FOREWORD

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The report covers the performance of work during the period from April 1, 1963 to March 31, 1964.

Machining of test specimens and construction of test equipment was accomplished by K. Chapman, A. Jackson, and D. Carlton. L. Barrus was primarily responsible for the construction of the compliance gage. C. Chave and J. McKeon assisted in the performance of tests. Their ready assistance and cooperation is greatly appreciated.

ABSTRACT

A preliminary study of the influence of testing system stiffness on the fracture of center-cracked sheet specimens of 7075-T6 aluminum indicated a noticeable effect of testing system stiffness on crack propagation in that decreasing the testing system stiffness resulted in the suppression of the slow or intermittent crack growth.

A controlled experimental program on titamium RS 140 to study the interplay between specimen length and crack length, the two variables affecting the stiffness of the specimen, showed an effect of testing system stiffness on both crack propagation and fracture strength. Compliance curves, obtained with a specially designed compliance gage, showed a higher strain energy release rate for a given incremental crack growth dc in short specimens. The lower fracture strength observed in short specimens may be explained on this basis.

Both energy and stress considerations of the effects of testing system stiffness are presented. An analysis of stiffness effects on crack propagation behavior is attempted.

This technical documentary report has been reviewed and is approved.

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INTRODUCTION

The influence of testing system stiffness on the deformation and fracture behavior of test specimens has often been recognized and discussed (Refs. 1, 2, 3, 4, 5). However, only a few direct investigations of this influence have been made (Refs. 3, 4, 5, 6, 7, 8). Most of the investigators studying fracture and plastic flow characteristics pay little attention to the stiffness of the testing system. The design of specimens and grips is generally based on such considerations as separation between machine platens, eccentricity, and stress concentration at fillets. The stiffness of the specimen-grip-machine assembly is seldom taken into account. However, as the following literature survey shows, stiffness effects may significantly influence the plastic flow and fracture characteristics of materials.

Kochendorfer and Wink (Ref. 4) investigated the effect of machine stiffness on yield point observation. They found that machine stiffness had considerable influence on the shape of the stress strain curve in the yield region and pointed out the necessity of a stiff machine with little inertia in the force measuring system, for resolving the upper and lower yield points.

Bolling, Hays and Wiedersich (Ref. 10) studied pseudo yield point effects which accompany a change in strain rate made during tensile deformation of metals. They examined Pb, Cu, Ag single crystals and polycrystalline Cu, Al and Fe in various tensile machines at several temperatures and strain rates. They found that part, and in some cases, all, of such a yield point effect is associated with the characteristics of the particular tensile testing machine used.

Almar-Naess (Ref. 5) studied the effect of external elastic energy released from test equipment on fracture behavior of notch bend specimens. He used short specimens, long specimens, and short specimens loaded in series with a spring and found that fracture appearance transition temperature is influenced by energy stored in the specimen or specimen and spring assembly. He also showed that while for an ordinary notch-bend specimen elastic energy release rate decreases with increase in crack length, in the case of a specimen loaded in series with a soft spring it increases with an increase in crack length.

de Leiris (Ref. 6) investigated the effect of length on strength and ductility of notch tension specimens. The specimens were 3.0 cm. thick, 3.8 cm. wide, and 27.3 and 418.5 cm. long. They contained 3 mm. deep 45° edge notches with 0.25 mm. notch root radius. The results indicate a decrease of both nominal fracture stress as well as ductility with increasing specimen length.

Wells (Ref. 11) investigated strain energy release rate in geometrically similar slow notched-bar bend specimens. He found good agreement between strain energy release rates calculated from load, loading span and ligament values at fracture and those measured by the temperature-wave method. He concluded that brittle fracture may not occur in sufficiently small specimens because of an insufficient strain-energy release rate.

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According to Kies (Ref. 12) experiments at the Naval Research Laboratory on centrally notched sheet specimens of polymethyl-methacrylate (plexiglass) showed that for short specimens a fairly uniform unbranched fast fracture was produced, whereas in longer specimens having a large excess of total energy a considerable amount of roughening and shattering occurred. The shattering and branching increased steadily as the crack progressed.

Grewal (Ref. 13) investigated plastic deformation in double-notched tension specimens (having different stress concentration factors) of AMS 6434 sheet, heat treated to two strength levels. Values of maximum fracture strain at notch root were nearly the same for the two strength levels; but maximum fracture strain at midwidth was lower for the higher strength material. Higher velocity fracture due to greater elastic energy stored in higher strength material could have resulted in lower fracture strain at midwidth.

Irwin and Kies (Ref. 3) carried out an analysis of the effect of specimen dimensions and crack length on the strain energy relase rate in notched sheets. Assuming fixed grip conditions and an infinitesimally small initial crack, they found that for long specimens (those having high length to width ratio) strain energy release rate increased monotomically with increase in crack length, while for short specimens strain energy release rate at first increased with a decreasing rate, reached a maximum value and then decreased with further increase in crack length. Thus for short and wide specimens a fast ductile fracture may not completely traverse the sheet but may be stopped due to decrease in strain energy release rate. Experiments in the Naval Research Laboratory on long and short aluminum foil specimens have demonstrated this conclusion.

According to Allen (Ref. 14) the amount of stored energy in a structure must have an effect on the toughness or brittleness of fracture. An ordinary gas cylinder, when tested to destruction with internal pressure of water, usually opened gradually, tearing apart along a longitudinal line. It is almost unknown for it to shatter entirely. Nevertheless, when gas cylinders filled with compressed gas storing a great amount of energy, failed in service, they often exploded and shattered. He concluded that the stored energy of the gas affected the follow through after the initial rupture, and in turn decided whether the failure would be brittle or ductile.

Ball and Turner (Ref. 7) investigated the effect of energy stored in the test piece and in the testing machine on fracture characteristics of both flat and round notch tension specimens. The more compliant condition of the test piece or machine normally gave transition temperature higher (by not more than 10°C) and maximum load lower by about 1-4 percent than those for the stiffer condition.

Yoshiki, Kanazawa and Machida (Ref. 8) and Kanazawa and Machida (Ref. 9) reviewed existing analyses of strain energy release rate and pointed out their inapplicability to short specimens and to specimens containing long cracks. They have given a strain energy release rate analyses which, they believe, gives a better picture of the behavior of short specimens. For sufficiently short specimens under fixed grip condition, they predict a $\frac{dE_s}{dc}$ versus c curve having a maximum and a minimum, with possibility for arrest or slow growth of the crack.

The objective of the present investigation was to study the effects of testing system stiffness on fractures of cracked sheet specimens. An extensive literature survey was conducted and is summarized above. A theoretical evaluation of the problem considering both energy and stress criteria of fracture follows this introduction.

The experimental phase of the program was initiated with exploratory experiments on 4 in. and 1.75 in. wide 7075-T6 specimens, which were tested under a wide variety of testing system stiffness.

It was realized that to gain an insight into the nature of the stiffness effects, the effect of crack length needs to be better understood. Thus an investigation of the interplay between specimen length (stiffness) and crack length was made on 4 in. wide, 0.025 in. thick RS 140 specimens. A special compliance gage was designed and constructed and automatic records of load-extension data were obtained. From these data stiffness versus crack length curves were drawn. Differences in the fracture characteristics of long and short specimens are interpreted in terms of the variation of their stiffness with crack length.

THEORETICAL CONSIDERATIONS

Energy considerations in fixed load and fixed grip conditions have been discussed by several authors (Refs. 3, 7, 8, 9, 11, 15, 18, 19). Bueckner has given a general analysis of energy supply in crack propagation. His main conclusions may be stated as follows:

1. Energy supplied for crack extension equals the difference of the strain energies of the stress fields before and after crack extension.

2. In the case of the constant load condition, strain energy of the specimen increases as the crack extends. But the virtual work, 2W, of the externally impressed forces equals twice the increase of the strain energy, and the surplus of work is available for crack propagation.

3. In the case of fixed grip condition, strain energy, E_s, of the specimen decreases as the crack extends, and the decrement in energy is available for crack propagation.

4. Energy available for finite crack extension is smaller for fixed grip condition than that for fixed load condition. However, for infinitesimal crack extension, $\frac{dW}{dc}$ (fixed load condition) and $-\frac{dE_s}{dc}$ (fixed grip condition tend to the same limit.

Consider a plate of thickness, t, with a central crack of length, 2c, normal to the tension axis. Let the compliance of the plate increase from M to M^1 as the crack extends from 2c to 2c'. Let e=MP be the extension of the plate under the influence of a load, P. The initial strain energy of the plate is

$$E_s = \frac{eP}{2} = \frac{MP^2}{2} = \frac{e^2}{2M} \qquad (1)$$

For constant load condition we have

$$\Delta W = (M^1 - M)\ \frac{P^2}{2}$$

For fixed grip condition, we have

$$-\Delta E_s = \frac{e^2}{2M} - \frac{e^2}{2M^1} = (M^1 - M)\ \frac{M}{M^1}\ \frac{P^2}{2}$$

Thus $-\Delta E_s$ is smaller than ΔW.

However, for infinitesimal crack extension

$$\frac{dW}{dc} = \frac{P^2}{2}\ \frac{dM}{dc} = -\frac{dE_s}{dc}$$

For fixed grip condition

$$- \frac{dE_s}{dc} = \frac{e^2}{2} \frac{d}{dc} \left(\frac{1}{M}\right) \qquad (2)$$

or

$$- \frac{dE_s}{dc} = \frac{M^2P^2}{2} \frac{d}{dc} \left(\frac{1}{M}\right) \qquad (3)$$

Thus at initial crack propagation under quasi-fixed grip conditions (sufficiently slow straining of a specimen in a stiff machine)

$$P^2 \propto \frac{1}{M^2 \frac{d}{dc} \left(\frac{1}{M}\right)} \qquad (4)$$

The occurrence of slow, intermittent or cataclysmic crack propagation under quasi-fixed grip conditions is to a large extent determined by the value of $\frac{d^2}{dc^2} \left(\frac{1}{M}\right)$ i. e. the curvature of $\frac{1}{M}$ versus c plot. Positive curvature means slow or intermittent crack growth and negative curvature cataclysmic crack propagation. The other important factor determining crack propagation behavior is the change in resistance to crack propagation with increase in crack length.

