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RESIDUAL-STATIC-STRENGTH AND SLOW-CRACK-GROWTH BEHAVIOR OF DUPLEX-ANNEALED Ti-8Al-1Mo-1V SHEET

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SUMMARY

Residual-static-strength tests were conducted at room temperature on centrally cracked Ti-8Al-1Mo-1V duplex-annealed sheet specimens 2, 4, 8, and 20 inches (5.1, 10.2, 20.3, and 50.8 cm) wide. Residual-static-strength tests were also conducted on specimens 8 inches (20.3 cm) wide in which cracks had been propagated either at various cyclic-stress levels or at various temperatures prior to static testing. The residual strength (based on net section prior to loading) for a given ratio of crack length to specimen width was less for wide specimens than for narrow ones. No effect of prior stress or temperature history on the residual static strength was found. The slow-crack-growth data obtained were approximated reasonably well by an equation of the form $\frac{a_c}{a} = 1 + A\left(\frac{w}{2a} - 1\right)^B$ where a_c is the half-length of the critical crack, a is the half-length of the initial crack, w is the specimen width, and A and B are constants which are determined empirically. The constants A and B are apparently some function of temperature. Analysis of the residual-strength data by both the unified notch-strength analysis method and a modified version of this method is discussed.

INTRODUCTION

Residual static strength is an important consideration in the design of aircraft structures. One parameter which is known to affect the residual-static-strength behavior is specimen width. Test data on aluminum and steel alloys (refs. 1 and 2) indicated that for a given ratio of crack length to specimen width, the residual static strength was less for wide specimens than for narrow ones and that the relative decreases in strength as a function of width were dependent on the material. In the present investigation, the effect of width on the residual strength of the titanium alloy Ti-8Al-1Mo-1V (duplex annealed) is studied at room temperature for specimen widths from 2 to 20 inches (5.1 to 50.8 cm). The experimental results are analyzed by using both the unified notch-strength analysis method and a modified version of this method (refs. 1 and 3, respectively).

In previous studies of residual static strength (refs. 4 and 5), the stress level and temperature at which the fatigue cracks were propagated prior to static testing were carefully selected to insure that a reasonably consistent stress state existed near the crack tip. In the present investigation, the effects of prior stress and temperature histories on the residual-static-strength behavior are studied. Also included is a discussion of the effect of static test temperature on the residual-strength behavior.

During static testing of cracked specimens, some slow crack growth normally occurs prior to complete failure. The stress at which slow crack growth initiates and the amount of slow crack growth prior to failure are of interest to improve the understanding of the fracture phenomenon. Slow-crack-growth data were obtained in the present test program to determine whether correlations exist between the slow-crack-growth behavior and the various geometrical and environmental factors.

SYMBOLS

The units used for the physical quantities defined in this paper are given both in U.S. Customary Units and in the International System of Units (SI) (ref. 6). Factors relating the two systems are given in the appendix.

a half-length of central crack prior to loading, inches or centimeters (cm)

a_c half-length of central crack corresponding to maximum load, inches or centimeters (cm)

a_t half-length of central crack immediately prior to complete failure, inches or centimeters (cm)

a_i instantaneous half-length of central crack, inches or centimeters (cm)

C_m material constant which describes crack sensitivity, inches$^{-1/2}$ or centimeters$^{-1/2}$ $\left(\text{cm}^{-1/2}\right)$

C_m' material constant C_m used in modified version of notch-strength analysis method, inches$^{-1/2}$ or centimeters$^{-1/2}$ $\left(\text{cm}^{-1/2}\right)$

E modulus of elasticity, ksi or giganewtons/meter^2 $\left(\text{GN/m}^2\right)$

$E_{s,u}$ secant modulus corresponding to stress at ultimate load, ksi or giganewtons/meter^2 $\left(\text{GN/m}^2\right)$

e elongation in 2-inch (5.08-cm) gage length, percent

K_u static notch-strength factor

$K_u' = \frac{\sigma_u'}{S_n}$ where $(\sigma_u' > \sigma_u)$

K_w finite-width factor

R ratio of minimum to maximum stress

S_c tensile strength of cracked specimen at failure (based on net section corresponding to a_c), ksi or meganewtons/meter^2 $(\mathrm{MN/m^2})$

S_i net-section stress of cracked specimen at onset of slow crack growth, ksi or meganewtons/meter^2 $(\mathrm{MN/m^2})$

S_n tensile strength of cracked specimen at failure (based on net section prior to loading), ksi or meganewtons/meter^2 $(\mathrm{MN/m^2})$

t thickness of specimen, inches or centimeters (cm)

T temperature, $^{\circ}$F or $^{\circ}$K

w specimen width, inches or centimeters (cm)

ρ' material constant (Neuber constant), inches or centimeters (cm)

σ_u ultimate tensile strength, ksi or meganewtons/meter^2 $(\mathrm{MN/m^2})$

σ_u' ultimate tensile strength σ_u used in modified version of notch-strength analysis method, ksi or meganewtons/meter^2 $(\mathrm{MN/m^2})$

σ_y yield strength (0.2-percent offset), ksi or meganewtons/meter^2 $(\mathrm{MN/m^2})$

SPECIMENS

All specimens were made from Ti-8Al-1Mo-1V (duplex-annealed) titanium alloy sheet obtained from the same mill heat. The tensile properties (obtained by using standard ASTM tensile specimens), the nominal chemical composition of the material, and details of the duplex-annealing heat treatment are listed in table I. Details of the specimen configurations are shown in figure 1. The specimen dimensions and grain orientation relative to the loading axis of the specimen are listed in the following table:

Width		Length		Thickness		Grain direction
in.	cm	in.	cm	in.	mm	
Width-effect study						
2	5.1	12	30	0.050	1.27	Longitudinal
4	10.2	12	30	.050	1.27	Longitudinal
8	20.3	24	61	.050	1.27	Transverse
[a]20	50.8	[a]40	102	.050	1.27	Longitudinal
20	50.8	48	122	.050	1.27	Longitudinal
Prior-stress- and prior-temperature-effect studies						
8	20.3	24	61	0.050	1.27	Longitudinal

[a]Specimens with modified ends.

Modifications were made to the ends of some of the 20-inch-wide (50.8-cm) specimens (hereafter referred to as specimens with modified ends) (see fig. 1) to permit use of 12-inch (30-cm) grips available on several testing machines. Doubler plates, 3/32 inch (2.38 mm) thick, were bonded to the ends of these specimens to aid in distributing the grip loads uniformly across the test section. The interior ends of the doubler plates were scarfed to zero thickness in 2 inches (5.1 cm) to provide gradual load transfer from the doublers to the test specimens.

A stress raiser in the form of a slit 0.01 inch (0.025 cm) wide was cut by a spark-discharge technique in the center of each specimen perpendicular to the direction of loading. The length of the slit was 0.10 inch (0.25 cm) in all except the specimens 20 by 48 inches (50.8 by 122 cm). In these specimens, the slits were cut approximately 1 inch (2.5 cm) less than the desired crack length for the static tests. The heat generated by the process was very localized and was not expected to affect the bulk of the material through which the fatigue cracks propagated.

EQUIPMENT

Two types of axial-load fatigue-testing machines were used to propagate the cracks to the desired lengths: a ±20 000-lbf-capacity (89-kN) subresonant machine which had an operating frequency of 1800 cpm (30 Hz), and a combination hydraulic and subresonant machine. The combination machine could apply alternating loads up to 66 000 lbf (294 kN) hydraulically at frequencies of 40 to 60 cpm (0.7 to 1 Hz) or 40 000 lbf (178 kN) subresonantly at frequencies of approximately 820 cpm (13.7 Hz). Loads were monitored continuously by measuring the output of a strain gage cemented to a dynamometer in series with the specimen. The maximum error anticipated for this monitoring system was ±1 percent.

The residual-static-strength tests were conducted either in a 120 000-lbf-capacity (534-kN) hydraulic jack or in a 1 000 000-lbf (4450-kN) fatigue and static testing machine. A load rate of 30 000 lbf/min (2225 N/s) was used in all tests. The maximum load during each static test was obtained from the load-indicating systems of these testing machines. The maximum error in load was ±1 percent.

