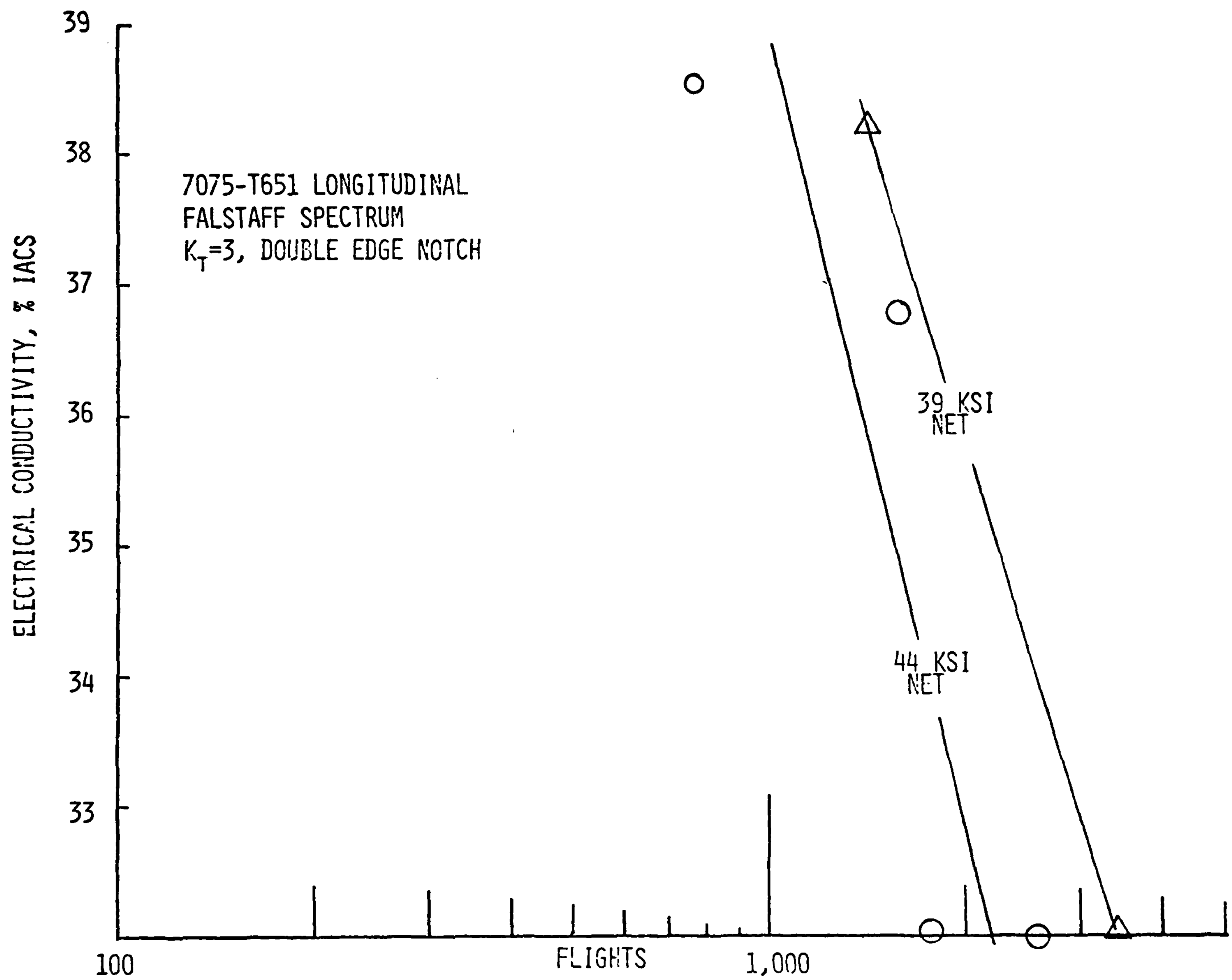

FIGURE 14. ELECTRICAL CONDUCTIVITY VERSUS FLIGHTS TO FAILURE

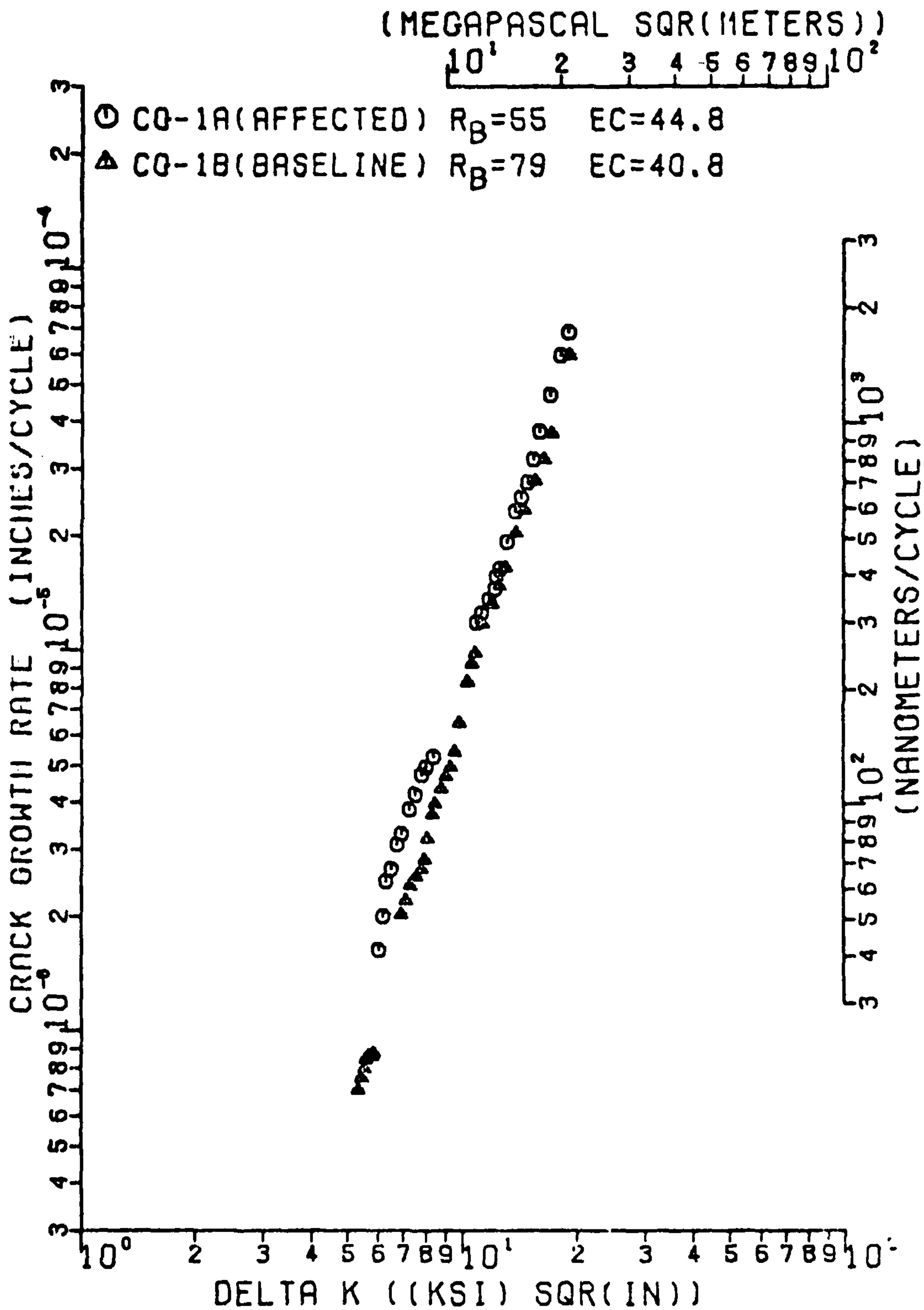

Figure 15. Fatigue Crack Growth Rate Data for 2124-T851 5-1/2" Aluminum Plate

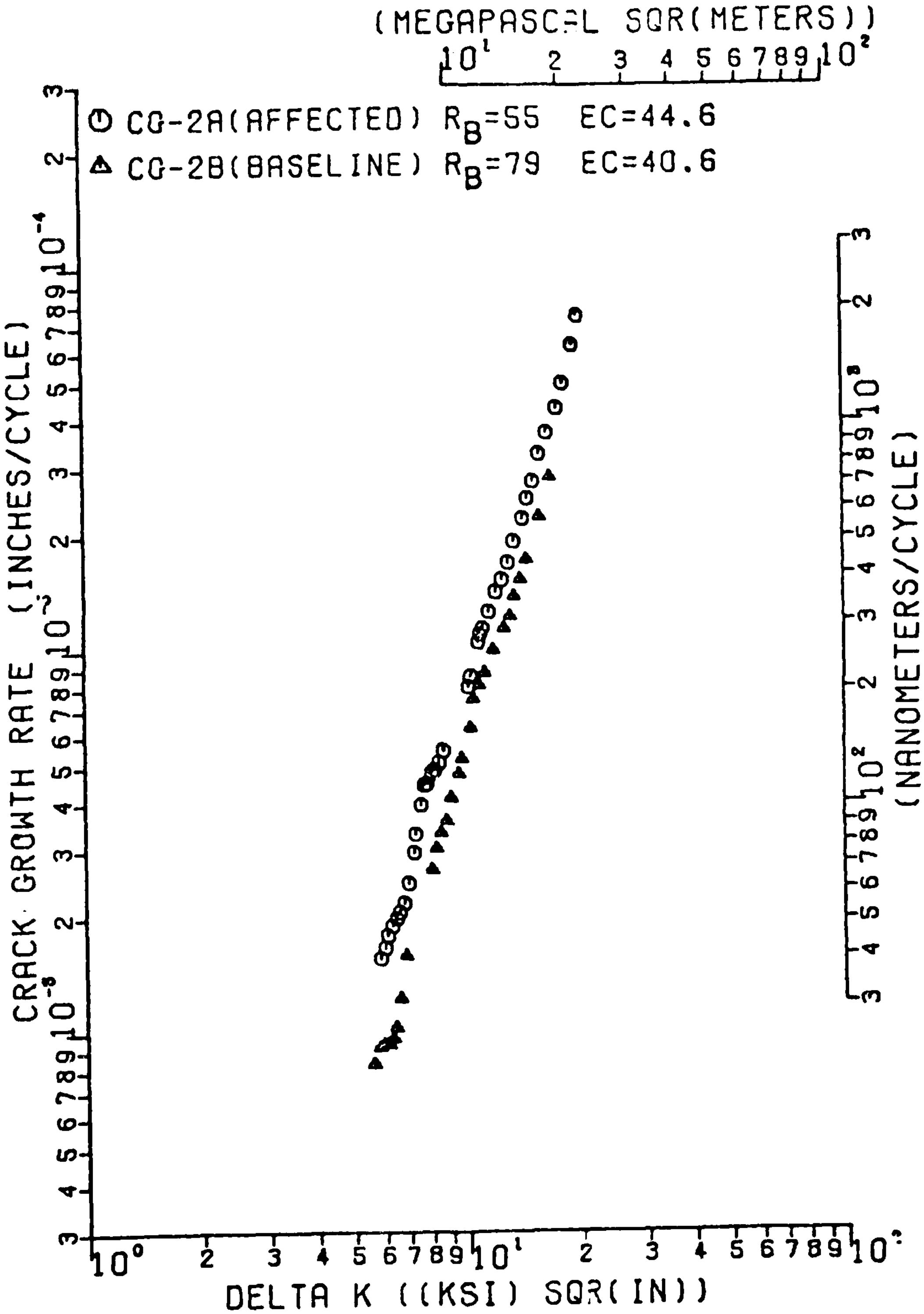

Figure 16. Fatique Crack Growth Rate Data for 2124-T851 5-1/2" Aluminum Plate

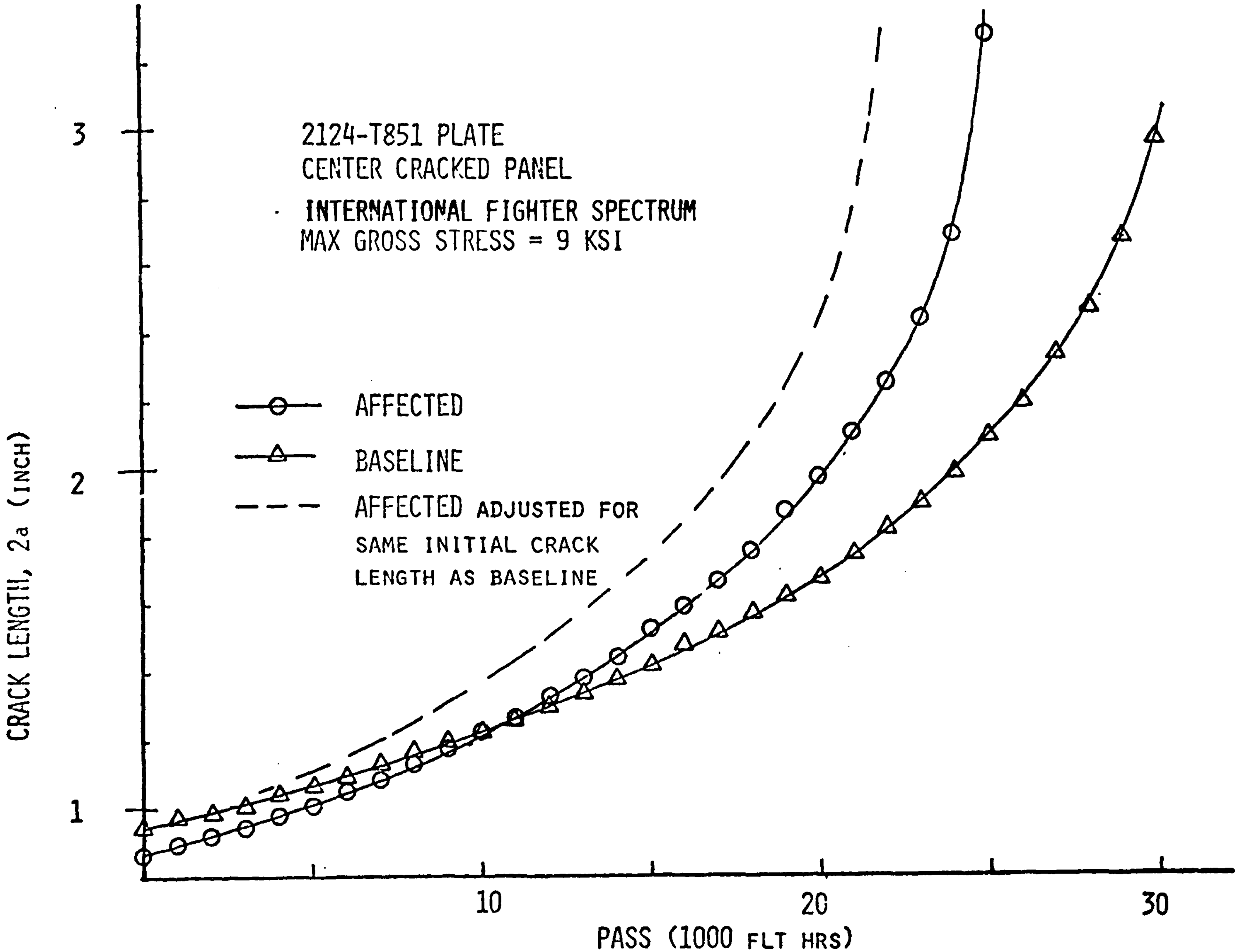

FIGURE 17. FATIGUE CRACK GROWTH DATA FOR CENTER CRACKED PANEL SPECIMENS.

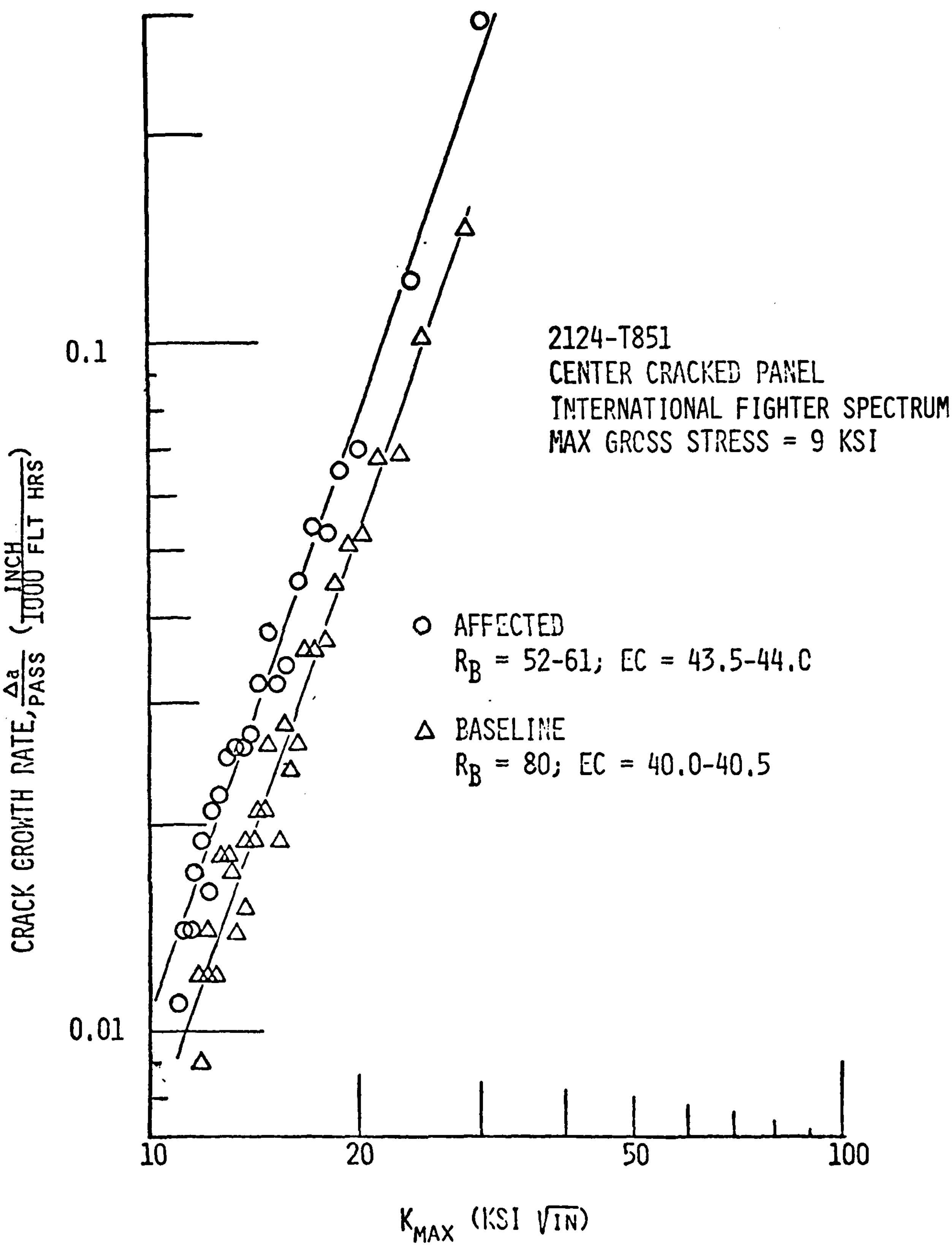

FIGURE 18. FATIGUE CRACK GROWTH RATE DATA FOR CENTER CRACKED PANELS.