Greenspan (Ref. 17) developed a relationship for the stiffness $\left(\frac{1}{M}\right)$ as a function of specimen and crack dimensions, which can be expressed as

$$M = \frac{L}{BtE} \left(1 + \frac{4\pi c^2}{2 - y^2 - y^4} \cdot \frac{1}{BL} \right) \qquad (5)$$

where: $y = 2c/B$
$2c$ = crack length
B = width of plate
L = length of plate
E = modulus of electricity
t = thickness of plate
A = area

Because of the assumptions involved in its derivation, Eq. 5 is not expected to hold for $2c > \frac{B}{2}$. Its failure for short specimens is evident since, instead of approaching 0, M approaches $\frac{4\pi c^2}{B^2 tE\,(2 - y^2 - y^4)}$ as L approaches 0. Despite these limitations, it is a useful relation and yields

$\frac{dE_s}{dc}$ versus c curves qualitatively similar to those given by more complicated analysis of Kanazawa and Machida (Ref. 9). With the help of Eq. 5, one can obtain the strain energy release rate for fixed load condition,

$$\frac{dW}{dc} = \sigma^2 \frac{2\pi Bt}{E} \frac{y(2 + y^4)}{(2 - y^2 - y^4)^2}$$

For a very wide plate this formula reduces to

$$\frac{dW}{dc} = \frac{2\pi t}{E} \sigma^2 c$$

For short cracks in fixed grip condition one obtains

$$-\frac{dE_s}{dc} = \sigma^2 \frac{2\pi Bt}{E} \frac{y(2 + y^4)}{\left[2 + (r - 1) y^2 - y^4\right]^2} \qquad (6)$$

where $r = \frac{\pi B}{L}$. Thus $-\frac{dE_s}{dc} < \frac{dW}{dc}$ for a given c. Fig. 1 gives a plot of $-\frac{dE_s}{dc}$ versus y with the shape factor r as parameter. As can be seen, there are a number of r-y combinations for which $\frac{dE_s}{dc} = 0$. Beyond these maxima the crack driving force decreases with increasing crack length.

Weiss has suggested an analysis in terms of the stress distribution at the crack tip which yields essentially identical results. With the help of Neuber's theory of sharp notches one can obtain the stress at the tip of a crack as

$$\sigma_{tip} = \sigma_N K_t$$

where σ_N is the net section stress and K_t the stress concentration factor of the crack or notch. The change in stress at the crack tip with increasing crack length (a measure of crack driving force) is given by

$$\frac{d\sigma_{tip}}{dc} = K_t \frac{d\sigma_N}{dc} + \sigma_N \frac{dK_t}{dc}$$

which can be expressed in terms of the gross section stress, $\sigma_G = \sigma_N (1 - 2c/B)$

as

$$\frac{d\sigma_{tip}}{dc} = K_t\left[\frac{2\sigma_G}{B}\,\frac{1}{(1-2c/B)^2} + \frac{1}{1-2c/B}\cdot\frac{d\sigma_G}{dc}\right] + \frac{\sigma_G}{1-2c/B}\,\frac{dK_t}{dc} \qquad (7)$$

The first term is always positive, the second terms is zero for fixed load conditions and negative for fixed grip conditions and the third term is positive for short cracks and negative for long cracks. Thus it is possible, under suitable conditions, for the crack driving force to decrease with increasing crack length. These conditions can be defined as

$$-\frac{d\sigma_G}{dc} \geqslant \sigma_G\left[\frac{2}{\left(1-\frac{2c}{B}\right)} + \frac{1}{K_t}\;\frac{dK_t}{dc}\right] \qquad (8)$$

Since $d\sigma_G$ is related to the testing system stiffness, stiff conditions are required for $d\sigma_{tip} = 0$ for shallow cracks, where dK_t/dc is strongly positive, while softer systems may suffice for deep cracks.

Slow crack growth under rising load or falling load is essentially defined by the equality sign in Eq. 8. Since for slow crack growth under rising load $d\sigma_G/dc$ must be positive, dk_t/dc must be strongly negative to compensate for the increase in net section stress. This can be accomplished by crack tip blunting or increase in plastic zone size with increasing crack length. Both dK_t/dc and the system stiffness determine whether or not slow crack growth also occurs under falling load.

EXPERIMENTAL PROCEDURE

The design of 7075-T6 specimens used in this preliminary investigation is shown in Fig. 2. These specimens had an overall length of 3 in., a gage length of 0.375 in., and two different widths, namely 4 in. and 1.74 in. Center notches of varying length were introduced with a 0.007 in. thick jeweler's saw. Specially designed wedge grips were used for the testing of these specimens, Fig. 4.

The stiffness of the testing system was varied by introducing additional linkage or a soft spring in series with the specimen. Stiffness values of different machines are given in Table 1.

The design of RS 140 titanium alloy specimens is shown in Fig. 3. The specimens were 4 in. wide and had two different gage lengths; 8 in. and 1 in., respectively.

Initial saw cuts were extended by tension-tension fatigue to give cracks of different lengths. Cracking was done in the solution treated condition. Subsequent aging reduced strain hardening at the crack tips and also tinted the crack surface, thereby facilitating accurate measurement of the crack length of the fractured specimen.

Wedge grips, designed for 7075-T6 specimens, were also used for RS 140 specimens by the insertion of spacers. For longitudinal specimens containing short cracks, cracking at the holes in the grips was experienced and this problem was remedied by drilling two additional holes in the spacers and in either end of the specimen and inserting short dowel pins into the holes.

A compliance gage to measure the stiffness of each specimen was designed and constructed. It is shown in Fig. 4. The gage was held in position by means of 1/16 in. dowel pins which passed through the specimen and rested in the grooves in the arm of the gage. The arms were slightly compressed together to start with and sprang apart as the specimen elongated. Upper arms, made out of hardened and tempered die steel, contained four strain gages (two on top and two on the bottom side) mounted on thin sections. The signal from the gages was fed into the preamplifier of the Instron machine and load-extension curves were obtained directly. For 8 in. gage length specimens, a spacer was inserted between the upper and lower arms of the gage and the gage was counterbalanced to eliminate extraneous strains introduced by the weight of the gage.

Separation between the grips, rather than the distance between the pins carrying the compliance gage, has been taken as the measure of the gage length. This corresponds to fixed displacement boundary condition assumed in Greenspan's analysis. In 1 in. gage length specimens the displacement between the grips is essentially the same as the displacement between pins of the compliance gage, since most of the extension along the centerline is taken up by the opening of the crack. In 8 in. gage length specimens, the difference between the displacement of the pins and that of the grips is obviously negligible as compared with the total displacement.

All the tests on RS 140 specimens and most of the test on 7075-T6 specimens were performed at the crosshead speed of 0.002 in. per minute. The effective rate of straining was somewhat less because of the springing out of the wedge grips.

EXPERIMENTAL RESULTS AND DISCUSSION

7075-T6 Specimens

The results of tests on 7075-T6 aluminum alloy specimens are summarized in Table 2 and in Fig. 5. Changing the stiffness by introducing additional linkage or a soft spring in series with the specimen does not seem to have any appreciable effect on the stress required to initiate crack propagation or on net section fracture strength. However, the specimen in series with a soft spring broke at maximum load with a loud noise, without any preceding slow crack propagation. Slow or stepwise crack growth was observed in all other 4 in. wide specimens.

Both the stress at initial crack propagation and net section fracture strength were considerably higher for 1.75 in. wide specimens. No slow or stepwise crack propagation was observed in 1.75 in. wide specimens which invariably fractured at maximum load. Thus it seems that in short gage length specimens, fracture stress decreases considerably with the decrease in length to width ratio.

RS 140 Specimens

Since significant influence of length to width ratio on fracture stress was found in 7075-T6 specimens tested under rather crude experimental conditions, it was decided to conduct a more controlled program on RS 140 titanium alloy specimens. The heat treatment, chemical composition, and properties of this alloy are given in Table 3. In these specimens, width was kept constant and two gage lengths, 8 in. and 1 in. were included. Fatigue cracks, instead of jeweler's saw cuts, were employed. A compliance gage was used to measure the extension of the specimens and load-extension curves were obtained for each test. Typical curves for 8 in. and 1 in. gage length specimens are given in Figs. 6 and 7, respectively. Departure from linearity of the loading curve and zig zag portions of unloading curve indicate slow crack extension. The last smooth portion of the curve is due to the inability of the Instron chart and pen to respond quickly enough to rapid changes in extension and load: and thus indicates fast crack propagation.

Test data obtained on RS-140 titanium is given in Table 4. Stiffness versus crack length curves for 8 in. and 1 in. gage length specimens are shown in Figs. 8 and 9, respectively. Theoretical values of stiffness, based on Eq. 5, are also given in these figures.

Compliance or stiffness measurements on single gage length specimens containing cracks of varying length have been reported by Brossman and Kies (Ref. 18), Morrison et al (Ref. 20), and Krafft, Sullivan and Boyle (Ref. 21).

As discussed earlier under theoretical considerations, curvature of the 1/M versus c curve is an important factor determining crack propagation behavior under quasi-fixed grip conditions; positive curvature indicating occurence of slow crack propagation. In the present experiments, slow crack growth was observed in all test points at which 1/M versus c curve had positive curvature, in spite of the fact that the testing machine was not sufficiently stiff. Slow crack growth was observed in all 1 in. gage length specimens with the exception of those having cracks less than 0.26 in. in length. On the other hand all 8 in. gage length specimens broke spontaneously at maximum load with the exception of one specimen with a 2.57 in. long crack.

Experimentally observed stiffness curves are qualitatively similar to those predicted by theory, although experimental points consistently fall below the theoretical curves. The difference between the theory and the experiment is very marked for 1 in. gage length specimens. As discussed earlier, Greenspan's relation is not likely to be accurate in this case and it is felt that these measurements represent fairly accurately the actual relationship between crack length and specimen stiffness. There may be slight error due to the specimen not being held very rigidly in the grips. However, it is not likely to be significant since some of the longitudinal specimens which contained 3 holes in the specimen end and the corresponding transverse specimens which contained only 1 hole gave essentially the same stiffness values.

Fracture strength (maximum load divided by initial net section area) versus crack length curves for 8 in. and 1 in. gage length longitudinal and 1 in. gage length transverse specimens are given in Fig. 10. The fracture strength of 8 in. gage length specimens is much higher than that of 1 in. gage length specimens. This is in accord with ideas developed under theoretical considerations. According to Eq. 4, the load at initial crack propagation under quasi-fixed grip conditions is given by

$$P^2 \propto \frac{1}{M^2 \frac{d}{dc}\left(\frac{1}{M}\right)}$$

Substituting experimental values of $\frac{d}{dc}\left(\frac{1}{M}\right)$ from Figs. 8 and 9 for an 0.8 in. long crack, we have

$$M^2 \frac{d}{dc}\left(\frac{1}{M}\right) = 5.7 \times 10^{-6}\ \text{lb}^{-1} \quad \text{for in. gage length specimen}$$

and

$$M^2 \frac{d}{dc}\left(\frac{1}{M}\right) = 1.13 \times 10^{-6}\ \text{lb.}^{-1} \quad \text{for 8 in. long specimens}$$

Thus

$$\frac{P_{8\ \text{in.}}}{P_{1\ \text{in.}}} = 2.2$$

which agrees well with the experimentally observed factor of 2 difference in fracture strength values.