TEST PROCEDURE

Residual-strength and slow-crack-growth data were obtained from three studies: one in which specimens of various widths were tested, one in which various constant-amplitude load histories were applied prior to static testing, and one in which the various temperature histories were applied prior to static testing. Details of the test procedures are described in the following sections.

Width-Effect Study

A crack-propagation investigation (reported in ref. 7) was conducted on all the specimens prior to the determination of the residual strength, with the exception of the specimens 20 by 48 inches (50.8 by 122 cm). In reference 7, cracks were grown at various stress levels at room temperature during the crack-propagation study. The stress levels used to grow the cracks are presented in table II. In the specimens 8 inches (20.3 cm) wide and those 20 by 40 inches (50.8 by 102 cm), the cracks were grown to within approximately 0.2 inch (0.51 cm) of the desired length for the static tests. In the present investigation, the nominal net-section-stress range was then adjusted to a range of 0 to 27 ksi (186 MN/m^2), and the cracks were grown at this stress range at room temperature until the desired crack lengths were obtained. In the specimens 20 by 48 inches (50.8 by 122 cm), the cracks were grown approximately 0.5 inch (1.27 cm) from each end of the initial stress raiser at 0 to 27 ksi (186 MN/m^2). Each specimen was then tested statically at room temperature.

The specimens were restrained from local buckling in the test section by means of lubricated guide plates similar to those described in reference 8. A clear plastic window was installed in the guides to facilitate photography of the specimen during the static test.

Prior-Stress-History Study

In the prior-stress-history study, cracks were grown at $R = 0$ at room temperature to a nominal total length of 1 inch (2.5 cm). The maximum stresses used were 10, 20, 30, 40, 50, 55, and 60 ksi (69, 138, 207, 276, 345, 379, and 414 MN/m^2). The specimens were then tested statically at room temperature. As in the width effect study, guide plates were used to prevent local buckling.

Prior-Temperature-History Study

In the prior-temperature-history study, cracks were grown to a nominal total length of 1 inch (2.5 cm) at a cyclic-stress level of 0 to 30 ksi (207 MN/m^2) at -109° F (195° K), room temperature, or 550° F (561° K). Hereafter, the temperatures of -109° F (195° K) and 550° F (561° K) are referred to as cryogenic and elevated temperatures, respectively. Residual-static-strength tests were then conducted on these specimens at each of the three temperatures. Details of the apparatus used to conduct tests at cryogenic and elevated temperatures are described in reference 5. The heating or cooling elements acted as guide plates in these cases.

Acquisition of Slow-Crack-Growth Data

A grid was photographically printed on each specimen to facilitate measurement of slow crack growth. The grid spacing was 0.05 inch (1.27 mm). Both metallographic and tensile tests revealed that the grid had no detrimental effects on the materials for the temperature range covered in this investigation. Details of the grid can be found in reference 9.

A 70-mm sequence camera operating at 20 frames per second was used to record slow-crack-growth data. The image of a load-indicating device was also photographed on each frame of film by using an optical prism. The load-indicating device measured the output from a load cell which was in series with the specimen.

The onset of slow crack growth was estimated from the film. The critical crack length a_c and corresponding maximum load were obtained from the picture frame immediately prior to the one in which the load decreased from its maximum value. In general, complete failure was observed in the first frame in which a decrease in load was indicated. However, in several instances, considerable slow crack growth (prior to complete failure) occurred while the load decreased from its maximum value. The frame immediately prior to the frame in which complete failure occurred was used to obtain the value of a_t.

RESULTS AND DISCUSSION

The results of the residual-static-strength studies on the effects of width, prior stress history, and prior temperature history are presented in figures 2, 3, and 4 and in tables II, III, and IV, respectively. Slow-crack-growth data are presented in tables II to IV and in figures 5 to 9.

Residual Static Strength

Effect of width.- The residual static strength of specimens 2, 4, 8, and 20 inches (5.1, 10.2, 20.3, and 50.8 cm) wide are presented in figure 2 and in table II. In figure 2 the residual strength (based on net section prior to loading) S_n is plotted against $2a/w$. As expected, the residual static strength was substantially less for the wide specimens than for the narrow ones. The residual static strength of the specimens 20 inches (50.8 cm) wide with and without modified ends was essentially the same. Data from reference 4 on specimens 8 inches (20.3 cm) wide tested in the longitudinal grain direction are also presented in figure 2 for comparison with the transverse-grain data. The residual strengths of the transverse-grain specimens were slightly higher than those of the longitudinal-grain specimens.

The data were analyzed by the following two methods (see figs. 2(a) and 2(b)): the unified notch-strength analysis method (ref. 1) and a modified version of the unified notch-strength analysis method which includes a so-called "notch strengthening" term (ref. 3). In figure 2(a), a value of $\sqrt{\rho'} = 0.235 \text{ inch}^{1/2}$ $\left(0.375 \text{ cm}^{1/2}\right)$ obtained from the plot of $\sqrt{\rho'}$ against σ_u for $\alpha\beta$ alloys in reference 4 was used in the analysis. (See discussion on application of $\sqrt{\rho'}$ curve for titanium in ref. 4.) It should be noted that for cracked specimens of a given material, the parameters $\sqrt{\rho'}$, $\frac{E_{s,u}}{E}$, and the constant 2 used in the notch-strength analysis expression can be combined into a single constant by using the following expression:

$$C_m = \frac{2E_{s,u}}{\sqrt{\rho'}\,E} \qquad (1)$$

The value of C_m obtained by substituting values of $\sqrt{\rho'}$ and $\frac{E_{s,u}}{E}$ into equation (1) is $0.65 \text{ inch}^{-1/2}$ $\left(1.04 \text{ cm}^{-1/2}\right)$. The constant C_m describes the crack sensitivity of the material. The equation for the static notch-strength factor K_u is written as

$$K_u = 1 + C_m K_w \sqrt{a} \qquad \left(S_n < \sigma_y\right) \qquad (2)$$

where K_w is a factor accounting for finite width (ref. 10) as given by the following equation:

$$K_W = \sqrt{\frac{1 - 2a/w}{1 + 2a/w}} \tag{3}$$

The predicted net-section stress at failure is given by the equation

$$S_n = \frac{\sigma_u}{K_u} \tag{4}$$

The reduction in strength as a function of width was predicted reasonably well by using this approach for all except the widest specimen. The predictions for the widest specimens were approximately 15 percent higher than the test results. An improvement in the correlation, particularly for the widest specimens (see fig. 2(b)), was obtained by using the modified version of the notch-strength analysis method. In the modified version, the nominal engineering ultimate tensile strength σ_u is replaced by σ_u', which is greater than σ_u. The value of σ_u' is thought to reflect the influence of triaxiality and local strain-rate effects at the crack tip, and possibly other factors which are not rigorously accounted for when the nominal ultimate strength is used in the analysis. The equations used in the modified version are written as

$$K_u' = 1 + C_m' K_W \sqrt{a} \qquad \left(S_n < \sigma_y\right) \tag{5}$$

and

$$S_n = \frac{\sigma_u'}{K_u'} \qquad \left(\sigma_u' > \sigma_u\right) \tag{6}$$

In this form both σ_u' and C_m' are determined empirically from residual-strength tests. Thus, at least two tests on cracked specimens, preferably at specimen widths as different as practicable, are required. Fitting the curves to the data in figure 2 for the narrowest and widest specimens gave values of $\sigma_u' = 180$ ksi $\left(1241\ \text{MN/m}^2\right)$ and $C_m' = 1.10\ \text{inch}^{-1/2}$ $\left(1.75\ \text{cm}^{-1/2}\right)$.

Effect of prior stress history.- The residual static strengths of specimens 8 inches (20.3 cm) wide with cracks propagated at various maximum stresses are presented in figure 3 and in table III. In figure 3, S_n is plotted against the maximum cyclic-stress level at which the fatigue crack had been propagated. No apparent trend was found in the residual-static-strength behavior as a function of the stress level at which the crack was propagated.