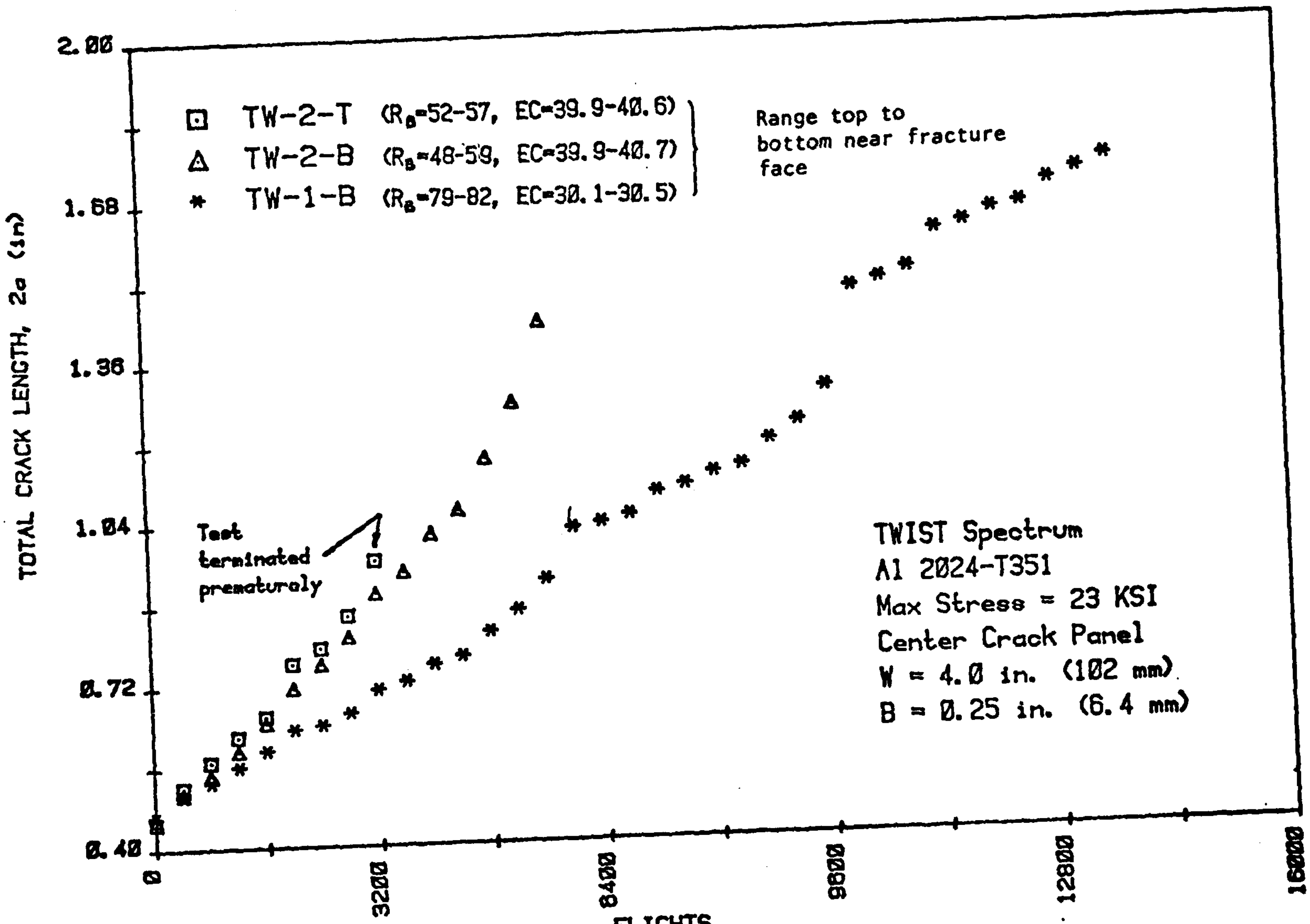

Figure 19. Total Crack Length. 2a. versus Flights for 2024-T351 Aluminum Plate

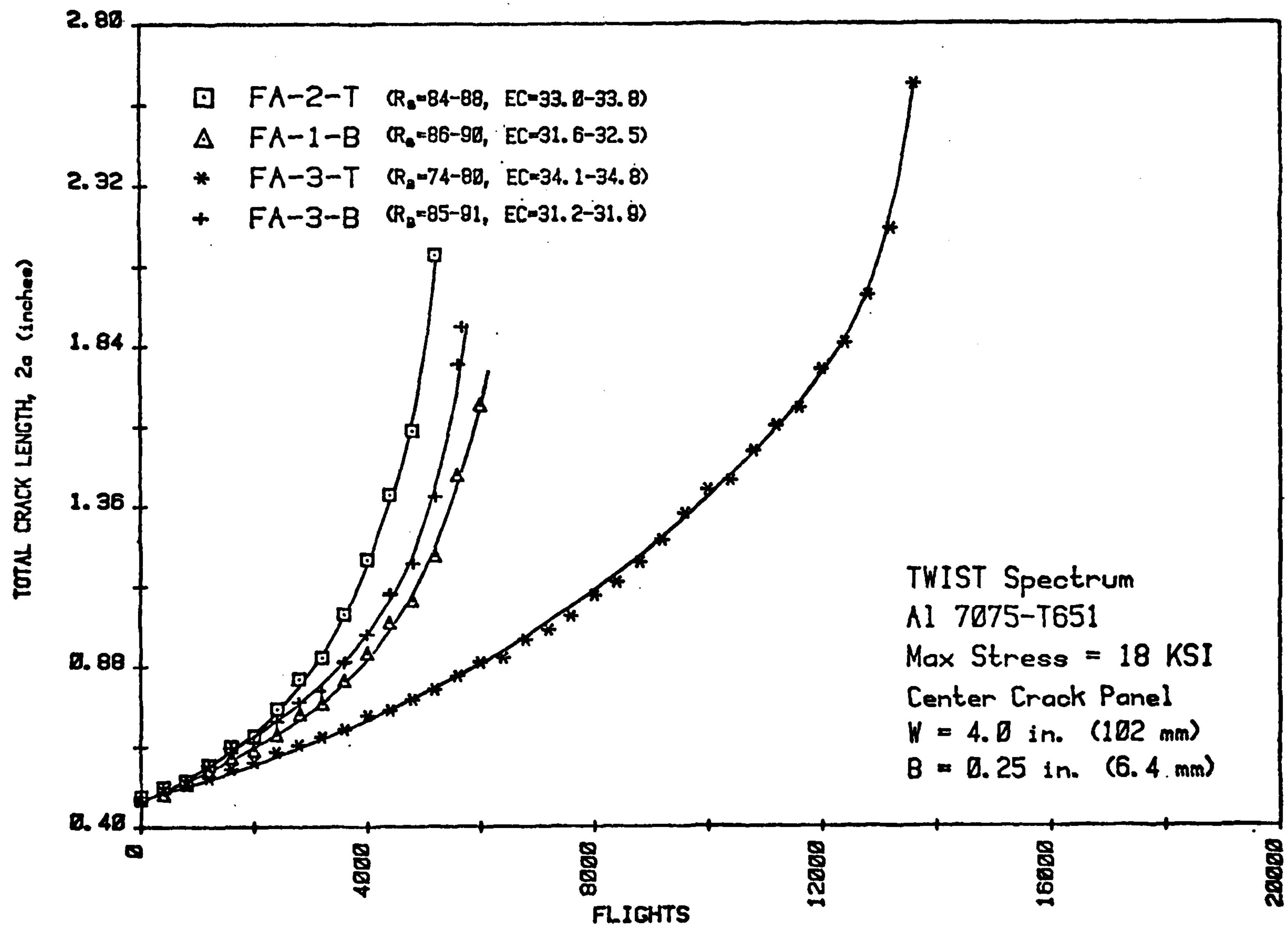

Figure 20. Total Crack Length, 2a, versus Flights for 7075-T651 Aluminum Plates: Max Spectrum Stress = 18KSI

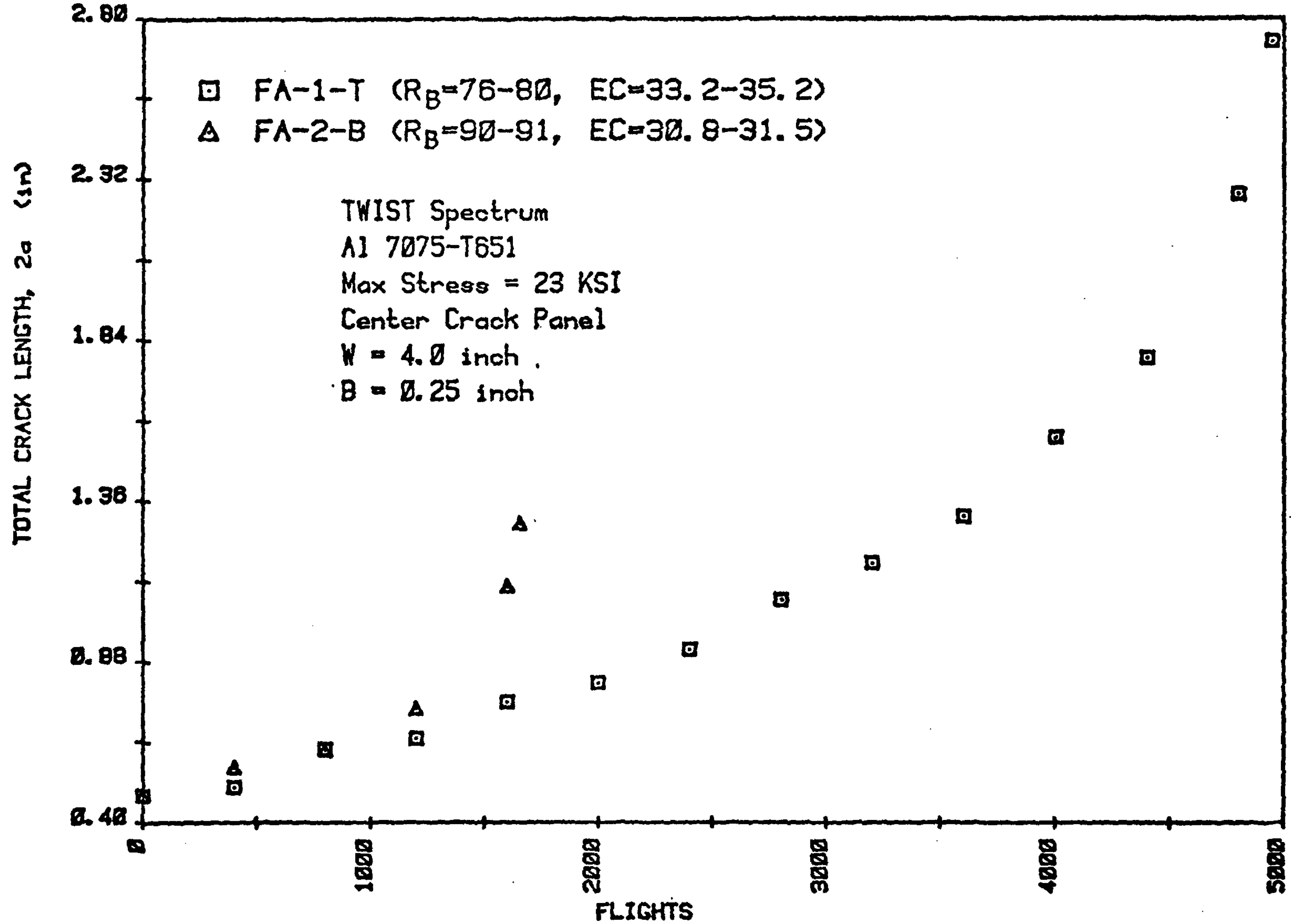

Figure 21. Total Crack Length, 2a, versus Flights for 7075-T651 Aluminum Plates: Max Spectrum Stress = 23KSI