The role of increased eccentricity in reducing the fracture strength of short specimens in comparison to the long ones needs to be considered. There is no doubt that eccentricity is a more serious problem in short specimens than in long specimens. Hence special care was taken from the beginning to keep eccentricity at a minimum. Design of the wedge grips was such as to permit self-alignment during initial loading of the specimens. This difference is due rather to difference in stress fields in the vicinity of the crack tip in the two cases and the resulting difference in strain energy release rates.

Fig. 10 also shows considerable difference between the fracture strengths of longitudinal and transverse 1 in. gage length specimens, particularly those containing short cracks. Thus, it seems short specimens tend to magnify and bring out small differences in fracture toughness which conventional fracture testing employing long specimens might ignore.

CONCLUSIONS

The following conclusions may be drawn from this investigation and would probably apply, in general, to fracture and crack propagation in thin center-cracked specimens of semi-brittle materials.

1. There is a noticeable effect of testing system stiffness on crack propagation. Decreasing the testing system stiffness generally results in the suppression of slow or intermittent crack propagation which precedes fast and final fracture in specimens tested under stiff conditions.

2. Stiffness versus crack length curves are extremely useful in an analysis of specimen stiffness effects on fracture under quasi-fixed grip conditions, since their slope is proportional to the energy release rate. Thus their positive curvature would result in slow crack growth and negative curvature would encourage fast crack propagation.

3. The fracture strength of long (8 in. gage length) specimens was considerably higher than corresponding short (1 in. gage length) specimens. This was shown to be due to higher strain energy release rates in short specimens.

4. Short specimens tend to bring out small differences in fracture toughness and may find important application in fracture testing.

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Table I

Machine Stiffness Values of the Various Machines Employed in the Investigation

Type	Capacity (lbs.)	Load Mechanism	Stiffness 10^4 lbs/in	Remarks
Instron	10,000	Screw	50	Tension load, without specimens or grips. 6 inches between platens
Instron	10,000	Screw	0.72	In series with 5000 lb. spring
Baldwin	60,000	Hydraulic	765	Compression load. 9.5 inches between platens.
Baldwin	60,000	Hydraulic	43	Tension load. 1 inch diam. bar 18 inches between platens
Riehle	300,000	Hydraulic	84	Tension load. 12 inches between platens

Table 2

Test Data on 7075-T6 Aluminum Alloy Specimens

Spec No	B (in)	AC (in)	t (in)	Load at initial crack growth (lbs)	Net Section Stress at initial crack growth (ksi)	Max load (lbs)	Remarks
1	4.00	0.257	.0475	10,450	59.0	10,450	Stiff system, intermittent crack growth
3	4.00	0.277	.049	10,800	59.2	11,260	Stiff system, intermittent crack growth
4	4.00	0.309	.053	11,450	58.5	11,450	Soft spring in series with the specimen. Instantaneous crack propagation at maximum load.
2	4.00	0.319	.051	10,600	56.5	10,900	Soft system. Intermittent crack growth
14	4.00	0.537	.046	6,200	38.9	6,900	Stiff system, intermittent crack growth
13	4.00	1.196	.048	~5000	~37.1	7,600	Stiff system, slow crack growth
11	1.75	0.164	.049	6170	79.4	6170	Stiff system, fast one-step crack propagation
12	1.75	0.494	.048	4800	79.6	4800	Stiff system, fast one-step crack propagation
10	1.75	0.503	.053	5000	75.7	5000	Stiff system, fast one-step crack propagation
15	1.75	0.897	.049	3200	76.5	3200	Stiff system, fast one-step crack propagation

Table 3

Chemical Composition, Heat Treatment and Strength Properties of RS 140 Titanium Alloy

Chemical Composition

Al	5.10	percent
Cr	3.10	percent
Fe	1.30	percent
C	0.031	percent
N_2	0.011	percent

Heat Treatment

Solution treated, descaled and aged at 700 F for 6 hours.

Strength Data

Ultimate tensile strength = 195 ksi
(0.375 in wide, 2 in gage length specimens)

Young's modulus = 1.64×10^7 lbs/in^2

Table 4

Test Data on RS 140 Titanium Alloy Specimens

Spec.	Gage	B	2c	t	Maximum	Fracture	Stiffness*
				Longitudinal Specimens			
B9	8	4.000	0.493	0.0228	3865	49.6	1.81
B13	8	4.000	0.707	0.0232	3105	40.6	1.70
B 4	8	4.000	1.149	0.0249	2665	37.5	1.85
B5	8	4.000	1.409	0.0251	2460	37.8	1.65
B19	8	4.000	1.750	0.0241	1705	31.5	1.49
B17	8	4.000	2.031	0.0245	1448	30.0	1.38
B15	8	4.000	2.571	0.0239	1032	30.2	1.22
B6	1	4.000	0.259	0.0250	3710	39.7	7.94
B7	1	4.000	0.475	0.0216	2130	28.0	6.02
B2	1	4.000	0.841	0.0250	1755	22.2	4.27
B14	1	4.000	1.284	0.0245	1262	19.0	2.51
B10	1	4.000	1.621	0.0227	966	17.9	1.79
				Transverse Specimens			
A14	1	4.003	0.211	0.0225	2010	23.6	8.75
A19	1	4.004	0.416	0.0230	1498	18.2	5.60
A17	1	4.003	0.419	0.0226	1686	20.8	5.44
A22	1	4.005	0.792	0.0234	1222	16.3	3.48
A21	1	4.005	0.794	0.0247	1546	19.5	3.56
A11	1	4.001	1.196	0.0217	920	15.1	-
A13	1	4.002	1.208	0.0236	1130	17.2	2.51
A12	1	4.001	1.211	0.0265	1123	15.2	2.28
A6	1	4.005	1.627	0.0232	832	15.1	1.64
A7	1	4.000	1.631	0.0235	839	15.1	1.51
A5	1	4.006	1.664	0.0231	890	16.4	1.34
A3	1	3.998	2.075	0.0236	826	18.2	1.09
A32	1	3.996	2.806	0.0257	689	22.5	0.63

* Stiffness values have been normalized to the thickness of 0.025 by multiplying with 0.025/t.

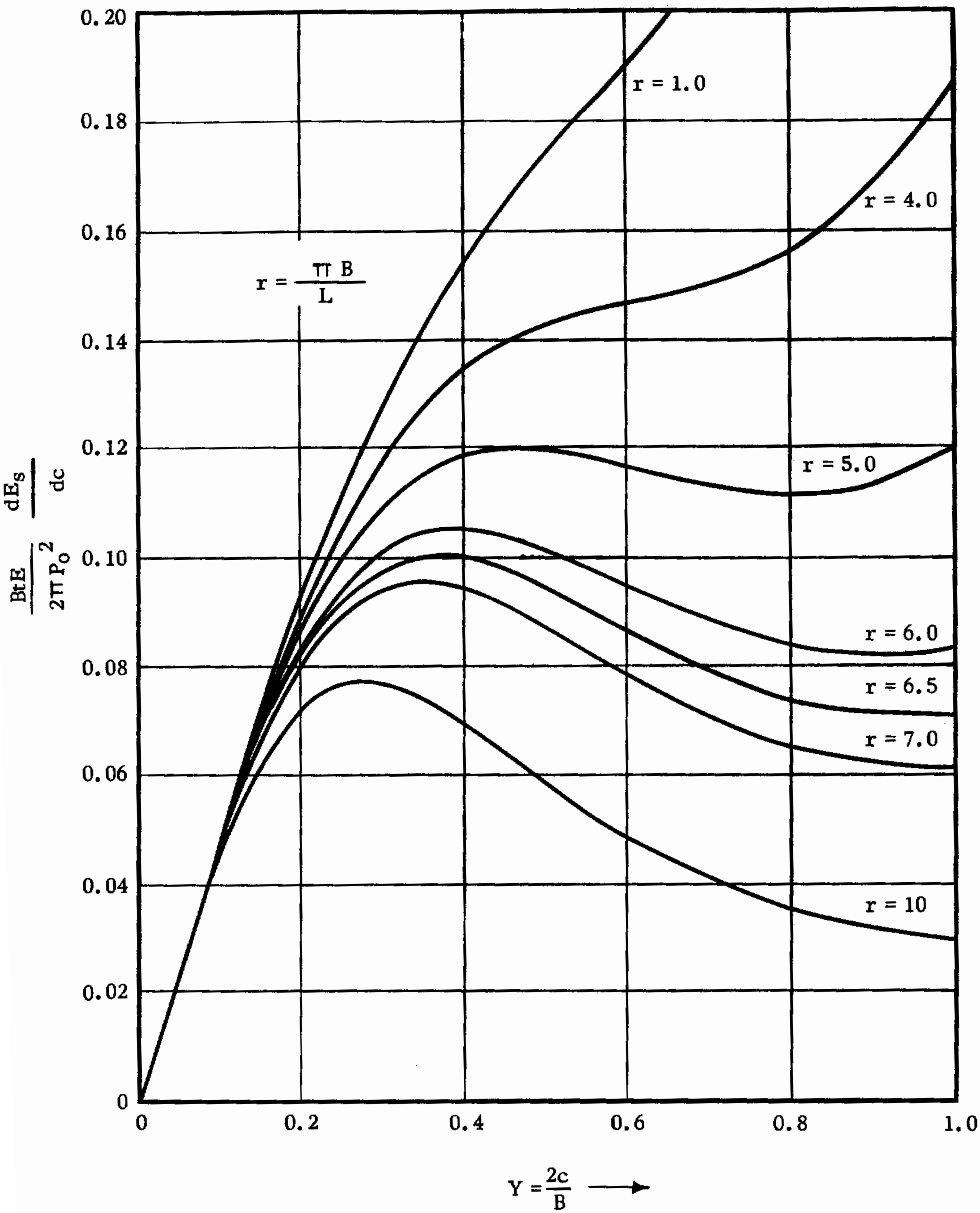

FIG. 1 VARIATION OF STRAIN ENERGY RELEASE RATE DURING THE GROWTH OF A SMALL INITIAL CRACK IN A SHEET UNDER FIXED GRIP CONDITIONS