Effect of prior temperature history.- The residual static strengths of specimens 8 inches (20.3 cm) wide in which cracks were propagated at cryogenic, room, and elevated temperatures prior to static testing for each of the three temperatures are presented in figure 4 and in table IV. In figure 4, values of S_n for the various temperatures at which the cracks were grown are plotted against the static test temperature. No apparent trend was found in the residual-static-strength behavior as a function of the temperature at which the crack was propagated.

Effect of static test temperature.- As in reference 4, the static test temperature influenced the residual strength behavior. The averages of the results at the cryogenic temperature and at the elevated temperature were approximately 7 and 14 percent lower, respectively, than the room-temperature test results. (See fig. 4.)

Predictions of the residual strength behavior at the three temperatures are also presented in figure 4. Again, values of $\sqrt{\rho'}$ (corresponding to σ_u at each temperature) obtained from reference 4 were used in the analysis. At cryogenic and room temperatures, the predictions fell slightly below the lower bound of the test results. The agreement at the elevated temperature was excellent.

Observations of Slow-Crack-Growth Behavior

Slow-crack-growth data are presented in figures 5 to 8. These figures show the variation of the instantaneous net-section stress with the instantaneous crack length a_i. A summary of the slow-crack-growth behavior is presented in figure 9 in which a_c/a is plotted against $2a/w$.

Effect of width.- Specimen width affected both the stress required to initiate slow crack growth and that required to produce failure. Values of the stresses required to initiate slow crack growth based on the initial net section and to produce failure based on the critical net section S_i and S_c, respectively, were somewhat lower in the specimens 20 inches (50.8 cm) wide than those required in the specimens 8 inches (20.3 cm) wide. This behavior is consistent with the residual-strength behavior (based on the initial net section) presented in figure 2. Considerable slow crack growth (up to 4.1 inches (10.4 cm)) occurred prior to rapid fracture as the load decreased from its maximum value in the specimens 20 inches (50.8 cm) wide. (See table II.) In general, this behavior was not observed in the specimens 8 inches (20.3 cm) wide.

Effect of prior stress and temperature histories.- Prior stress or temperature history had no apparent effect on the slow-crack-growth behavior. (See figs. 7 and 8.)

Effect of static test temperature.- The static test temperature affected both the stress required to initiate slow crack growth and that required to produce failure. (See fig. 8.) The stresses required to initiate slow crack growth were substantially below the yield strengths of the material at the cryogenic and room temperatures (approximately 40 and 60 percent, respectively). However, at the elevated temperature the stresses required to initiate slow crack growth were approximately equal to the yield strength at that temperature. The critical stresses at failure were lower than σ_y at the cryogenic temperature; whereas, at the room and elevated temperatures the stresses fell between σ_y and σ_u. On an absolute basis, approximately a 20-percent-higher stress was required to initiate slow crack growth at the elevated temperature than at either the cryogenic or the room temperature. However, at the elevated temperature the critical stresses at failure were approximately 16 and 21 percent lower than at the cryogenic or the room temperature, respectively. Considerable slow crack growth occurred prior to rapid fracture as the load decreased from its maximum value in the specimens tested at the elevated temperature. (See table IV.) In general, this behavior was not evident in the specimens of the same width at the cryogenic or room temperatures.

Correlation of slow-crack-growth data.- The slow-crack-growth behavior is summarized in figure 9. In general, the data for specimens 8 inches (20.3 cm) wide tested at cryogenic and room temperatures fell along the same curve, whereas the elevated-temperature data fell along a lower curve. The data for the specimens 20 inches (50.8 cm) wide fell slightly below the data for the specimens 8 inches (20.3 cm) wide. However, since the variation between the data for the two widths was substantially less than the scatter obtained in duplicate tests (see fig. 9), it is believed that the data can be represented by a single curve. This assumption is further substantiated by the data presented in reference 11 which indicate that the slow-crack-growth behavior for specimens ranging in width from 3 to 48 inches (7.6 to 122 cm) at room temperature can be correlated by a single curve. An equation proposed in reference 11 of the form

$$\frac{a_c}{a} = 1 + A\left(\frac{w}{2a} - 1\right)^B$$

was used to fit the present data. The constants A and B were adjusted to fit the data and are apparently a function of temperature. The proposed equation approximates the trend of the existing data reasonably well. However, caution should be used when applying this equation for wide specimens in which $2a/w$ is small because the computed values of a_c appear to be unrealistically large.

SUMMARY OF RESULTS

Three series of residual-static-strength tests were conducted on centrally cracked Ti-8Al-1Mo-1V duplex-annealed specimens: one in which specimens 2, 4, 8, and 20 inches (5.1, 10.2, 20.3, and 50.8 cm) wide were tested at room temperature, one in which central cracks were propagated in specimens 8 inches (20.3 cm) wide at various constant-amplitude load levels at room temperature prior to static testing at room temperature, and one in which cracks were propagated in specimens 8 inches (20.3 cm) wide at -109° F (195° K), 80° F (300° K), or 550° F (561° K) prior to static testing at each of these temperatures. Slow-crack-growth behavior was also studied. From these tests, the following results were obtained:

1. The residual strength (based on net section prior to loading) for a given ratio of crack length to specimen width was less for wide specimens than for narrow ones. The reduction in strength as a function of width was predicted reasonably well by use of a modified version of the unified notch-strength analysis method.

2. The residual strengths (based on net section prior to loading) of transverse-grain specimens at room temperature was slightly higher than longitudinal-grain specimens.

3. The temperature or stress at which the fatigue cracks were propagated did not appear to affect the residual strength or slow-crack-growth behavior.

4. The slow-crack-growth behavior at -109° F (195° K) and 80° F (300° K) was essentially the same regardless of specimen width. The slow crack growth at 550° F (561° K) was less than that at cryogenic or room temperatures.

5. An equation of the form $\frac{a_c}{a} = 1 + A\left(\frac{w}{2a} - 1\right)^B$, where a_c is the half-length of the critical crack, a is the half-length of the initial crack, and w is the specimen width, approximated the trend of the slow-crack-growth data reasonably well. The constants A and B are apparently a function of temperature.

6. Considerable slow crack growth occurred prior to rapid fracture as the load decreased from its maximum value in the specimens 8 inches (20.3 cm) wide tested at the elevated temperature and in those 20 inches (50.8 cm) wide tested at room temperature.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., July 5, 1967,
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APPENDIX

CONVERSION OF U.S. CUSTOMARY UNITS TO SI UNITS

The International System of Units (SI) was adopted by the Eleventh General Conference of Weights and Measures, Paris, October 1960, in Resolution No. 12 (ref. 6). Conversion factors for the units used herein are given in the following table:

Physical quantity	U.S. Customary Unit	Conversion factor (*)	SI Unit
Force	lbf	4.448222	newtons (N)
Length	in.	2.54×10^{-2}	meters (m)
Pressure	ksi	6.894757	meganewtons/meter^2 (MN/m^2)
Temperature . .	^{o}F	$\frac{5}{9}(^{o}F + 459.67)$	degrees Kelvin (^{o}K)
Frequency . . .	cpm	1.67×10^{-2}	hertz (Hz)

*Multiply value given in U.S. Customary Unit by conversion factor to obtain equivalent value in SI Unit.