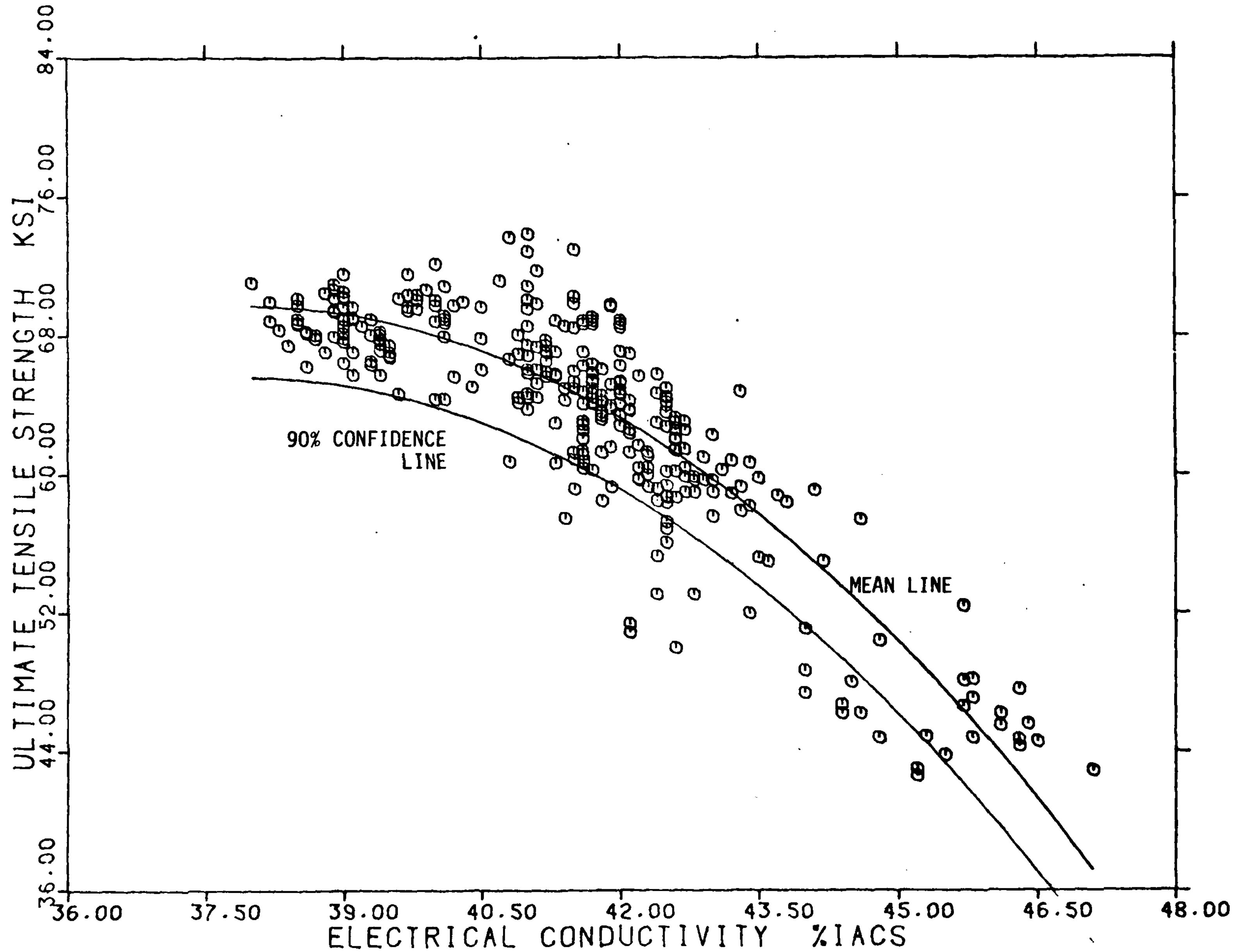

FIGURE 22. ULTIMATE TENSILE STRENGTH VS. CONDUCTIVITY; 2124 T851 PLATE - ALL THICKNESSES

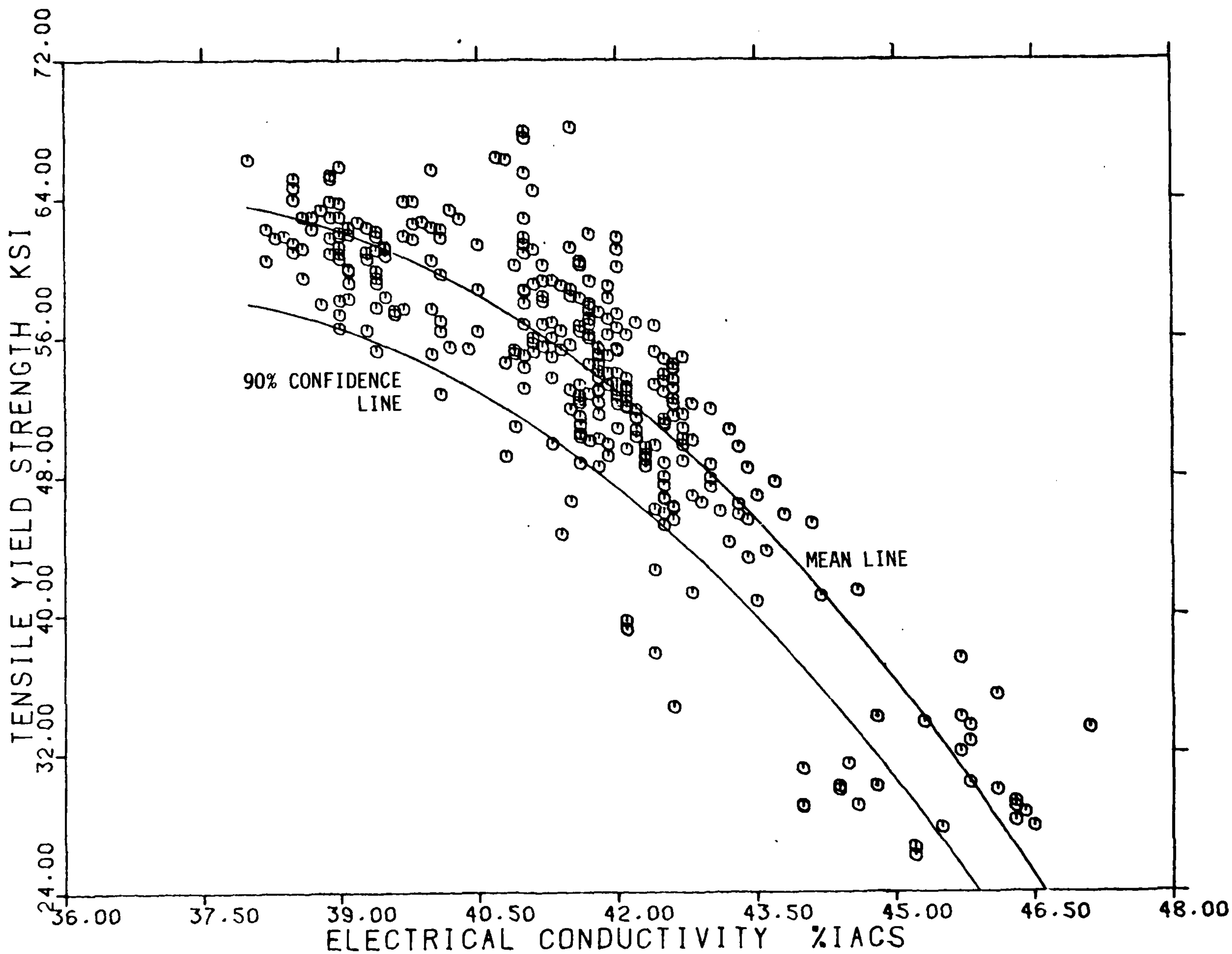

FIGURE 23. TENSILE YIELD STRENGTH VS. CONDUCTIVITY; 2124 T851 PLATE - ALL THICKNESSES

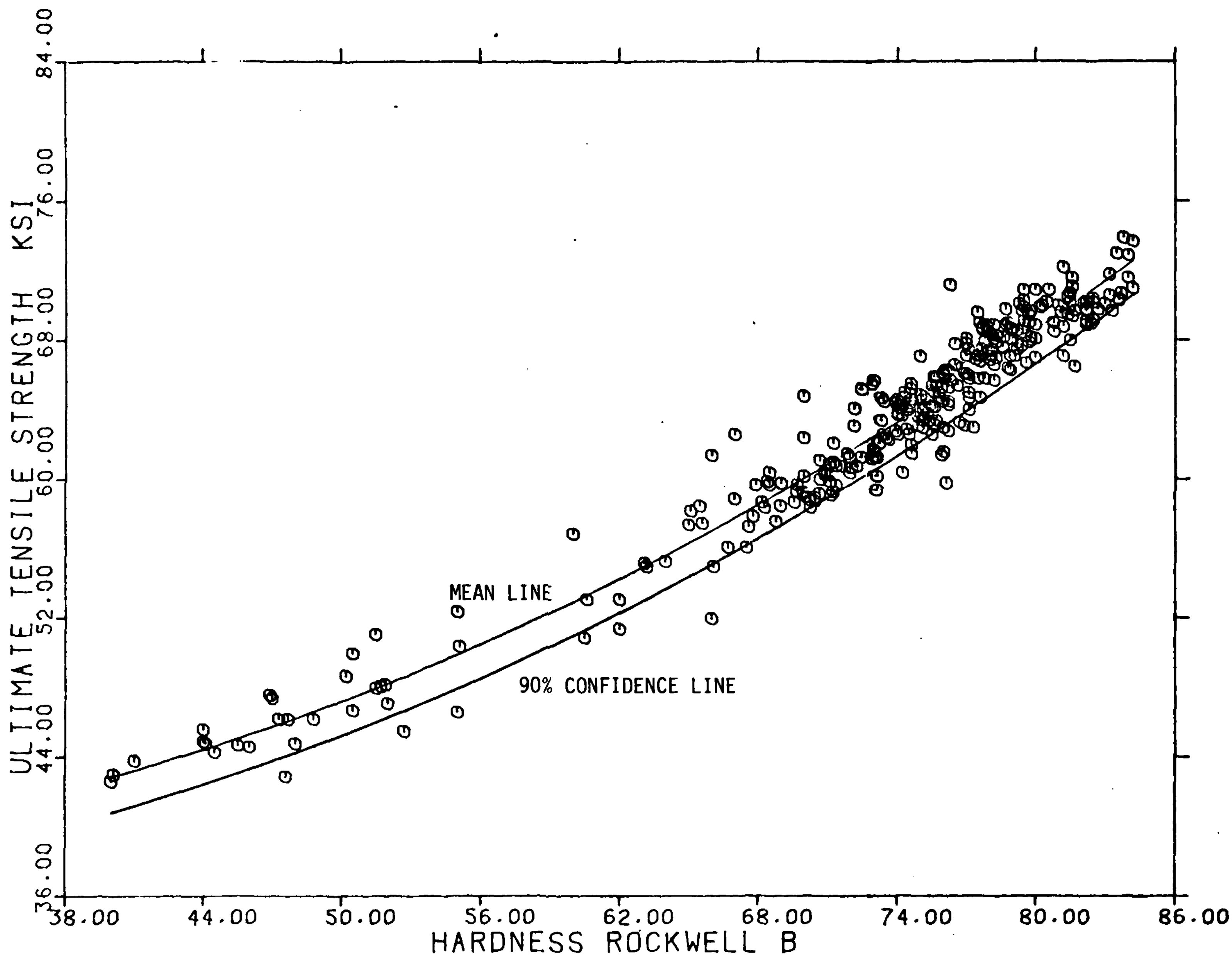

FIGURE 24. ULTIMATE TENSILE STRENGTH VS. HARDNESS; 2124 T851 PLATE - ALL THICKNESSES