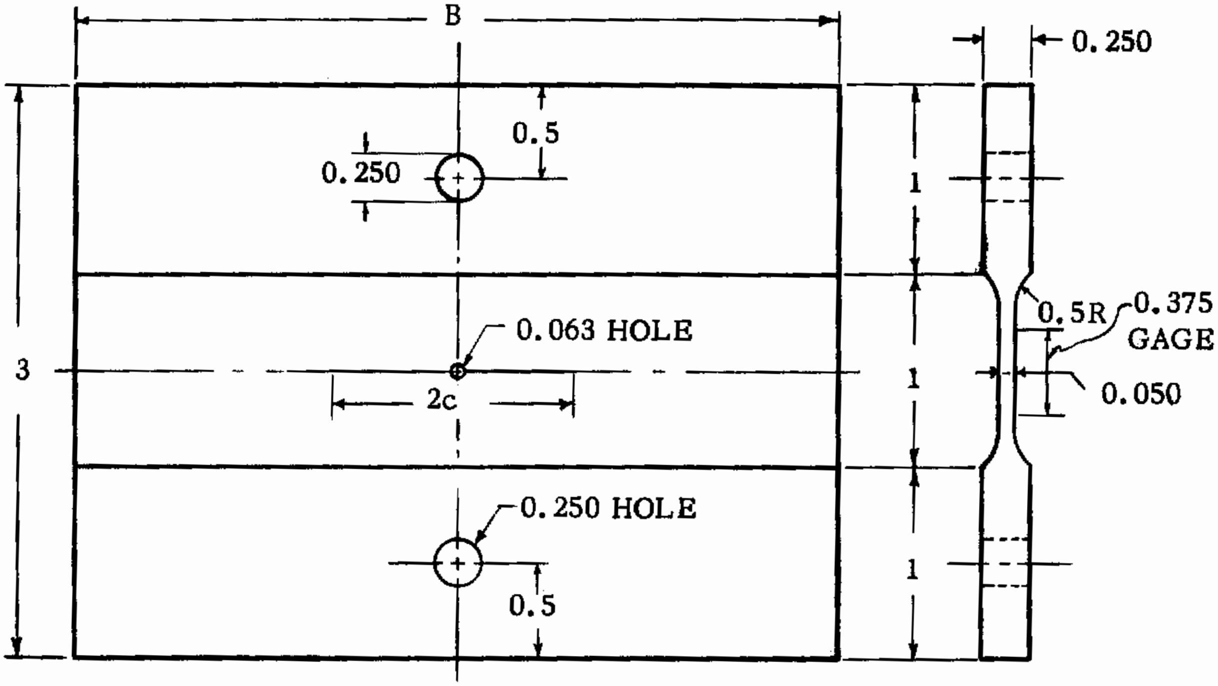

FIG. 2 7075-T6 ALUMINUM SPECIMEN

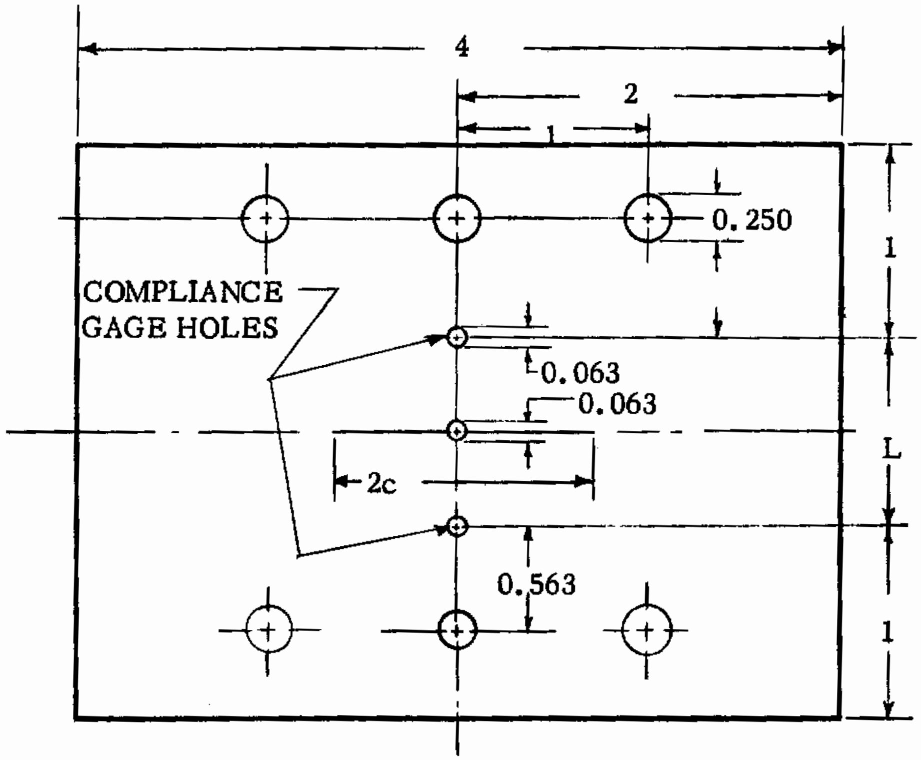

FIG. 3 RS-140 TITANIUM SPECIMEN

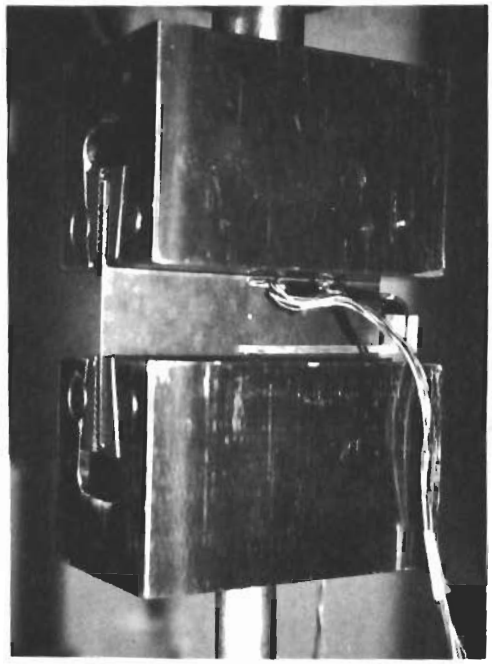

FIG. 4a THE WEDGE GRIPS

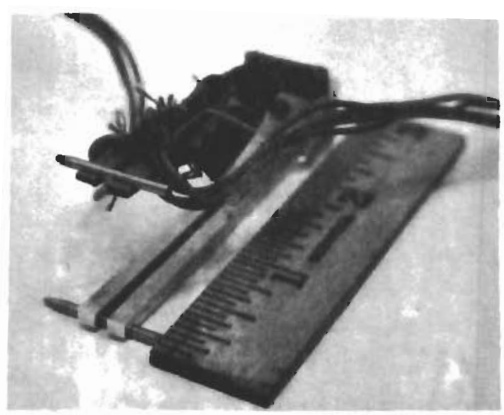

FIG. 4b THE COMPLIANCE GAGE

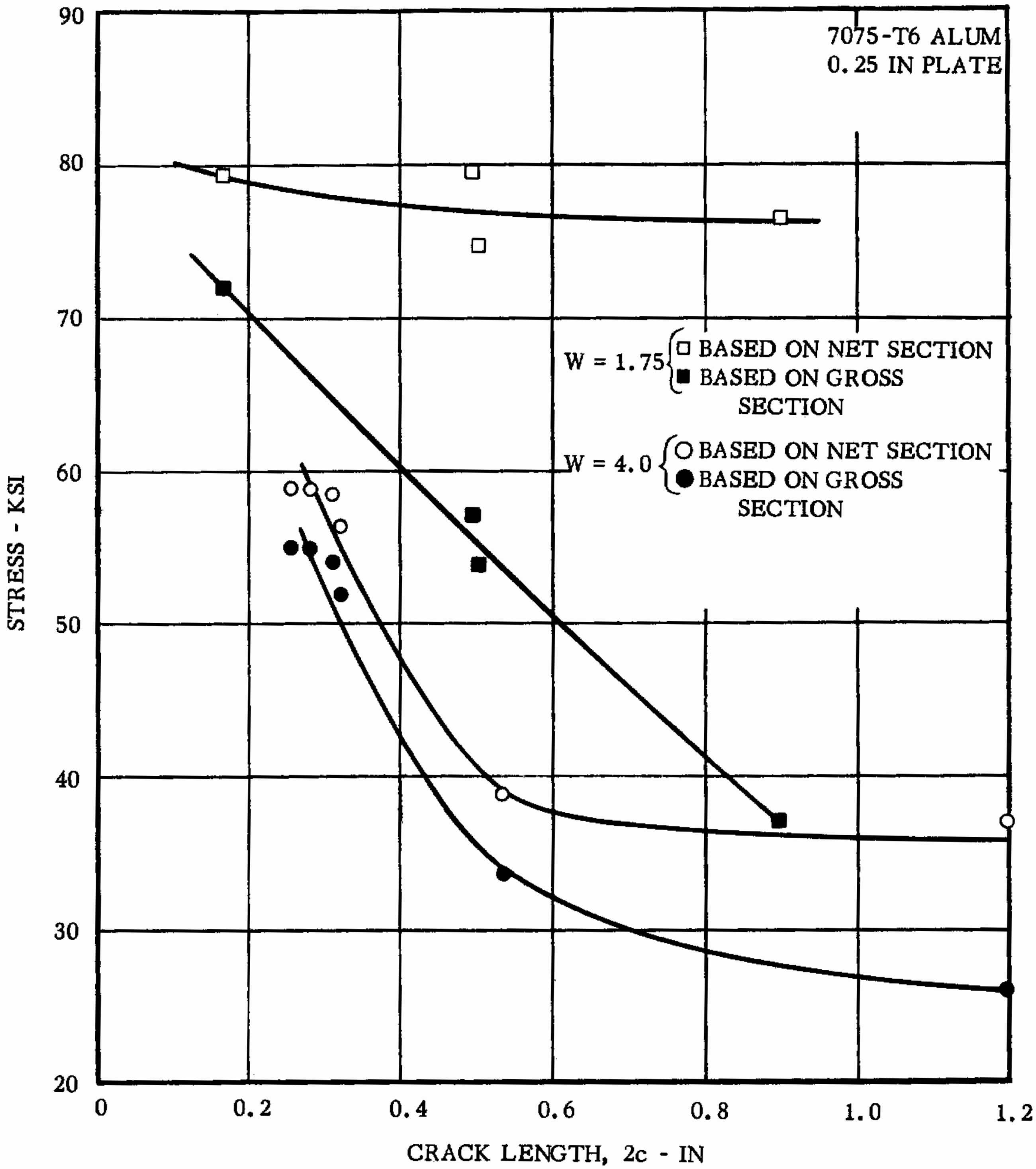