Prefixes to indicate multiples of units are as follows:

Prefix	Multiple
milli (m)	10^{-3}
centi (c)	10^{-2}
kilo (k)	10^{3}
mega (M)	10^{6}
giga (G)	10^{9}

REFERENCES

1. Kuhn, Paul; and Figge, I. E.: Unified Notch-Strength Analysis for Wrought Aluminum Alloys. NASA TN D-1259, 1962.
2. Kuhn, Paul; and Hardrath, Herbert F.: An Engineering Method for Estimating Notch-Size Effect in Fatigue Tests on Steel. NACA TN 2805, 1952.
3. Kuhn, Paul: Residual Strength in the Presence of Fatigue Cracks (Part I). Presented to the Structures and Materials Panel of AGARD (Turin, Italy), Apr. 17, 1967.
4. Figge, I. E.: Residual Strength of Alloys Potentially Useful in Supersonic Aircraft. NASA TN D-2613, 1965.
5. Figge, I. E.: Residual Static Strength of Several Titanium and Stainless-Steel Alloys and One Superalloy at -109° F, 70° F, and 550° F. NASA TN D-2045, 1963.
6. Mechtly, E. A.: The International System of Units – Physical Constants and Conversion Factors. NASA SP-7012, 1964.
7. Hudson, C. Michael: Investigation of Fatigue Crack Growth in Ti-8Al-1Mo-1V (Duplex-Annealed) Specimens Having Various Widths. NASA TN D-3879, 1967.
8. Brueggeman, W. C.; and Mayer, M., Jr.: Guides for Preventing Buckling in Axial Fatigue Tests of Thin Sheet-Metal Specimens. NACA TN 931, 1944.
9. Hudson, C. Michael: Fatigue-Crack Propagation in Several Titanium and Stainless-Steel Alloys and One Superalloy. NASA TN D-2331, 1964.
10. Dixon, J. R.: Stress Distribution Around Edge Slits in a Plate Loaded in Tension – The Effect of Finite Width of Plate. J. Roy. Aeron. Soc. (Tech. Notes), vol. 66, no. 617, May 1962, pp. 320-322.
11. Newman, J. C., Jr.: Fracture of Cracked Plates Under Plane Stress. NASA paper presented at the National Symposium on Fracture Mechanics (Bethlehem, Pa.), June 19-21, 1967.

TABLE I.- DESCRIPTION OF Ti-8Al-1Mo-1V (DUPLEX ANNEALED)

[t = 0.050 inch (1.27 mm)]

(a) Average tensile properties

Temperature		Grain direction	σ_u		σ_y		E		e, percent 2-in. (5.08-cm) gage	Number of tests
$^\circ F$	$^\circ K$		ksi	MN/m^2	ksi	MN/m^2	ksi	GN/m^2		
[a] -109	195	Longitudinal	178.0	1228	162.7	1123	17.7×10^3	121	15.3	3
[a] 80	300	Longitudinal	152.0	1049	133.6	922	18.3	126	12.5	3
80	300	Transverse	149.2	1029	135.3	933	16.9	117	11.2	3
[a] 550	561	Longitudinal	115.5	797	93.7	647	14.1	97	12.0	3

[a]Data from reference 4.

(b) Nominal chemical composition

[Values given in percent]

C	Mo	V	Al	N	H	Ti	Fe
0.08 max.	0.75 to 1.25	0.75 to 1.25	7.50 to 8.50	0.05 max.	0.015 max.	Balance	0.30 max.

(c) Description of duplex-annealing heat treatment

(1) Heat to 1450° F (1061° K) for 8 hours.
(2) Furnace cool.
(3) Heat to 1450° F (1061° K) for 15 minutes.
(4) Air cool.

TABLE II.- RESIDUAL-STRENGTH AND SLOW-CRACK-GROWTH TEST RESULTS FROM WIDTH-EFFECT STUDY

[Tests conducted at 80° F (300° K)]

Specimen width		Stress at which crack was propagated				2a/w	S_n based on 2a/w		Stress at start of slow crack growth S_i		$2a_c/w$	$2a_t/w$	S_c based on $2a_c/w$	
		Max.		Min.										
in.	cm	ksi	MN/m^2	ksi	MN/m^2		ksi	MN/m^2	ksi	MN/m^2			ksi	MN/m^2
2.0	5.1	27	186	0	0	0.100	137.0	945	---	---	----	----	----	----
2.0	5.1	27	186	0	0	.199	126.2	871	---	---	----	----	----	----
2.0	5.1	27	186	0	0	.298	126.6	874	---	---	----	----	----	----
2.0	5.1	50	345	0	0	.400	125.6	867	---	---	----	----	----	----
2.0	5.1	40	276	10	69	.401	120.6	832	---	---	----	----	----	----
2.0	5.1	35	242	15	104	.414	122.2	843	---	---	----	----	----	----
2.0	5.1	27	186	23	159	.500	114.4	789	---	---	----	----	----	----
2.0	5.1	30	207	20	138	.505	116.9	807	---	---	----	----	----	----
4.0	10.2	27	186	0	0	.103	127.9	883	---	---	----	----	----	----
4.0	10.2	50	345	0	0	.200	121.0	835	---	---	----	----	----	----
4.0	10.2	40	276	10	69	.303	116.9	807	---	---	----	----	----	----
4.0	10.2	35	242	15	104	.400	111.5	769	---	---	----	----	----	----
4.0	10.2	27	186	23	159	.498	114.8	792	---	---	----	----	----	----
4.0	10.2	30	207	20	138	.499	109.2	753	---	---	----	----	----	----
[a]8.0	20.3	[b]50	345	0	0	.127	117.9	814	86.2	595	[c]0.263	----	[c]42.5	983
[a]8.0	20.3	[b]40	276	10	69	.188	109.1	753	76.3	526	[c].381	----	[c]41.2	974
[a]8.0	20.3	[b]35	242	15	104	.249	102.8	709	70.3	485	[c].424	----	[c]37.5	949
[a]8.0	20.3	[b]30	207	20	138	.438	92.9	641	48.0	331	[c].599	----	[c]32.1	916
[a]8.0	20.3	[b]27	186	23	159	.626	96.2	664	50.7	350	[c].713	----	[c]17.3	809
[d]8.0	20.3	[b]50	345	0	0	.125	119.7	826	74.2	512	.281	0.281	146.0	1007
[d]8.0	20.3	[b]40	276	10	69	.190	112.1	773	63.9	441	.387	.387	149.8	1034
[d]8.0	20.3	[b]35	242	15	104	.252	106.5	735	57.3	395	.393	.456	132.0	911
[d]8.0	20.3	[b]30	207	20	138	.367	98.1	677	62.1	428	.531	.531	132.2	912
[d]8.0	20.3	[b]27	186	23	159	.614	97.4	672	69.7	481	[e].712	[e].712	131.2	905
[f]20.0	50.8	[b]50	345	0	0	.101	86.6	598	32.4	224	.200	.200	96.7	667
[f]20.0	50.8	[b]40	276	10	69	.213	75.7	522	46.9	324	.338	.375	88.2	608
[f]20.0	50.8	[b]35	242	15	104	.302	69.9	482	38.4	265	.420	.500	82.1	566
[f]20.0	50.8	[b]30	207	20	138	.401	73.3	506	44.2	305	.510	[e].725	87.2	602
[f]20.0	50.8	[b]27	186	23	159	.497	74.5	514	45.3	313	.575	[e].750	85.6	590
20.0	50.8	[g]27	186	0	0	.103	96.4	665	69.5	480	.205	[e].250	108.0	745
20.0	50.8	[g]27	186	0	0	.188	80.5	555	59.9	413	.262	.376	94.6	653
20.0	50.8	[g]27	186	0	0	.340	72.1	497	55.2	381	.429	[e].554	80.0	552
20.0	50.8	[g]27	186	0	0	.499	61.0	421	38.5	266	.575	.780	71.7	495

[a]Data from reference 4.

[b]Crack grown to within approximately 0.2 inch (0.51 cm) of desired length at stress indicated; stress range changed to 0 to 27 ksi (186 MN/m^2); and crack grown to desired length.

[c]a_c is presented as a_f in reference 4.

[d]Transverse grain.

[e]Estimated, one side of crack grew under guide plate.

[f]Modified ends.

[g]Stress raiser cut to within approximately 1 inch (2.5 cm) of desired crack length and crack propagated to desired length at stress indicated.