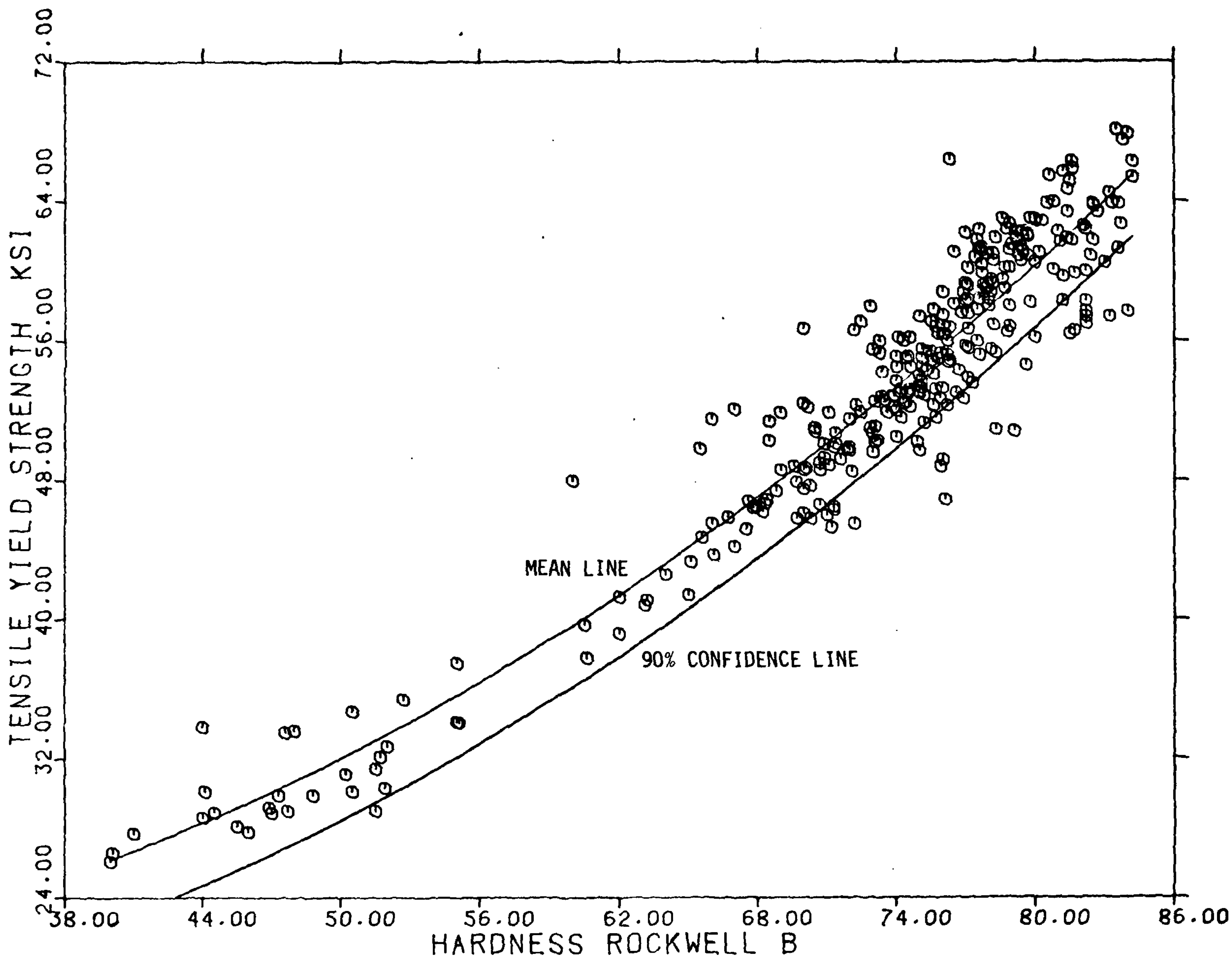

FIGURE 25. TENSILE YIELD STRENGTH VS. HARDNESS; 2124 T851 PLATE - ALL THICKNESSES

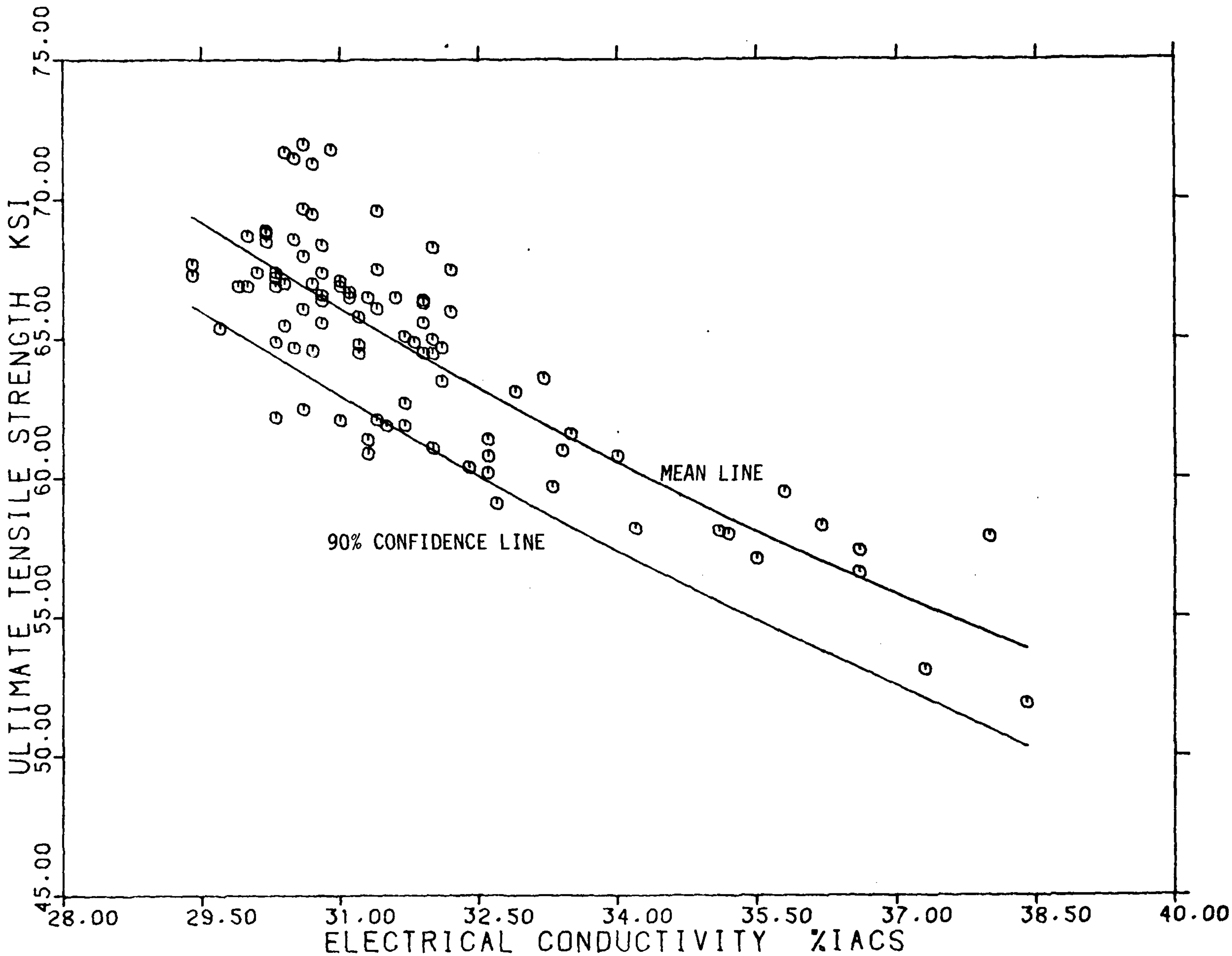

FIGURE 26. ULTIMATE TENSILE STRENGTH VS. CONDUCTIVITY; 2024 T351 PLATE - ALL THICKNESSES

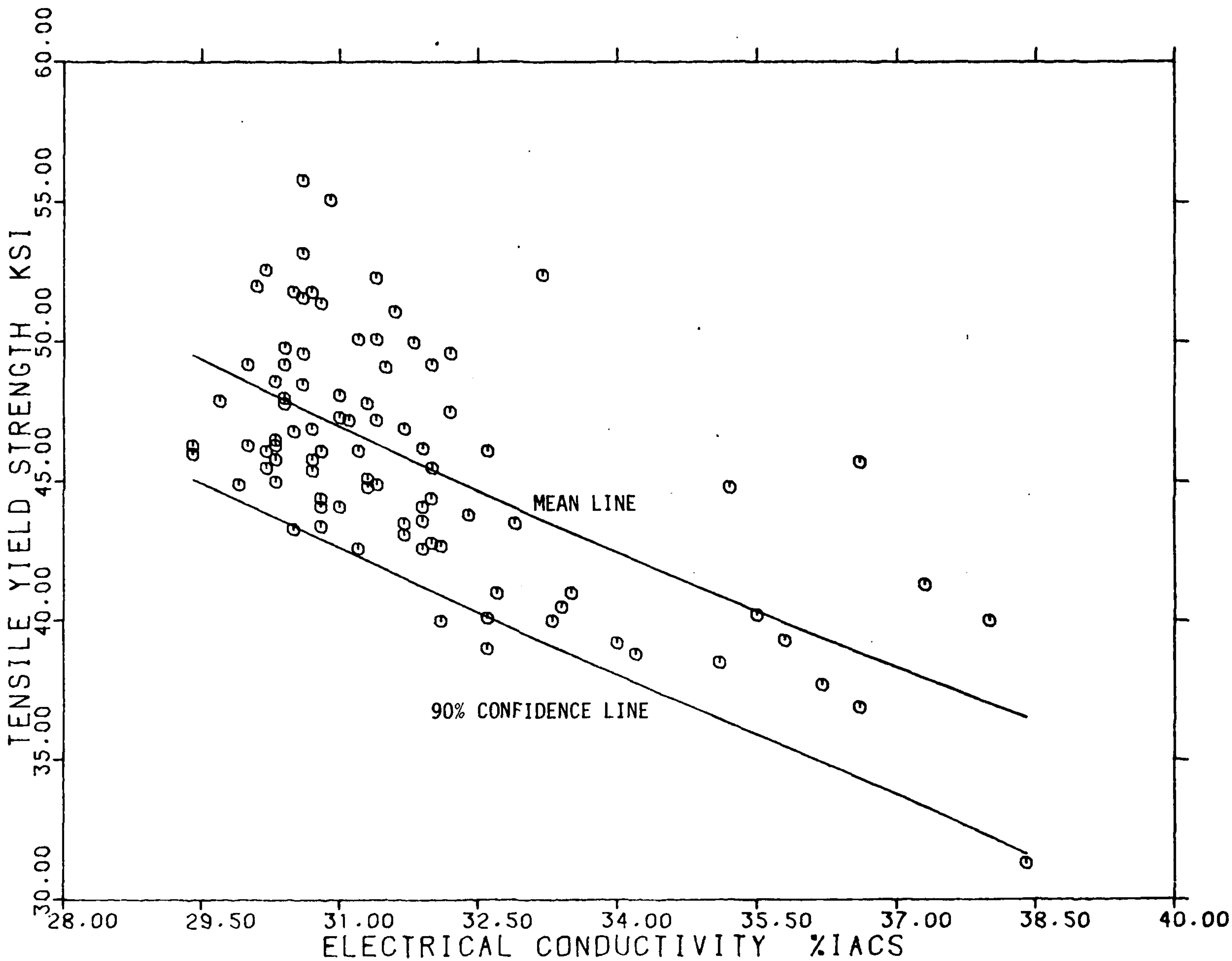

FIGURE 27. TENSILE YIELD STRENGTH VS. CONDUCTIVITY; 2024 T351 PLATE - ALL THICKNESSES