FIG. 5 VARIATION OF STRESS AT INITIAL CRACK PROPAGATION WITH CRACK LENGTH IN 7075-T6 ALUMINUM ALLOY SPECIMENS

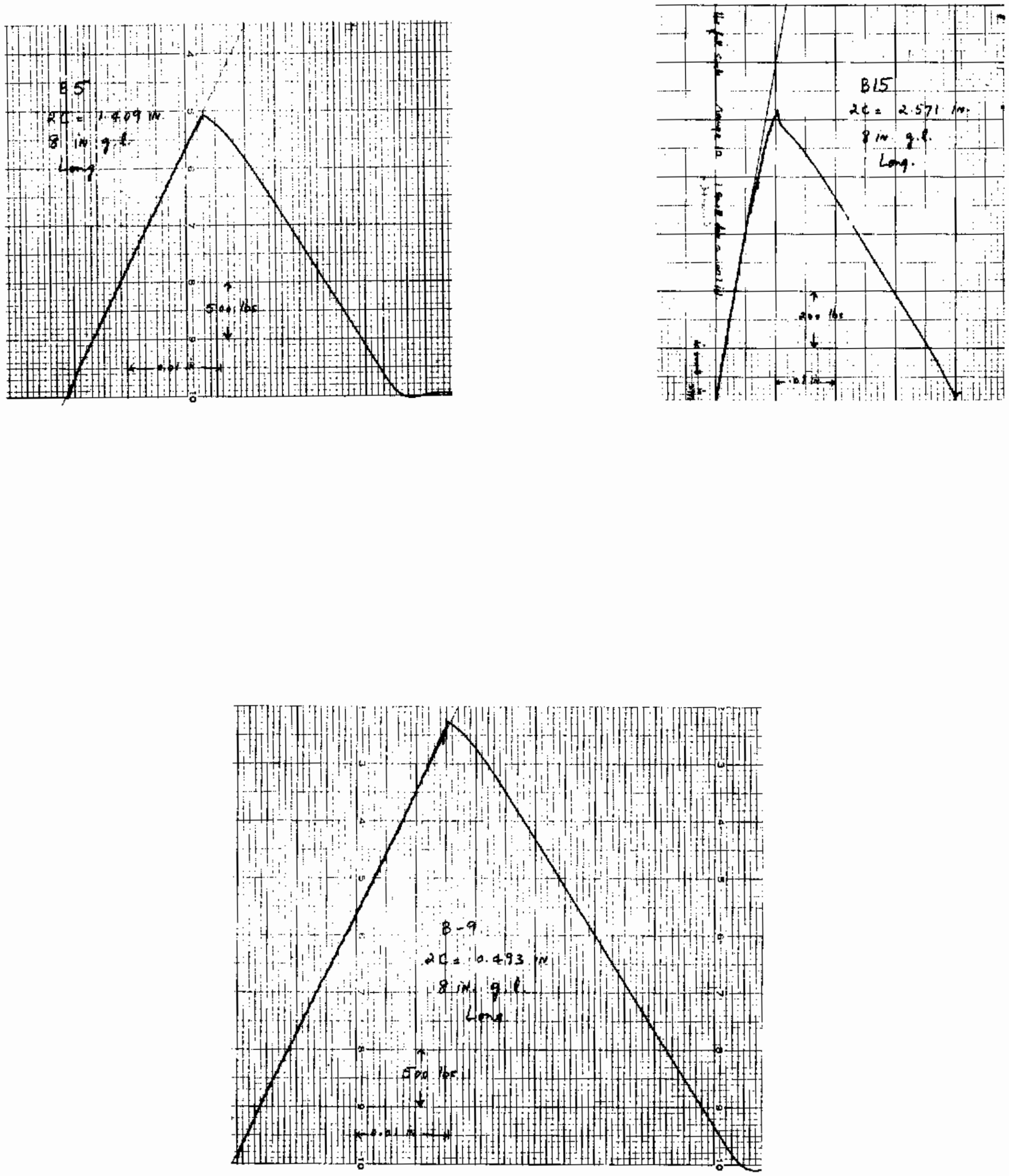

FIG. 6 TYPICAL LOAD-EXTENSION CURVES FOR 8 INCH GAGE LENGTH SPECIMENS

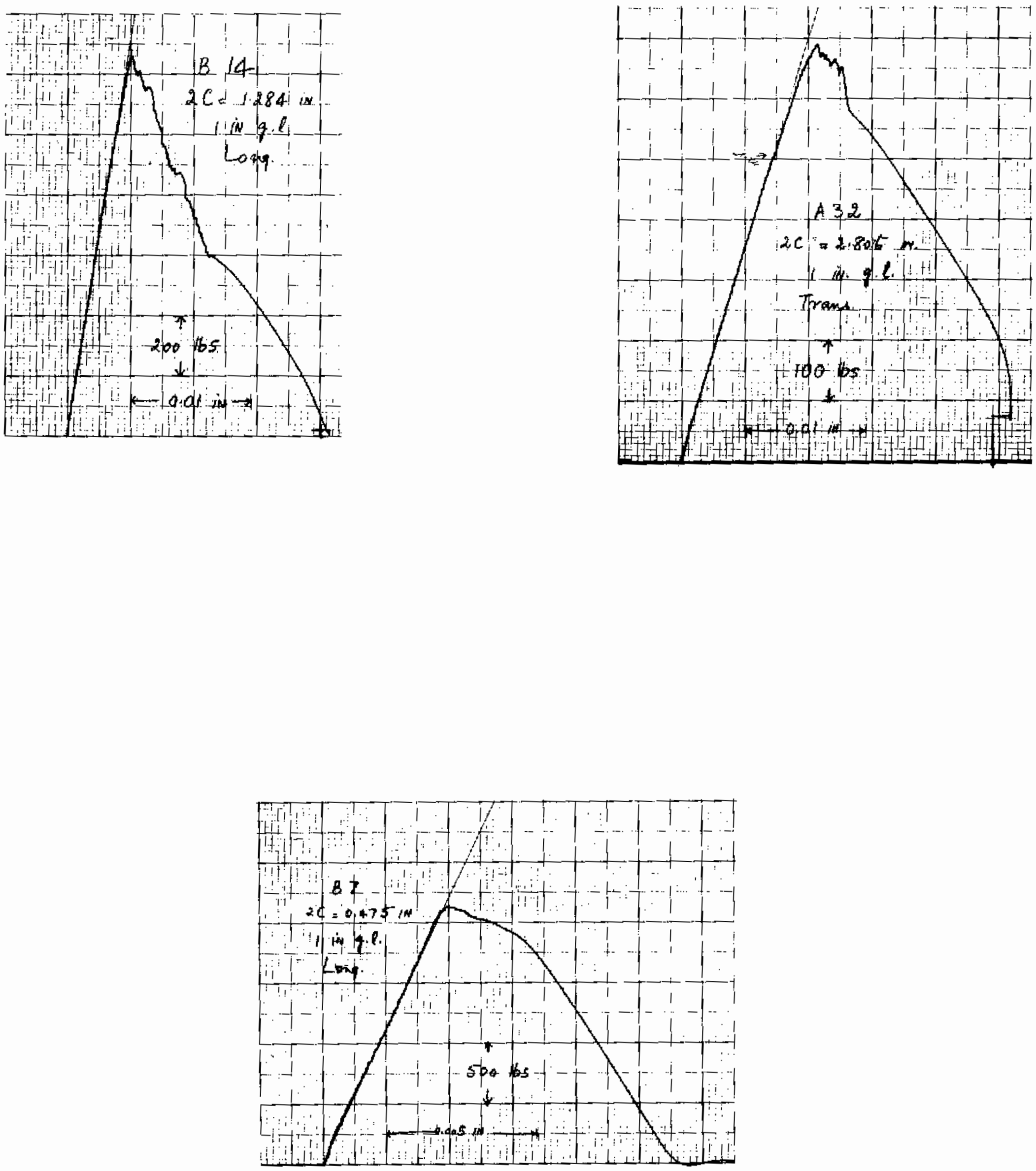

FIG. 7 TYPICAL LOAD-EXTENSION CURVES FOR 1 INCH GAGE LENGTH SPECIMENS

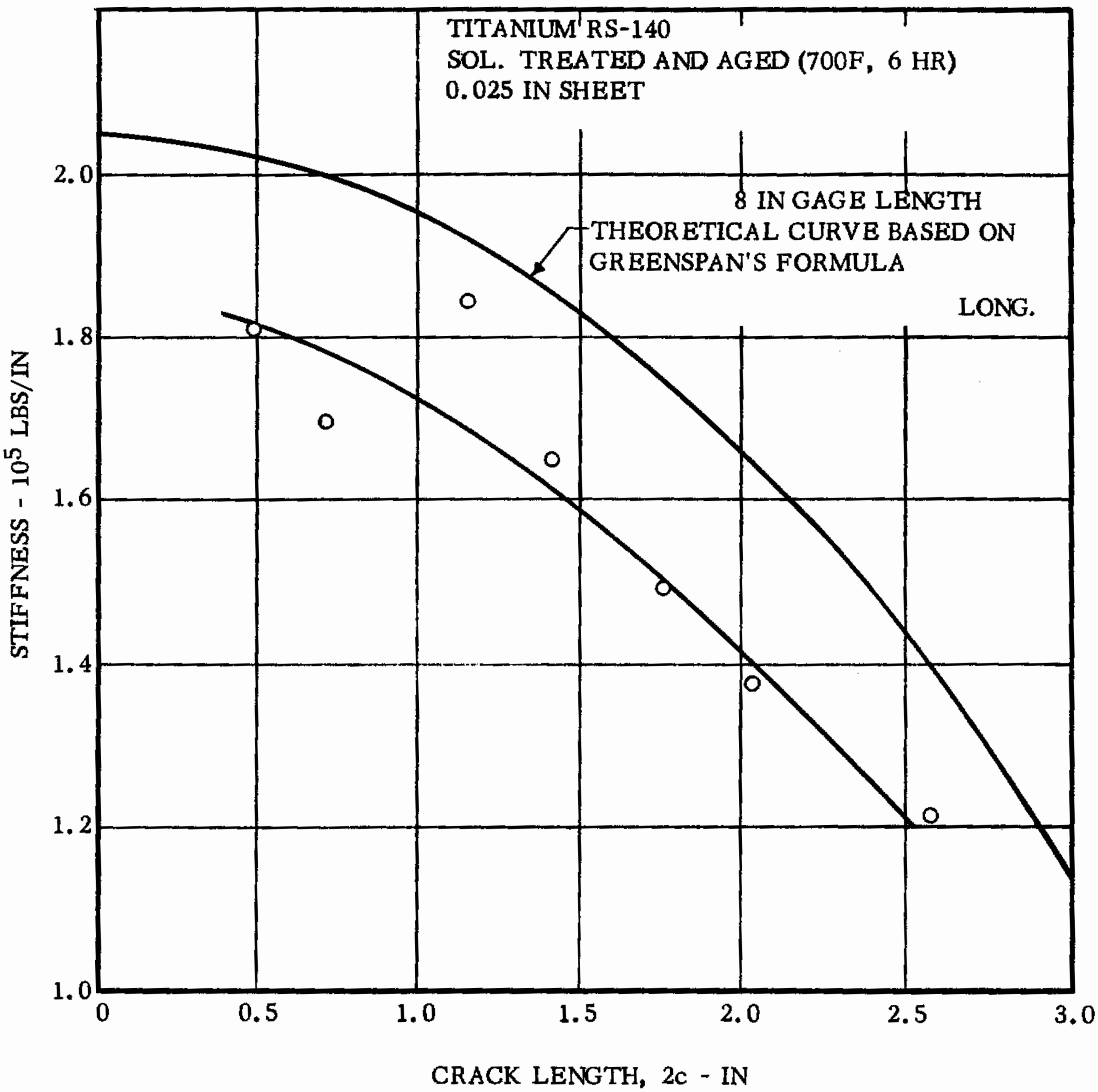

FIG. 8 VARIATION OF STIFFNESS WITH CRACK LENGTH IN 8 IN GAGE LENGTH RS-140 TITANIUM ALLOY SPECIMENS