TABLE III.- RESIDUAL-STRENGTH AND SLOW-CRACK-GROWTH TEST RESULTS FROM PRIOR-STRESS-HISTORY STUDY

[Tests conducted at 80° F (300° K)]

Specimen width		Maximum stress at which crack was propagated (minimum stress = 0)		$2a/w$	S_n based on $2a/w$		Stress at start of slow crack growth S_i		$2a_c/w$	$2a_t/w$	S_c based on $2a_c/w$	
in.	cm	ksi	MN/m^2		ksi	MN/m^2	ksi	MN/m^2			ksi	MN/m^2
8.0	20.3	10	69	0.125	114.8	792	69.8	482	[a]0.264	[a]0.264	138.3	954
8.0	20.3	20	138	.125	114.3	789	67.2	464	[a].256	[a].256	136.3	940
8.0	20.3	30	207	.125	113.2	781	69.2	477	[a].262	[a].262	136.0	938
8.0	20.3	40	276	.125	118.1	815	62.2	429	.256	.256	141.1	974
8.0	20.3	40	276	.124	115.0	794	72.5	500	.288	.288	144.5	997
8.0	20.3	40	276	.126	116.4	803	78.7	543	.263	.263	140.4	969
8.0	20.3	50	345	.121	121.1	836	---	---	----	----	----	----
8.0	20.3	50	345	.126	116.3	802	77.2	533	.306	.306	148.4	1024
8.0	20.3	50	345	.126	116.1	801	75.8	523	.300	.300	144.7	998
8.0	20.3	50	345	.125	118.1	815	83.2	574	.240	.240	134.5	928
8.0	20.3	50	345	.132	116.3	802	95.4	658	.250	.250	137.1	946
8.0	20.3	50	345	.126	118.5	818	78.4	541	[a].275	[a].275	146.0	1007
8.0	20.3	50	345	.125	116.7	805	80.2	553	.263	.288	132.0	911
8.0	20.3	55	380	.126	114.3	789	82.8	571	.253	----	135.4	934
8.0	20.3	55	380	.131	114.1	787	72.6	501	.263	.263	134.5	928
8.0	20.3	60	414	.125	115.3	796	82.2	567	.275	.275	141.0	973
8.0	20.3	60	414	.126	116.8	806	79.3	547	.225	.288	127.9	883

[a]Estimated, one side of crack grew under guide plate.

TABLE IV.- RESIDUAL-STRENGTH AND SLOW-CRACK-GROWTH TEST RESULTS

FROM PRIOR-TEMPERATURE-HISTORY STUDY

[Cracks propagated at 0 to 27 ksi (186 MN/m^2)]

Specimen width		Temperature at which crack was propagated		Temperature for static test		$2a/w$	S_n based on $2a/w$		Stress at start of slow crack growth S_i		$2a_c/w$	$2a_t/w$	S_c based on $2a_c/w$	
in.	cm	°F	°K	°F	°K		ksi	MN/m^2	ksi	MN/m^2			ksi	MN/m^2
8.0	20.3	-109	195	-109	195	0.125	112.2	774	69.3	478	0.271	----	138.2	954
8.0	20.3	-109	195	-109	195	.120	106.5	735	67.5	466	.213	0.213	119.7	826
8.0	20.3	-109	195	-109	195	.125	110.1	760	58.2	402	.273	.273	132.8	916
8.0	20.3	-109	195	80	300	.124	112.9	779	76.2	526	.250	.331	133.7	923
8.0	20.3	-109	195	550	561	.125	100.0	690	---	---	----	----	----	---
8.0	20.3	80	300	-109	195	.126	102.8	709	70.8	489	.225	.225	115.5	797
8.0	20.3	80	300	-109	195	.124	106.6	736	61.2	422	.298	.298	133.4	920
8.0	20.3	80	300	-109	195	.135	108.5	749	62.8	433	.275	.275	129.6	894
8.0	20.3	80	300	80	300	.128	115.3	796	64.1	442	.269	.269	140.0	966
8.0	20.3	80	300	550	561	.126	99.4	686	88.3	609	.188	[a].438	107.4	741
8.0	20.3	550	561	-109	195	.124	102.7	709	81.4	562	.291	.291	126.2	871
8.0	20.3	550	561	-109	195	.123	108.9	751	76.9	531	.263	.263	130.0	897
8.0	20.3	550	561	-109	195	.123	107.9	745	76.8	530	.250	.250	125.4	865
8.0	20.3	550	561	80	300	.126	114.3	789	73.9	510	.255	[a].325	136.8	944
8.0	20.3	550	561	550	561	.128	97.6	673	82.4	569	.175	[a].463	108.5	749

[a]Estimated, one side of crack grew under guide plate.

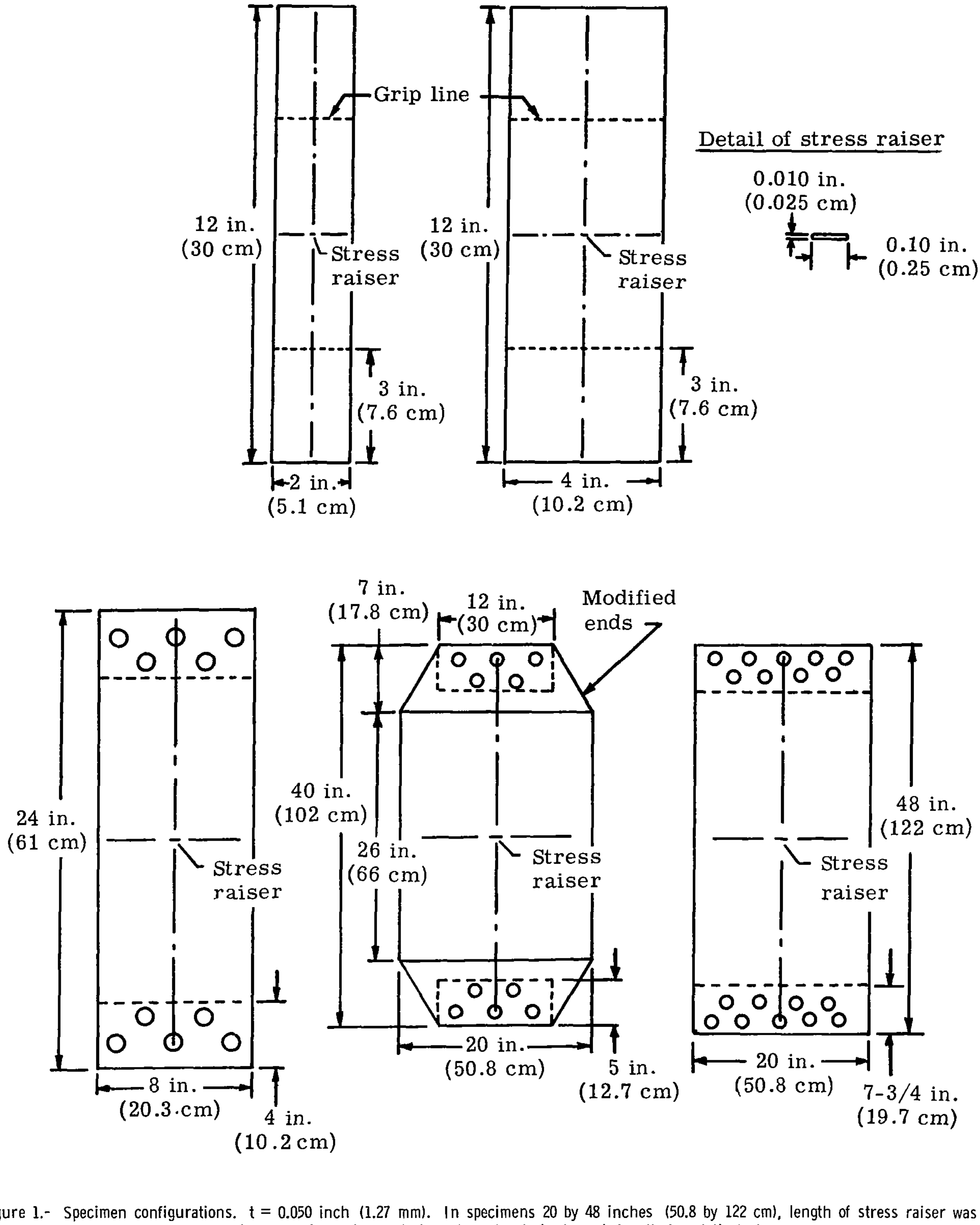
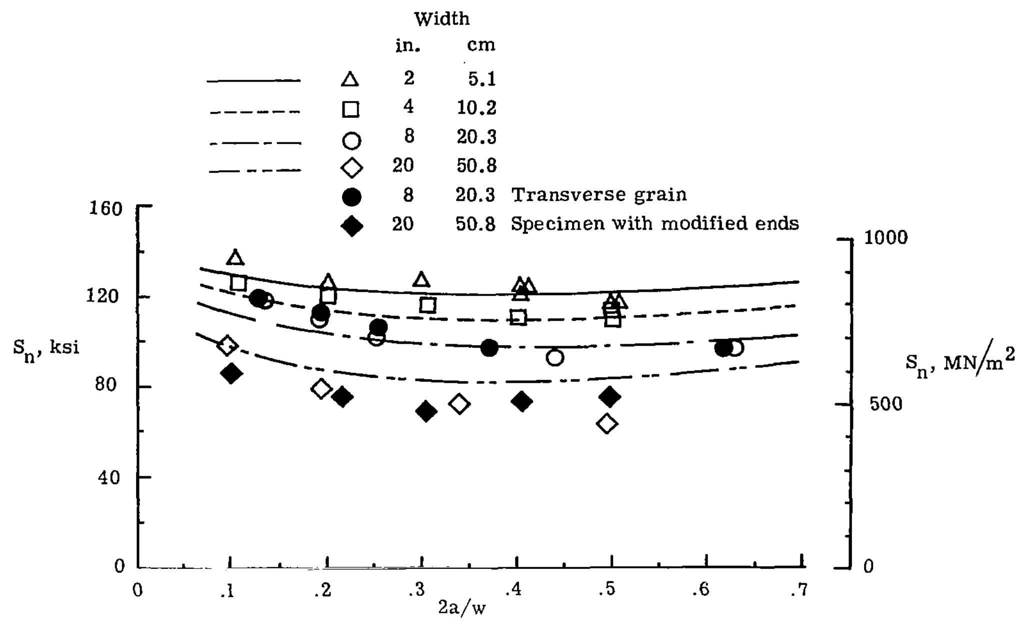
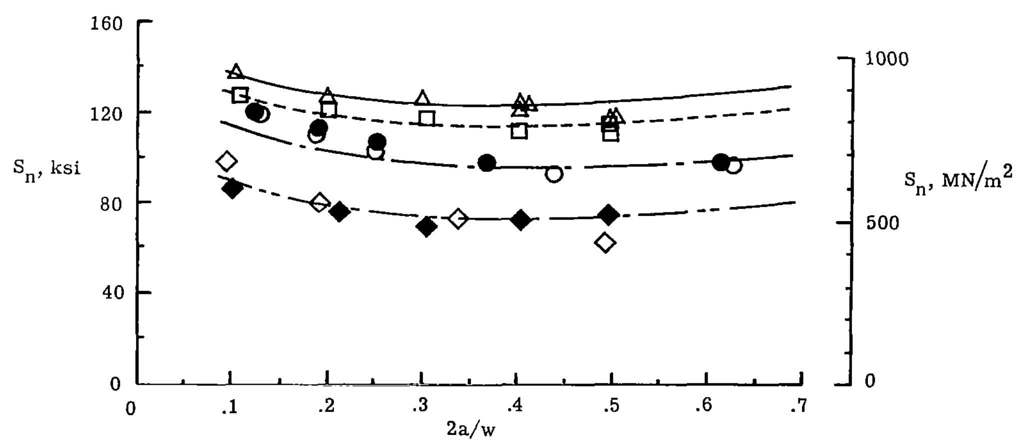