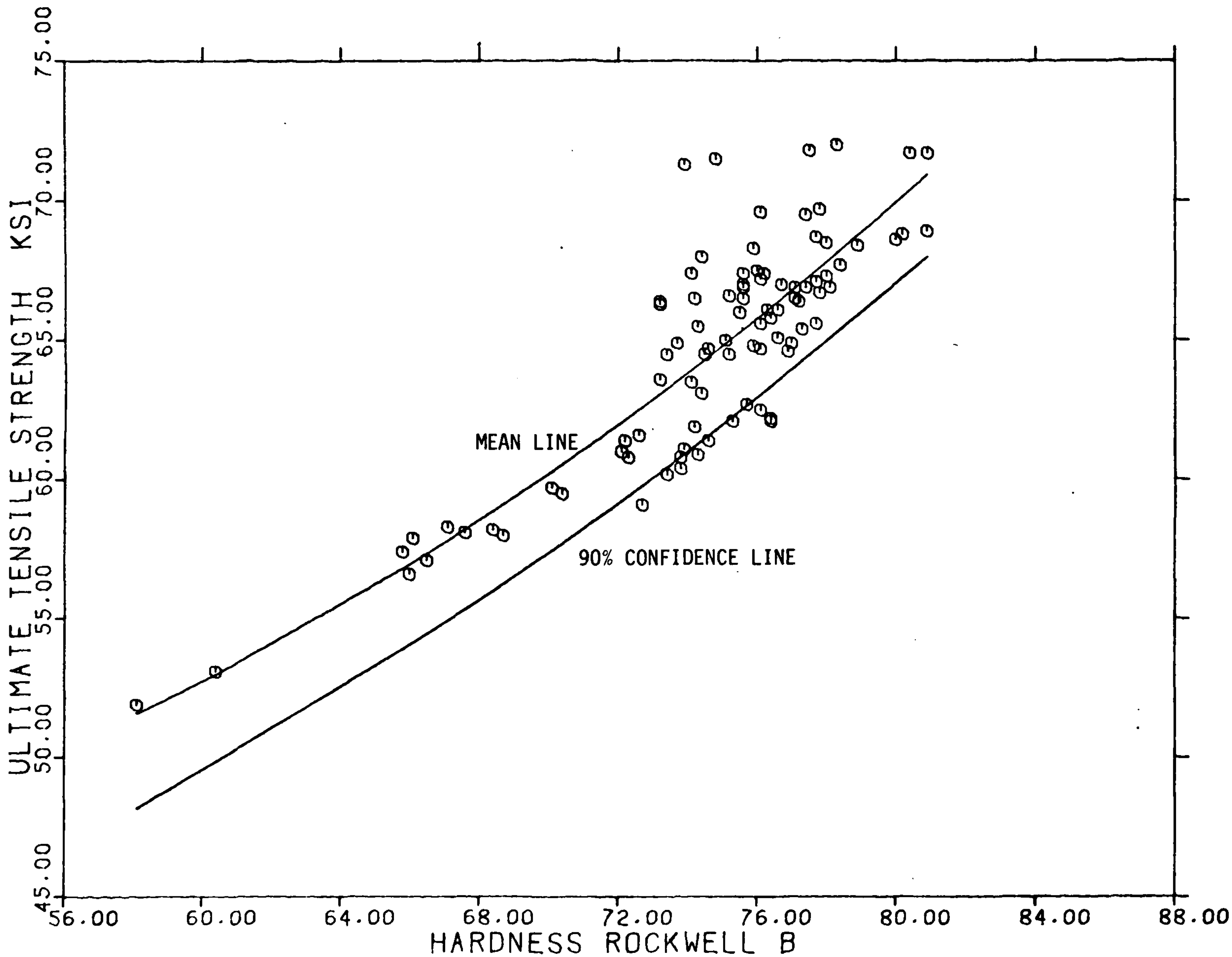

FIGURE 28. ULTIMATE TENSILE STRENGTH V.S. HARDNESS; 2024 T351 PLATE - ALL THICKNESSES

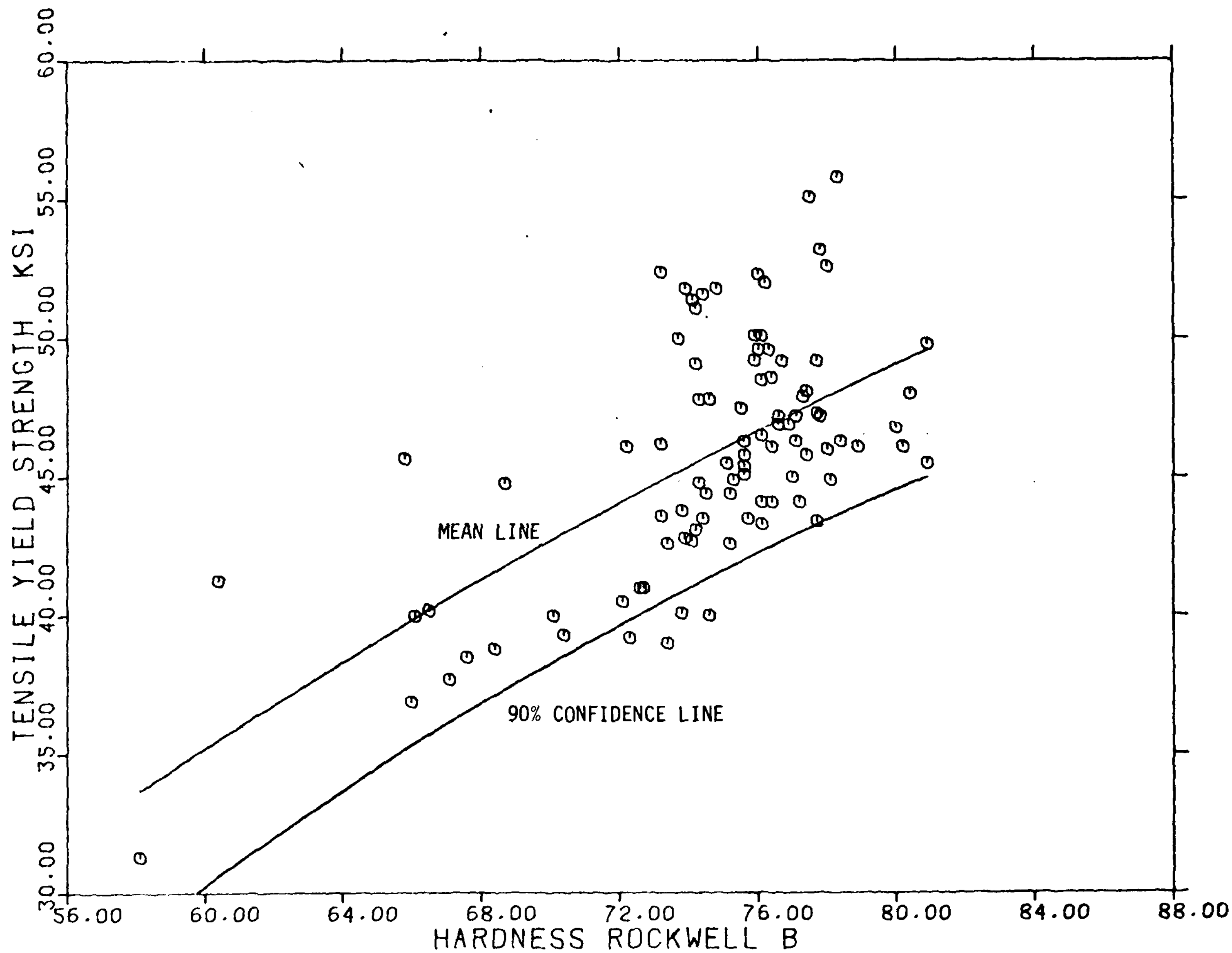

FIGURE 29. TENSILE YIELD STRENGTH VS. HARDNESS; 2024 T351 PLATE - ALL THICKNESSES

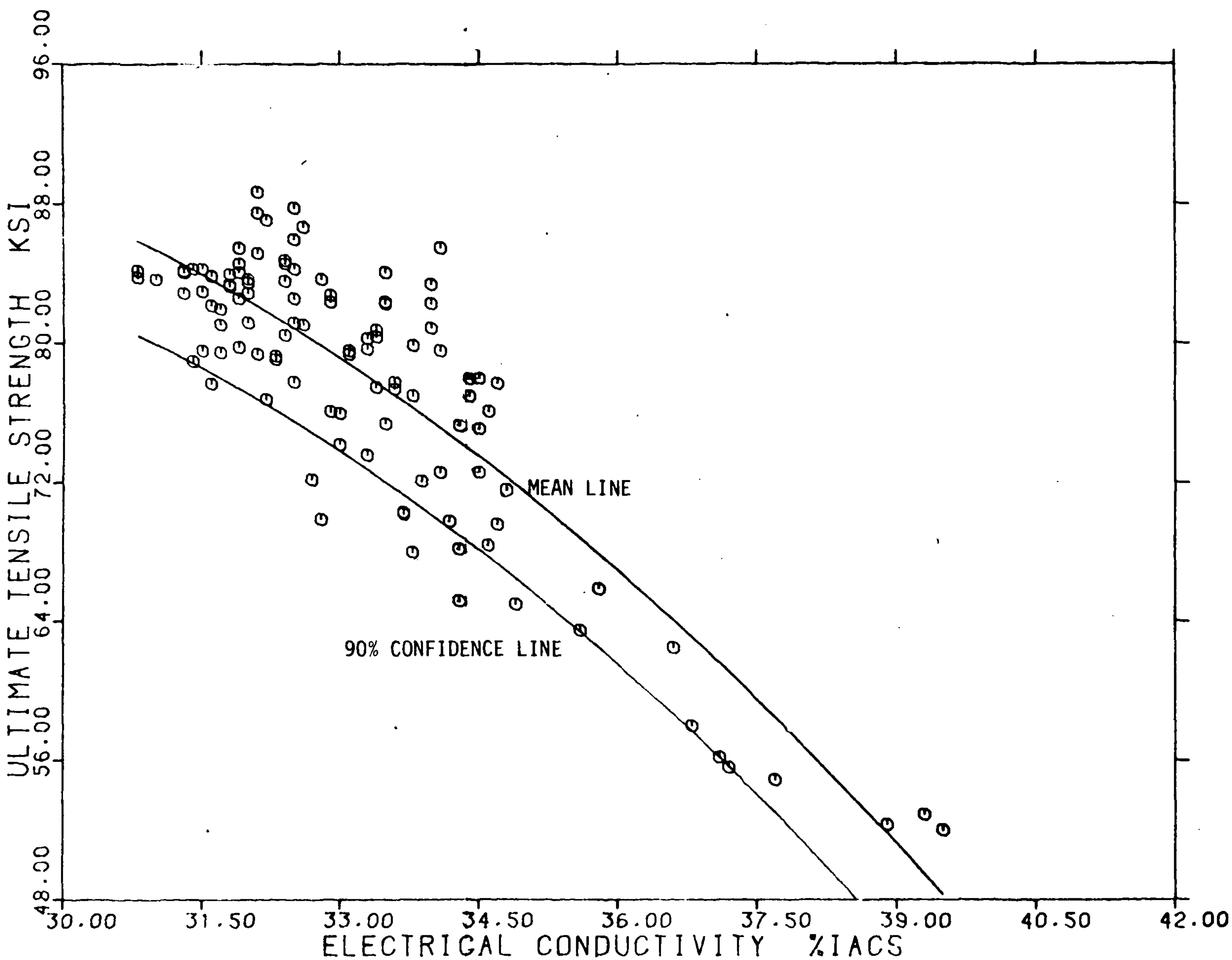

FIGURE 30. ULTIMATE TENSILE STRENGTH VS. CONDUCTIVITY; 7075 T651 PLATE - ALL THICKNESSES