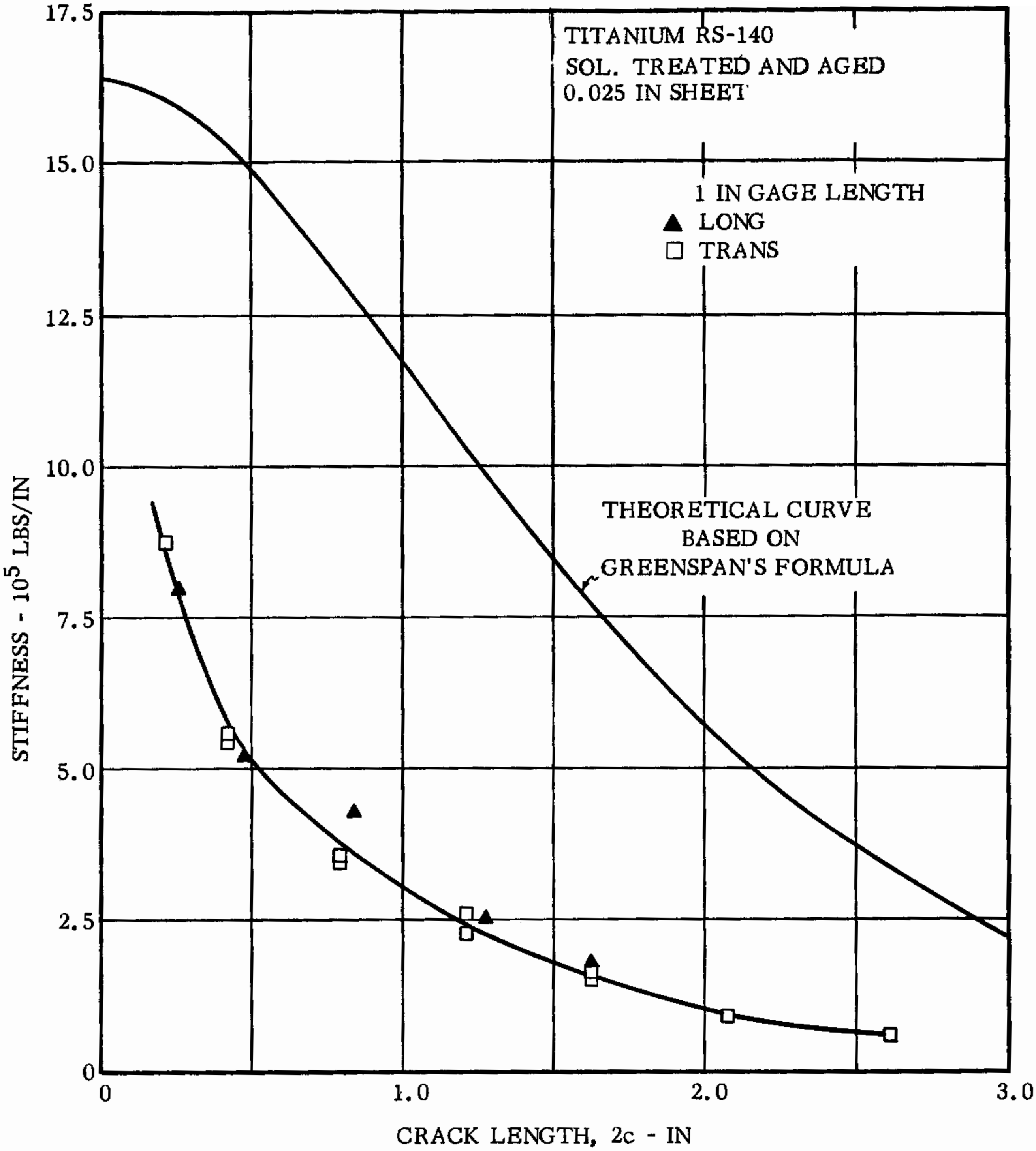

FIG. 9 VARIATION OF STIFFNESS WITH CRACK LENGTH IN 1 IN GAGE LENGTH RS-140 TITANIUM ALLOY SPECIMENS

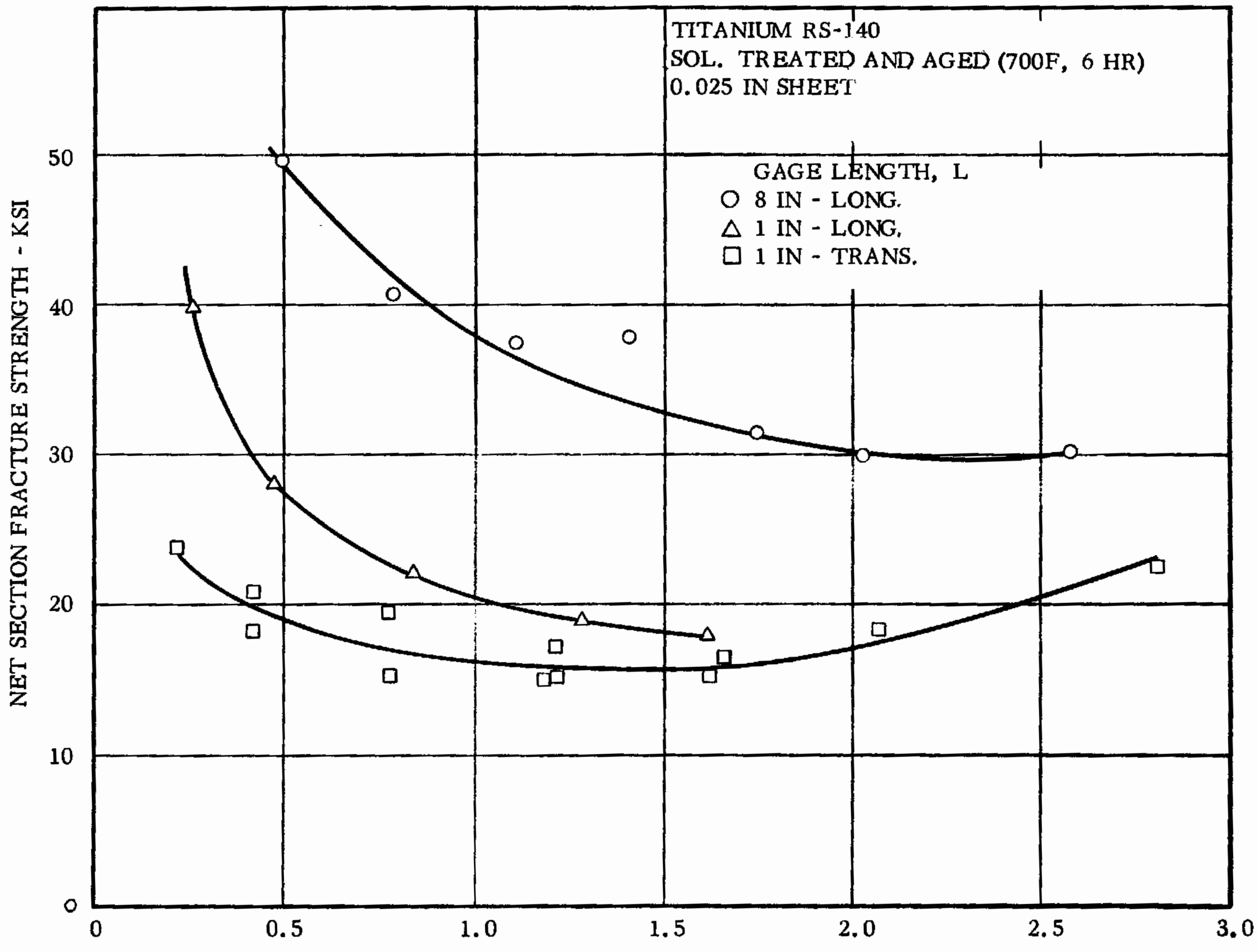

FIG. 10 VARIATION OF NET SECTION FRACTURE STRENGTH WITH CRACK LENGTH FOR RS-140 TITANIUM ALLOY SPECIMENS

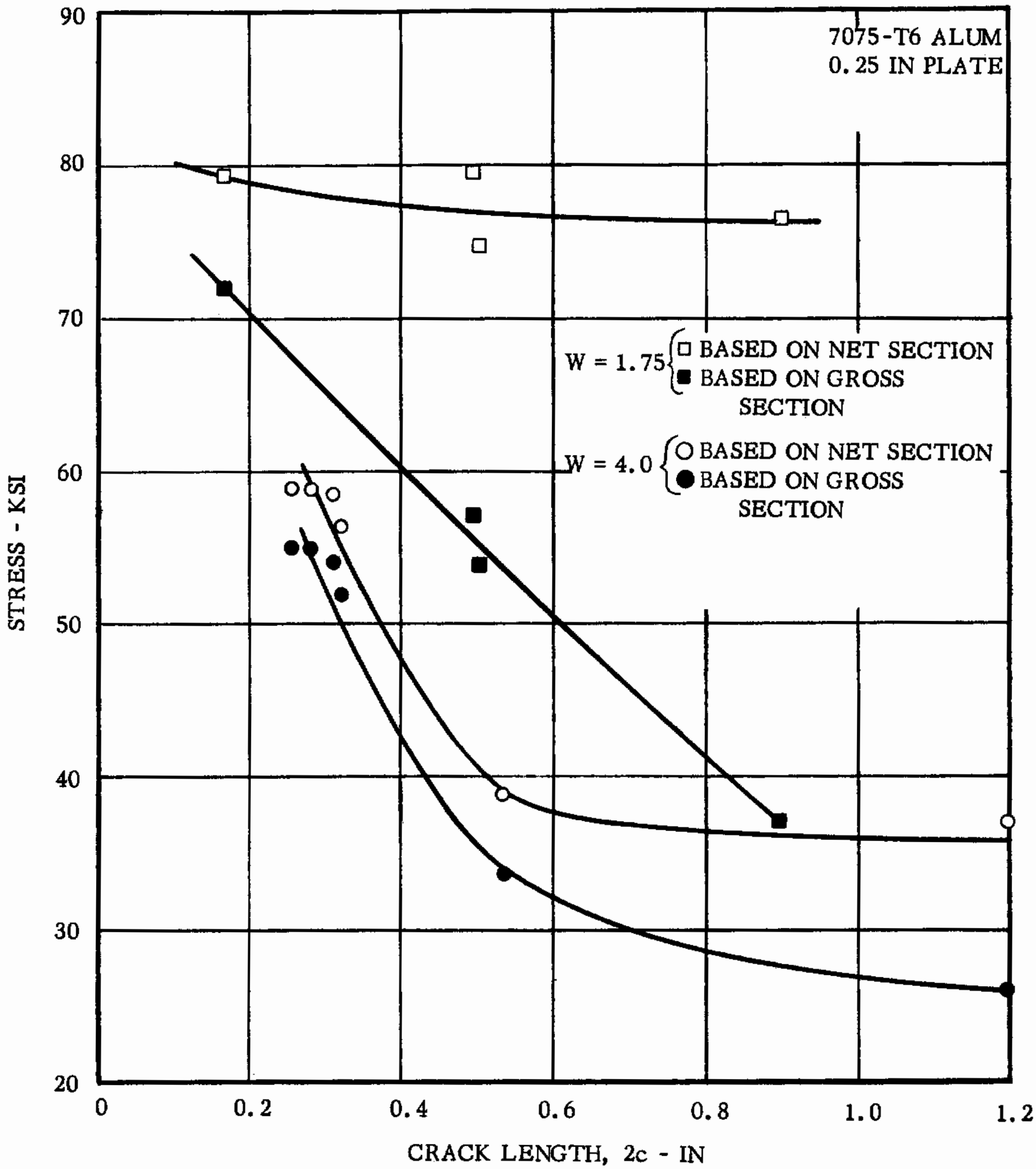