Figure 1.- Specimen configurations. t = 0.050 inch (1.27 mm). In specimens 20 by 48 inches (50.8 by 122 cm), length of stress raiser was approximately 1 inch (2.5 cm) less than the desired crack length for static tests.



(a) Curves calculated by unified notch-strength analysis method. σ_u = 152 ksi (1047 MN/m^2); C_m = 0.65 inch$^{-1/2}$ (1.04 cm$^{-1/2}$).



(b) Curves calculated by modified notch-strength analysis method. σ_u' = 180 ksi (1241 MN/m^2); C_m' = 1.10 inch$^{-1/2}$ (1.75 cm$^{-1/2}$).

Figure 2.- Effect of specimen width on residual static strength of Ti-8Al-1Mo-1V (duplex annealed). t = 0.050 inch (1.27 mm); T = 80^0 F (300^0 K).

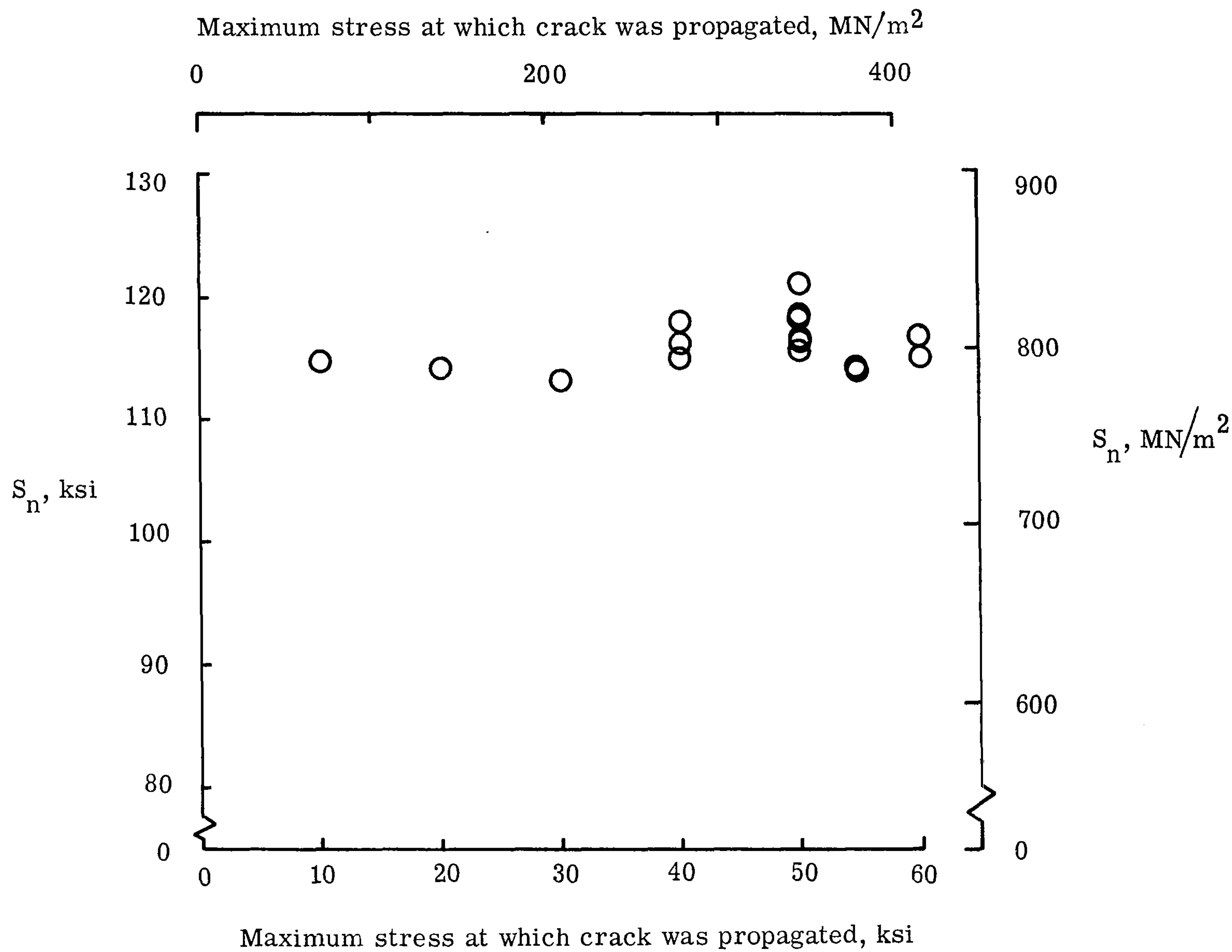


Figure 3.- Effect of prior stress history on residual static strength of 8-inch-wide (20.3-cm) Ti-8Al-1Mo-1V (duplex-annealed) specimens. t = 0.050 inch (1.27 mm); 2a = 1.0 inch (2.5 cm); T = 80° F (300° K); longitudinal grain.