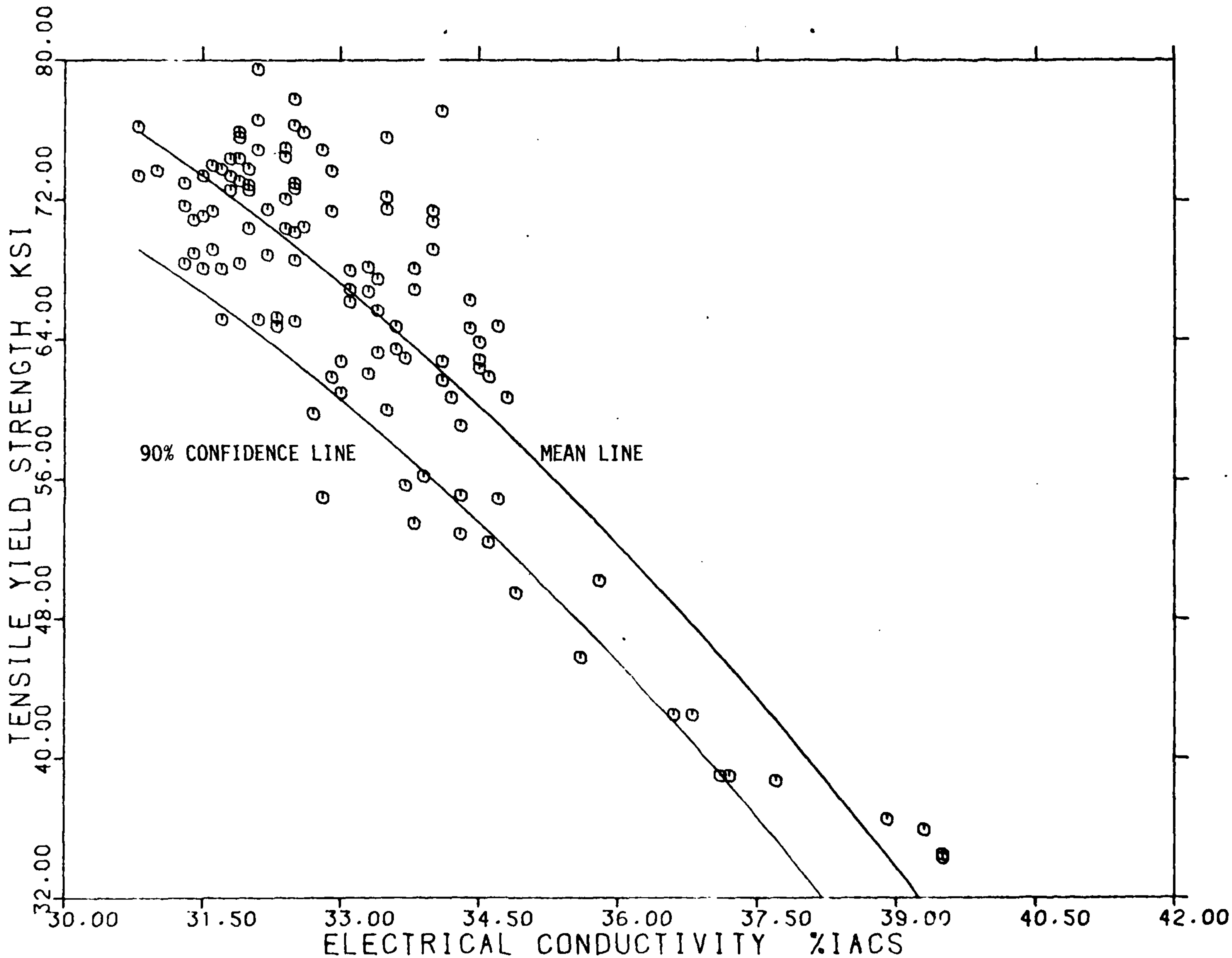

FIGURE 31. TENSILE YIELD STRENGTH VS. CONDUCTIVITY; 7075 T651 PLATE - ALL THICKNESSES

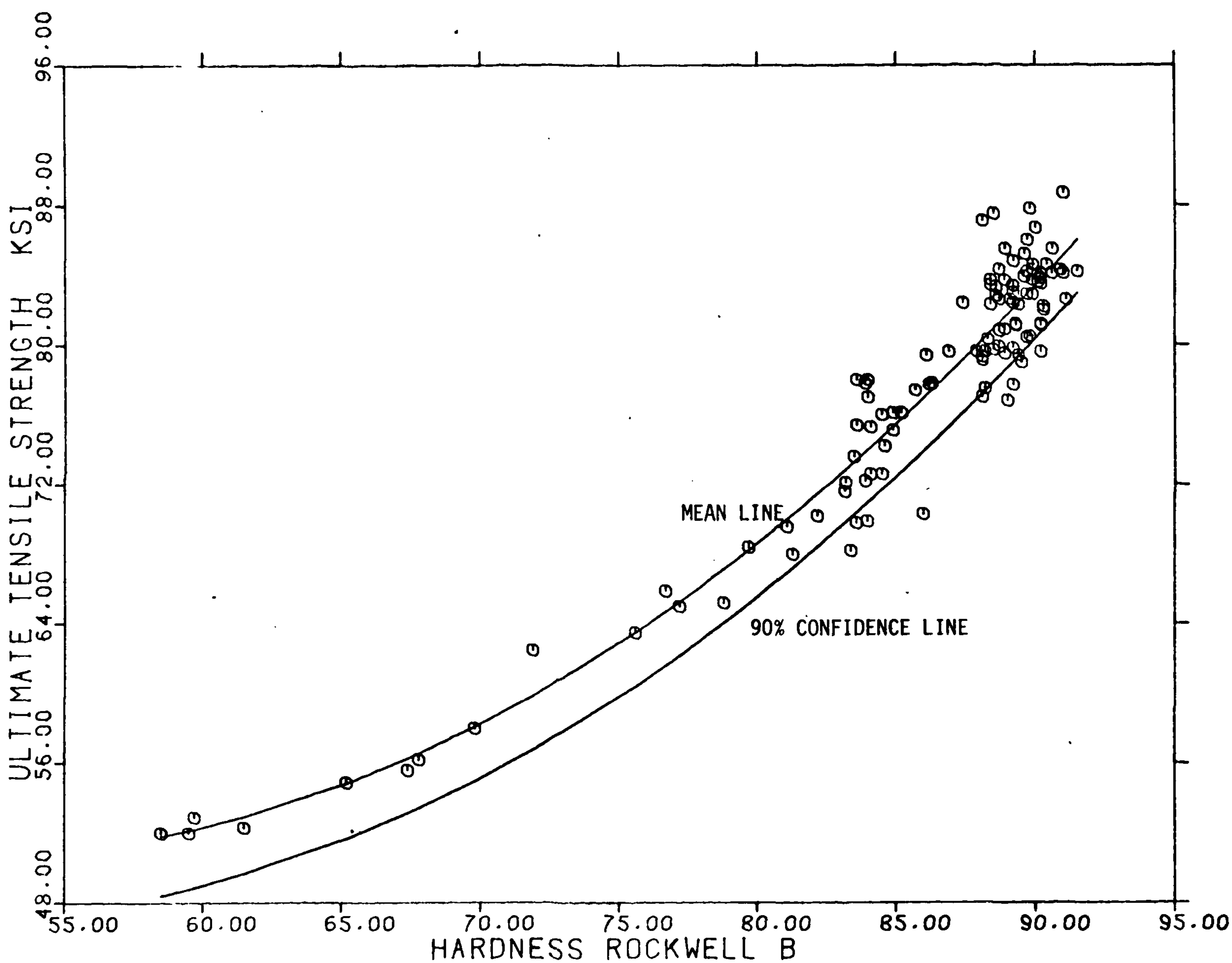

FIGURE 32. ULTIMATE TENSILE STRENGTH VS. HARDNESS; 7075 T651 PLATE - ALL THICKNESSES

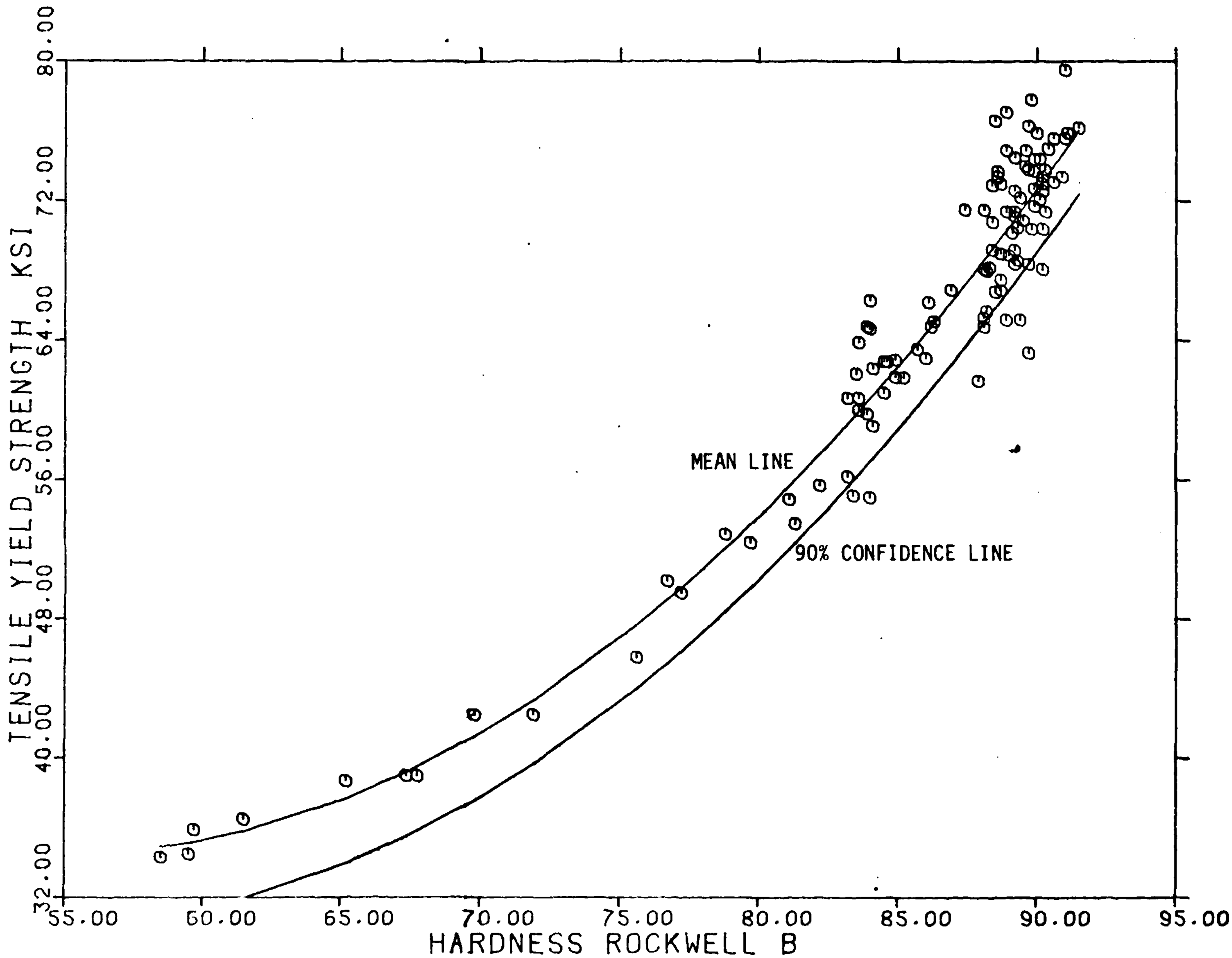