FIG. 5 VARIATION OF STRESS AT INITIAL CRACK PROPAGATION WITH CRACK LENGTH IN 7075-T6 ALUMINUM ALLOY SPECIMENS

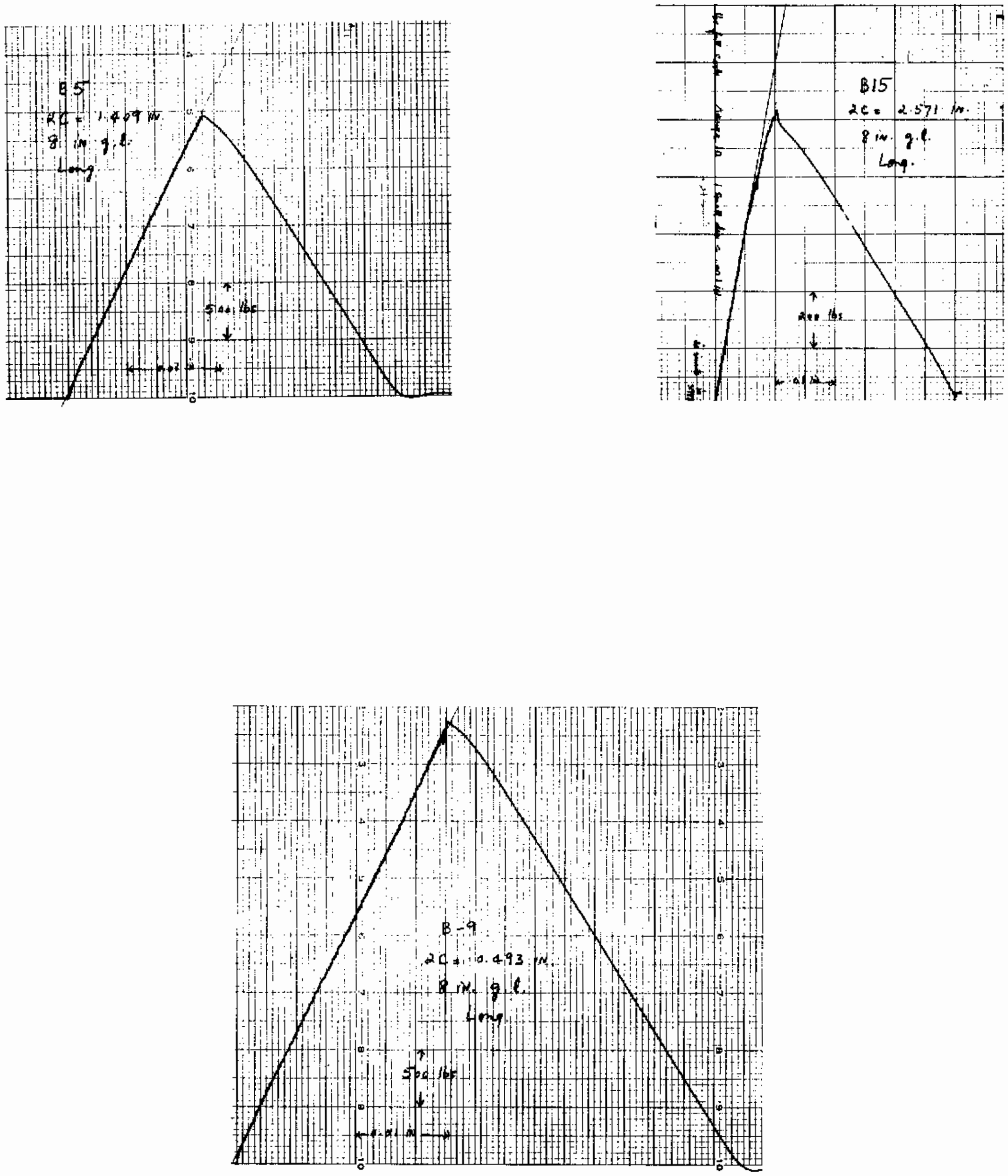

FIG. 6 TYPICAL LOAD-EXTENSION CURVES FOR 8 INCH GAGE LENGTH SPECIMENS

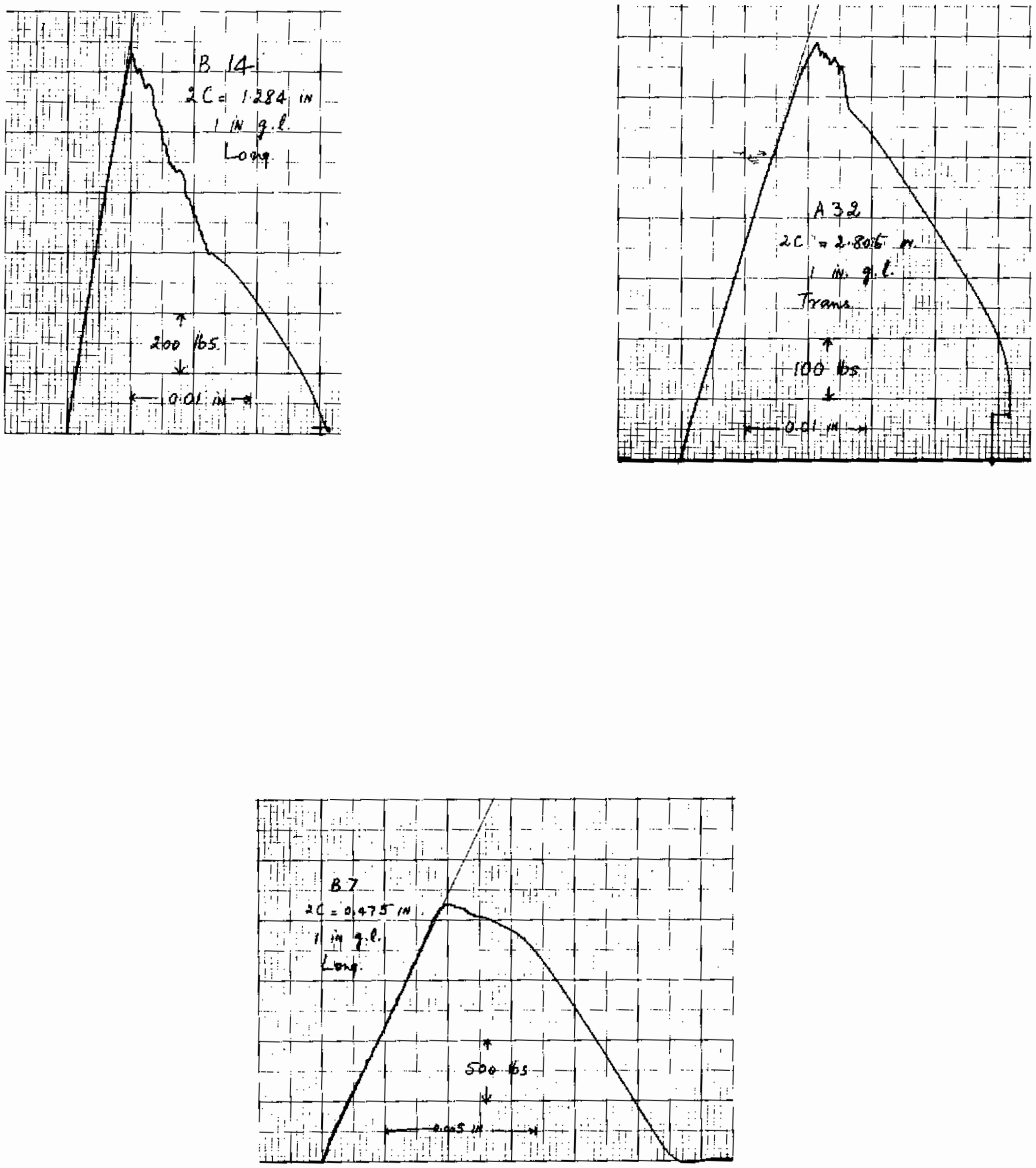

FIG. 7 TYPICAL LOAD-EXTENSION CURVES FOR 1 INCH GAGE LENGTH SPECIMENS

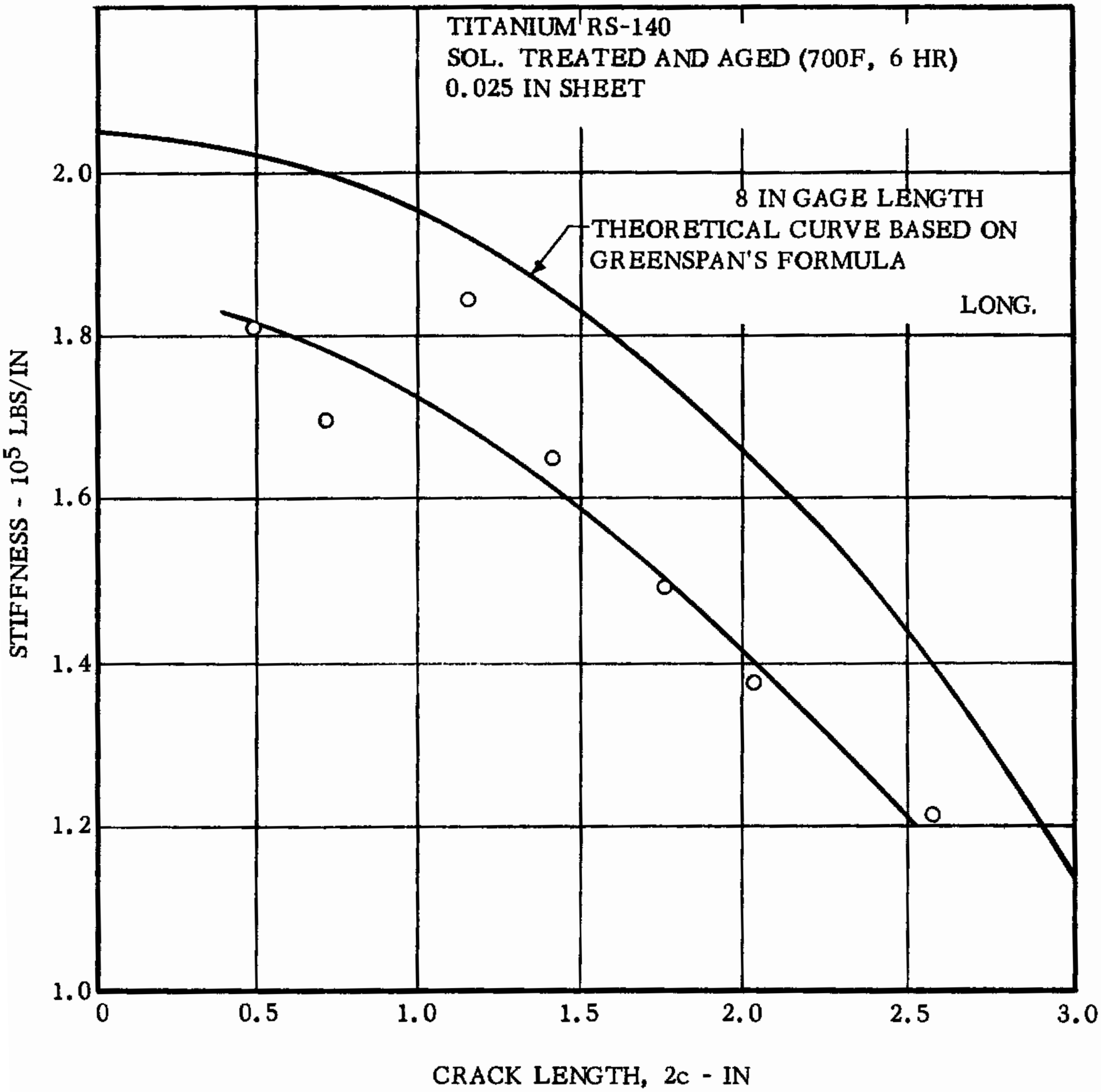