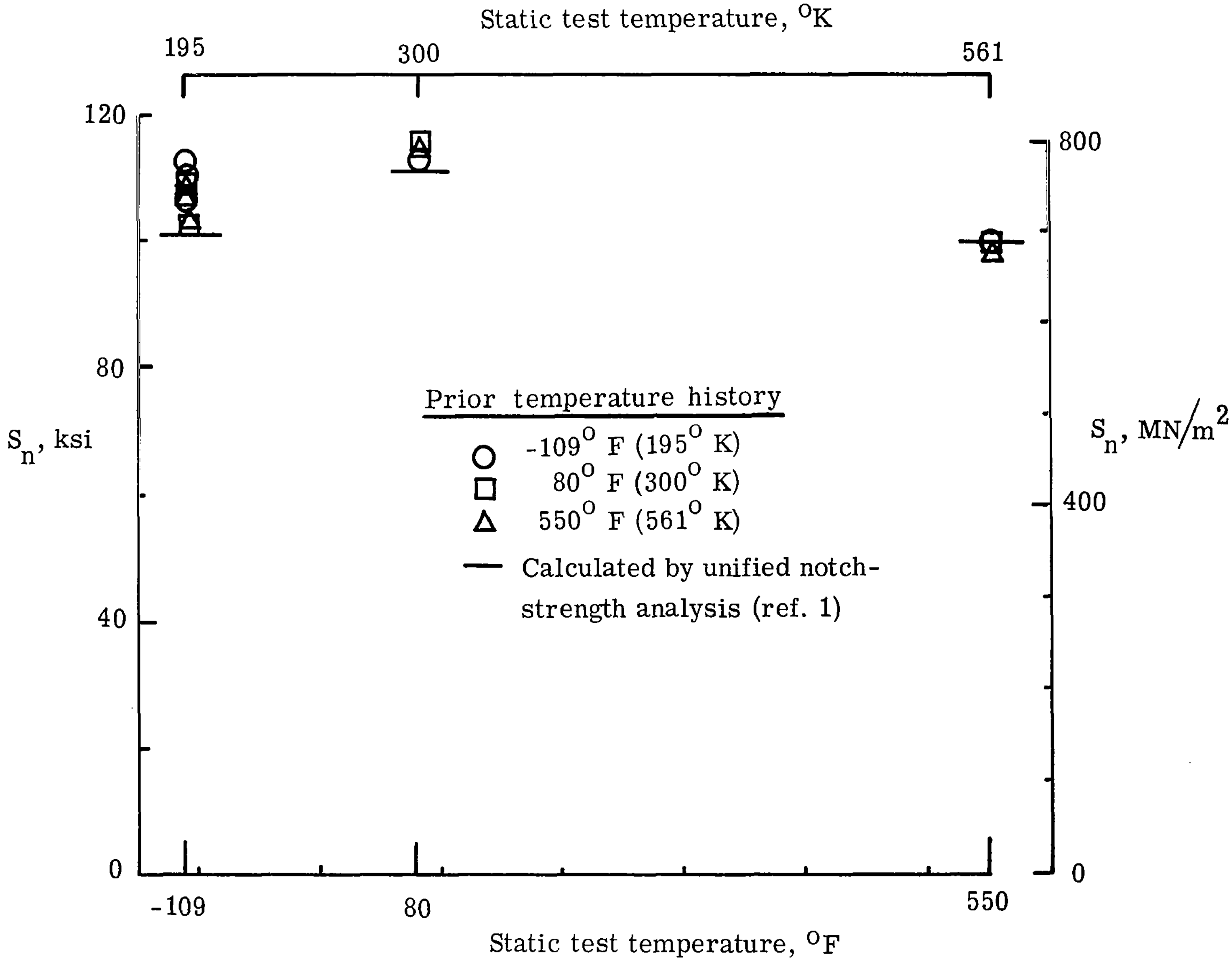


Figure 4.- Effect of prior temperature history on residual static strength of 8-inch-wide (20.3-cm) Ti-8Al-1Mo-1V (duplex-annealed) specimens. t = 0.050 inch (1.27 mm); $2a$ = 1.0 inch (2.5 cm); longitudinal grain.

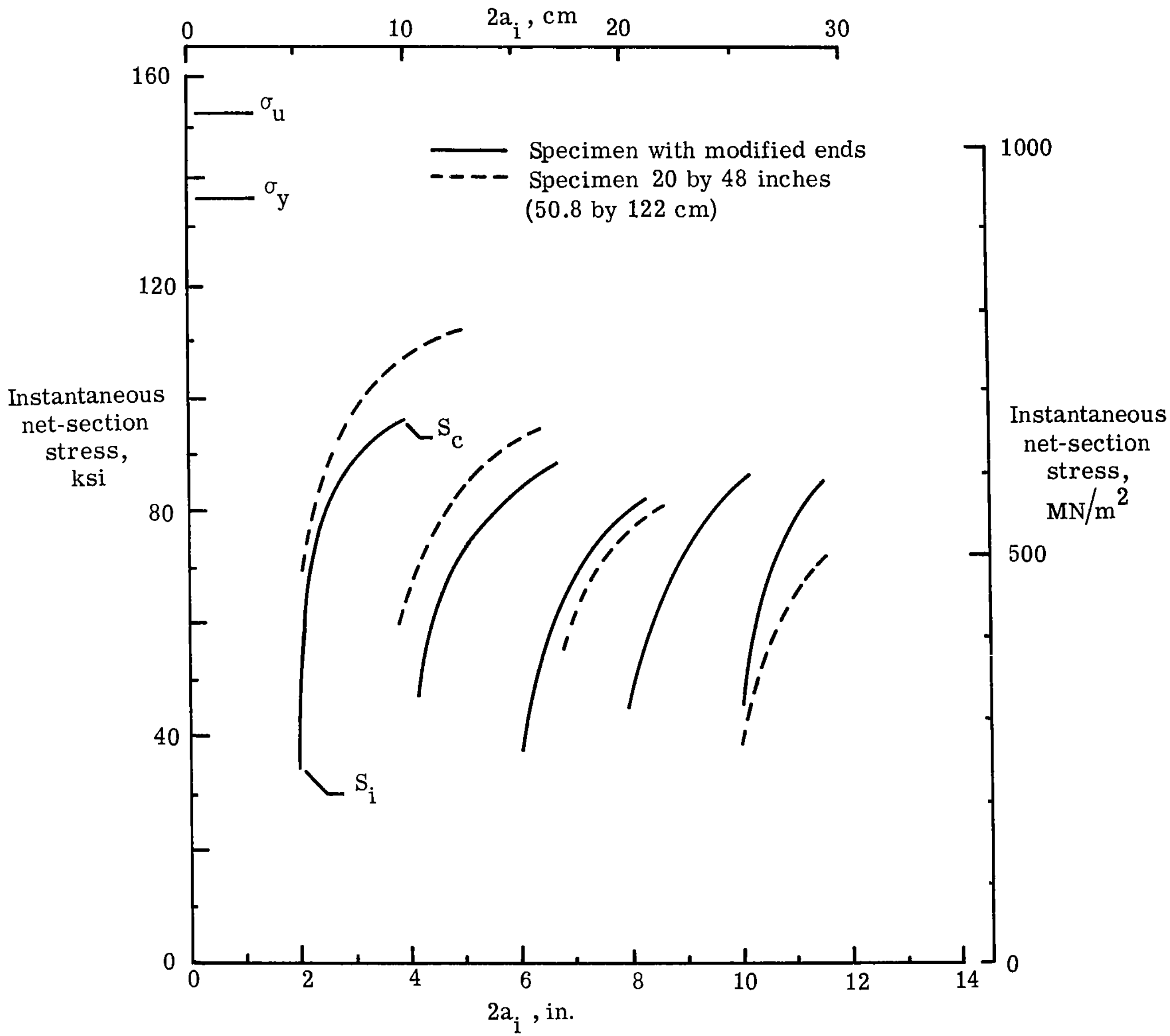


Figure 5.- Slow-crack-growth data for 20-inch-wide (50.8-cm) Ti-8Al-1Mo-1V (duplex-annealed) specimens. $t = 0.050$ inch (1.27 mm); $T = 80^{\circ}$ F (300° K); longitudinal grain.