FIGURE 33. TENSILE YIELD STRENGTH VS. HARDNESS; 7075 T651 PLATE - ALL THICKNESSES

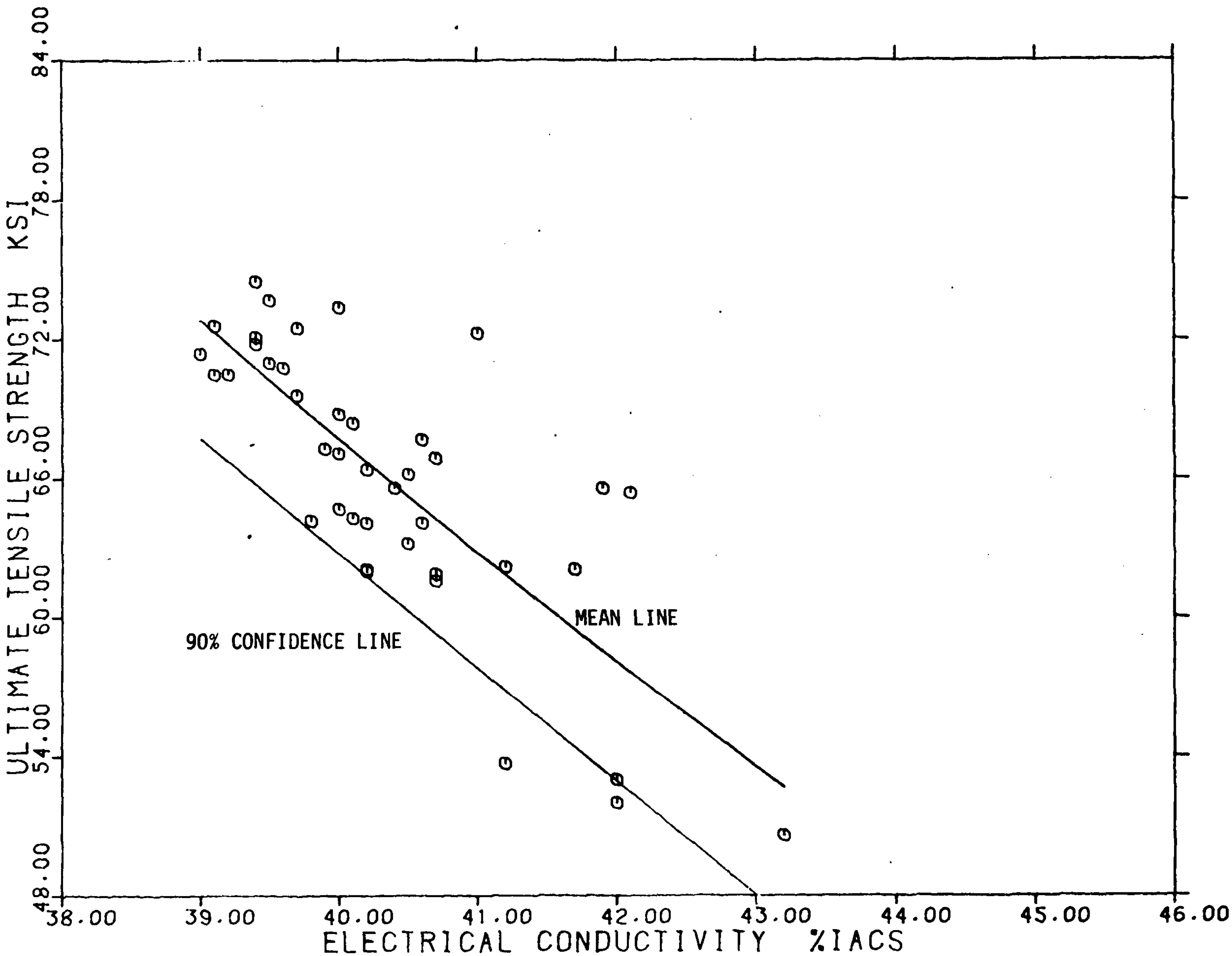

FIGURE 34. ULTIMATE TENSILE STRENGTH VS. CONDUCTIVITY; 7075 T7351 PLATE - ALL THICKNESSES

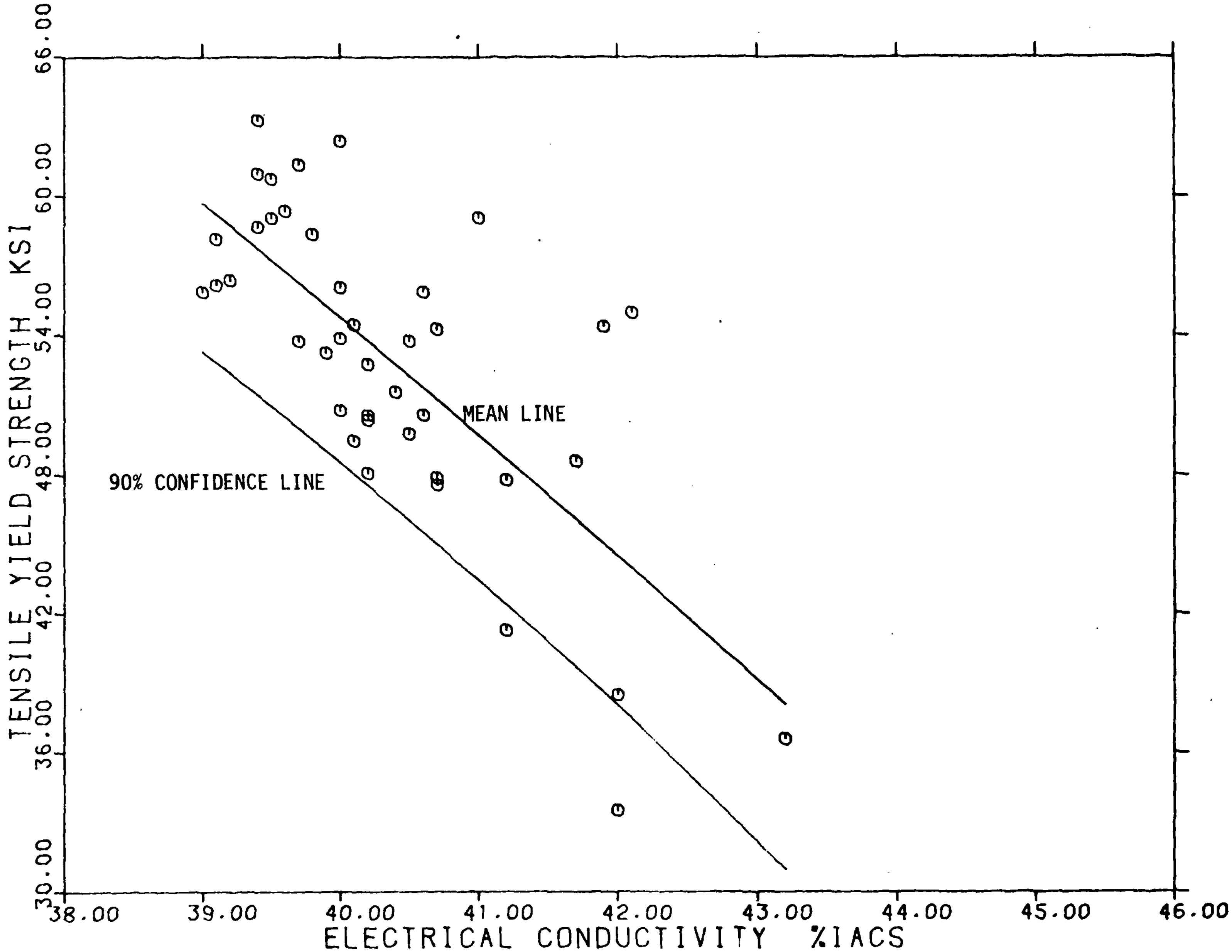

FIGURE 35. TENSILE YIELD STRENGTH VS. CONDUCTIVITY; 7075 T7351 PLATE - ALL THICKNESSES

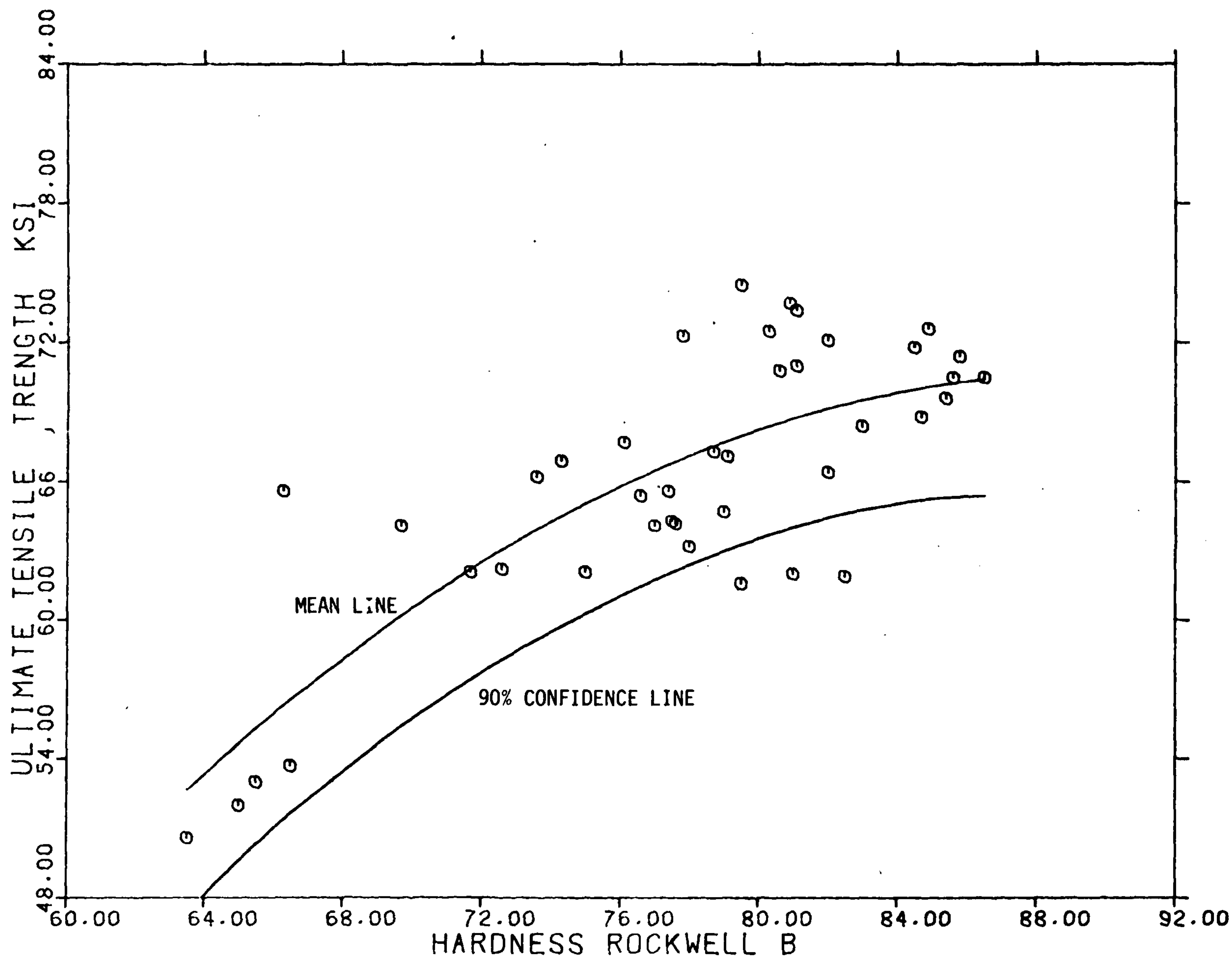