FIG. 8 VARIATION OF STIFFNESS WITH CRACK LENGTH IN 8 IN GAGE LENGTH RS-140 TITANIUM ALLOY SPECIMENS

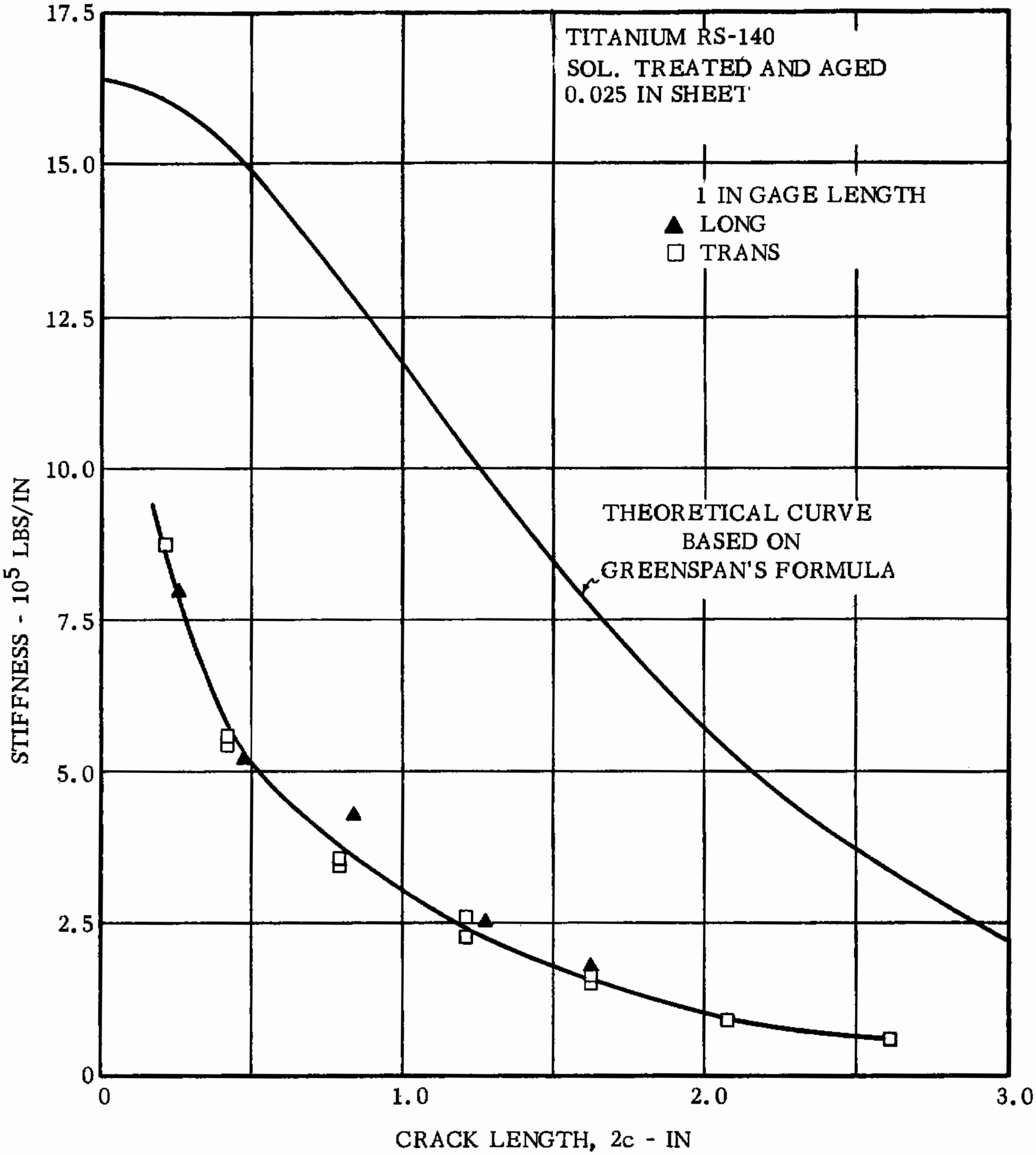

FIG. 9 VARIATION OF STIFFNESS WITH CRACK LENGTH IN 1 IN GAGE LENGTH RS-140 TITANIUM ALLOY SPECIMENS

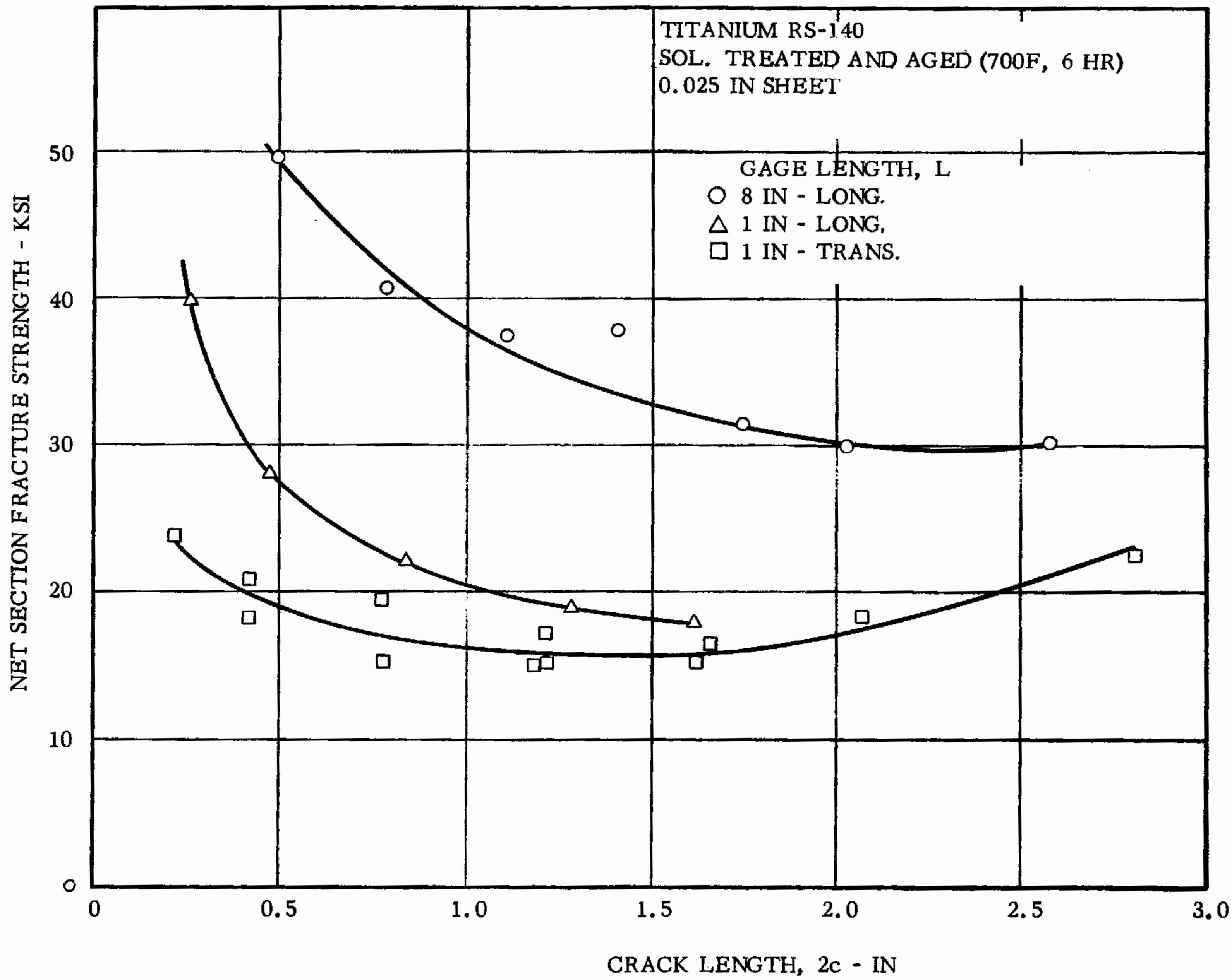

FIG. 10 VARIATION OF NET SECTION FRACTURE STRENGTH WITH CRACK LENGTH FOR RS-140 TITANIUM ALLOY SPECIMENS