FIGURE 36. ULTIMATE TENSILE STRENGTH VS. HARDNESS; 7075 T7351 PLATE - ALL THICKNESSES

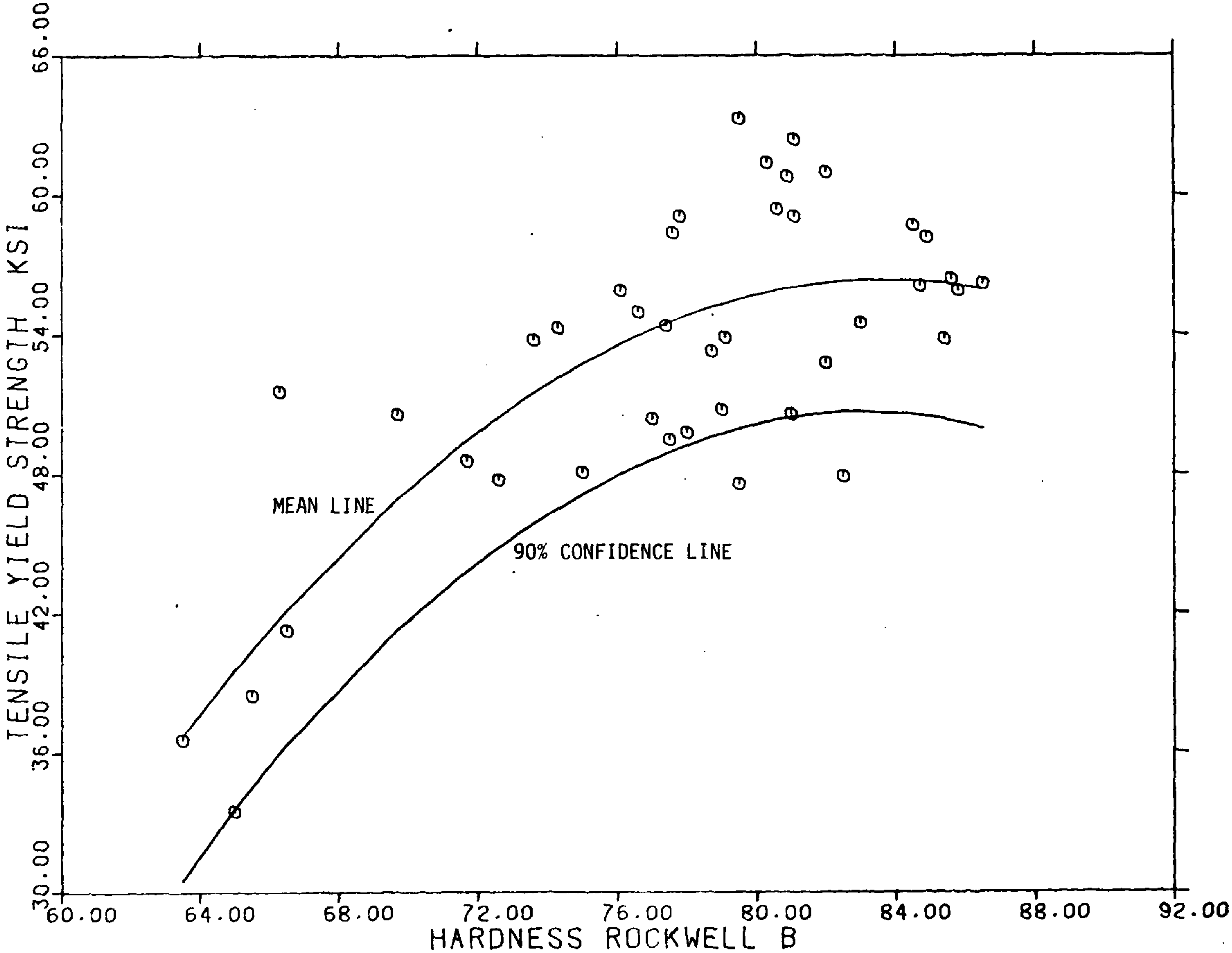

FIGURE 37. TENSILE YIELD STRENGTH VS. HARDNESS; 7075 T7351 PLATE - ALL THICKNESSES

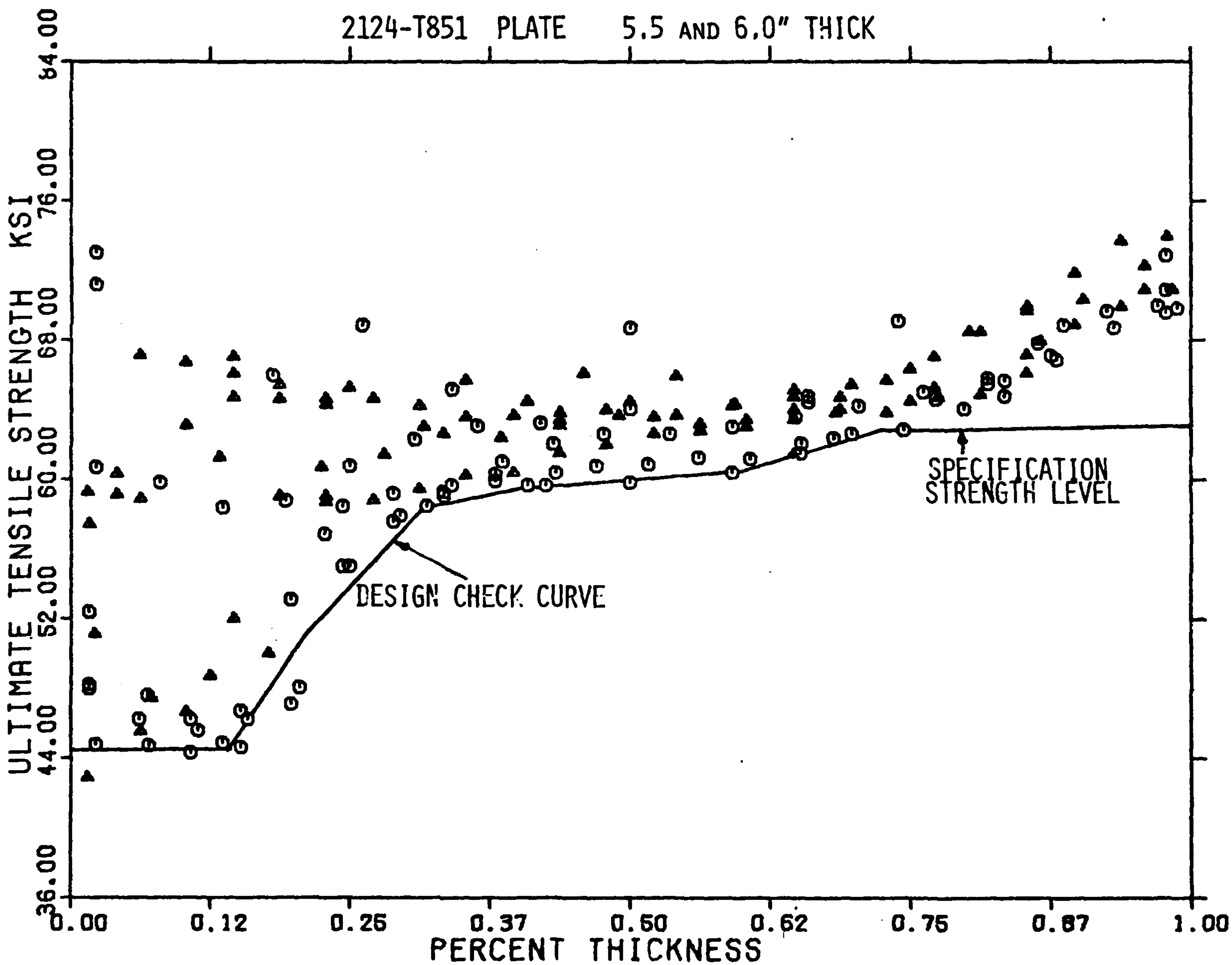

Figure 38. Ultimate Strength Design Check Curve

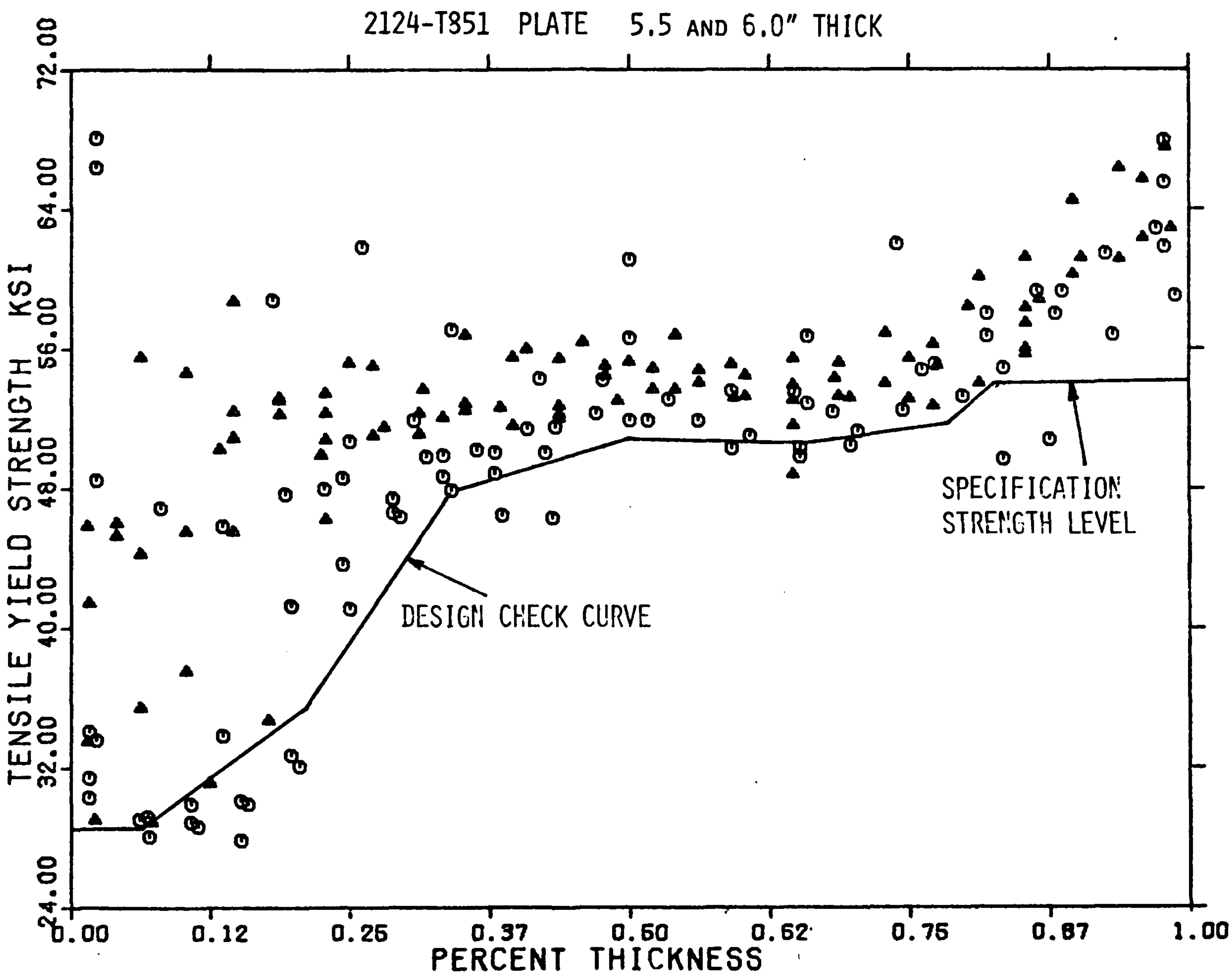

Figure 39. Yield Strength Design Check Curve