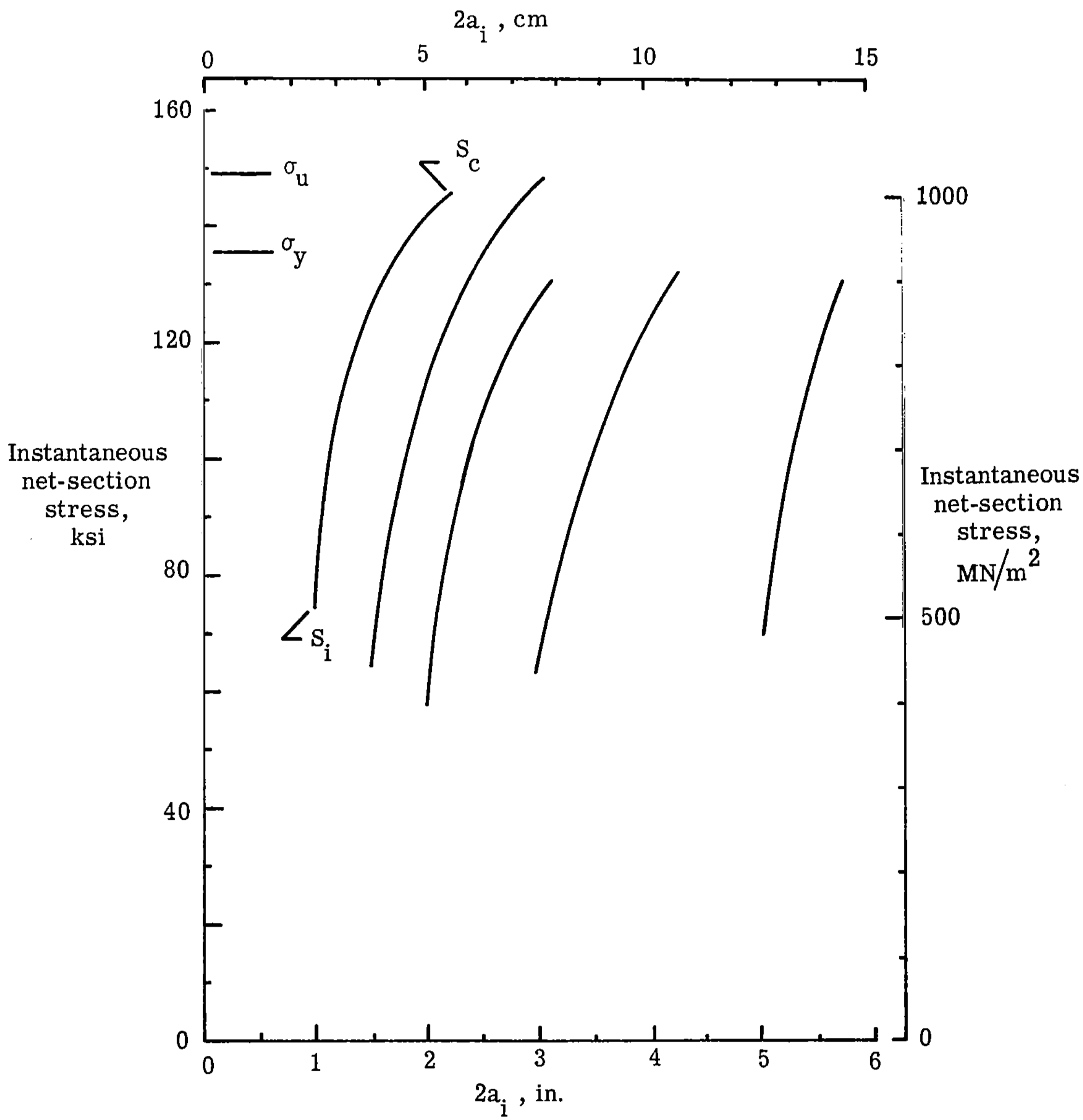


Figure 6.- Slow-crack-growth data for 8-inch-wide (20.3-cm) Ti-8Al-1Mo-1V (duplex-annealed) specimens. t = 0.050 inch (1.27 mm); T = 80° F (300° K); transverse grain.

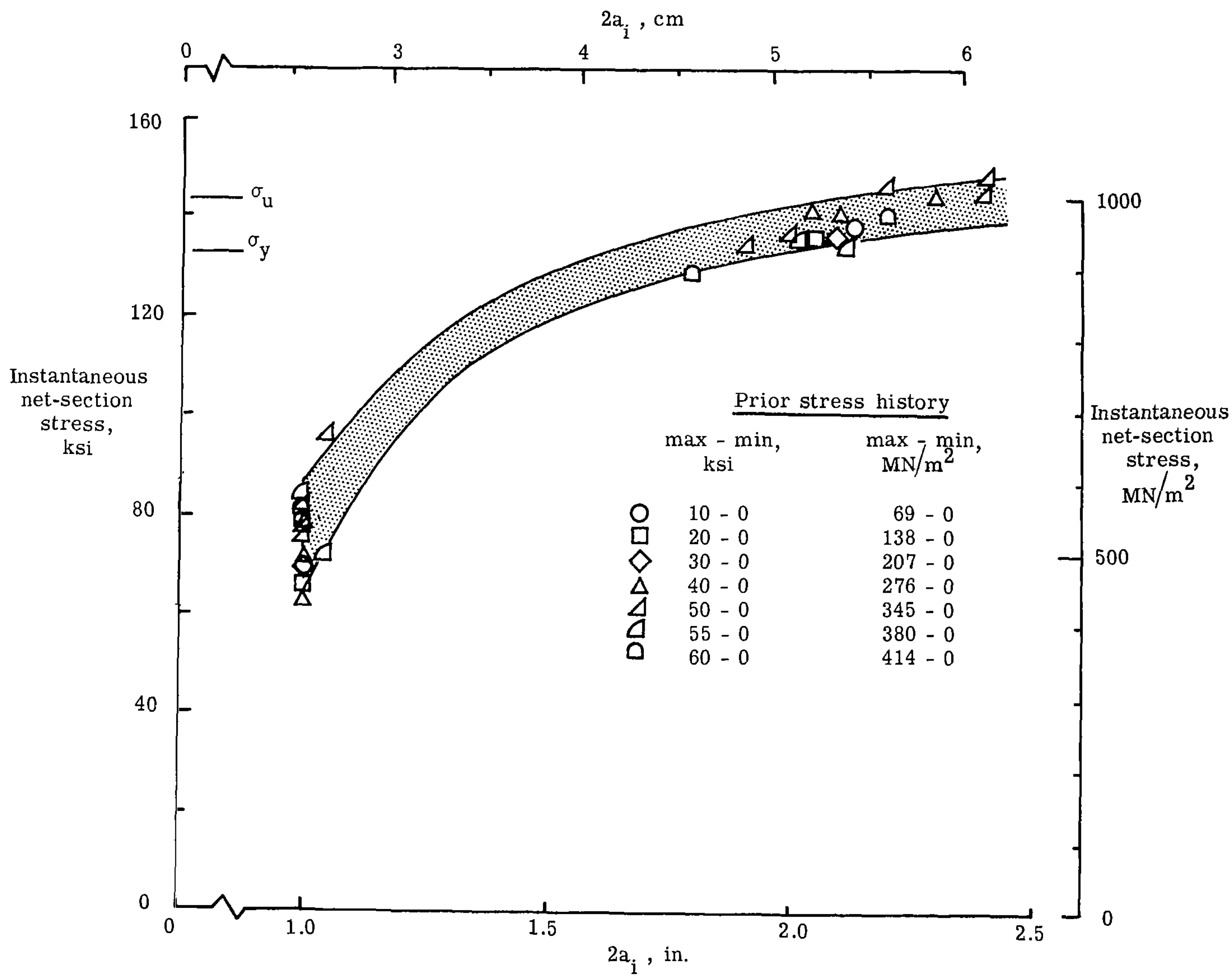


Figure 7.- Effect of prior stress history on slow crack growth of 8-inch-wide (20.3-cm) Ti-8Al-1Mo-1V (duplex-annealed) specimens. t = 0.050 inch (1.27 mm); T = 80^0 F (300^0 K); longitudinal grain. Data at left indicate initiation of slow crack growth; data at right indicate critical conditions; scatterband indicates trend of slow-crack-growth data.

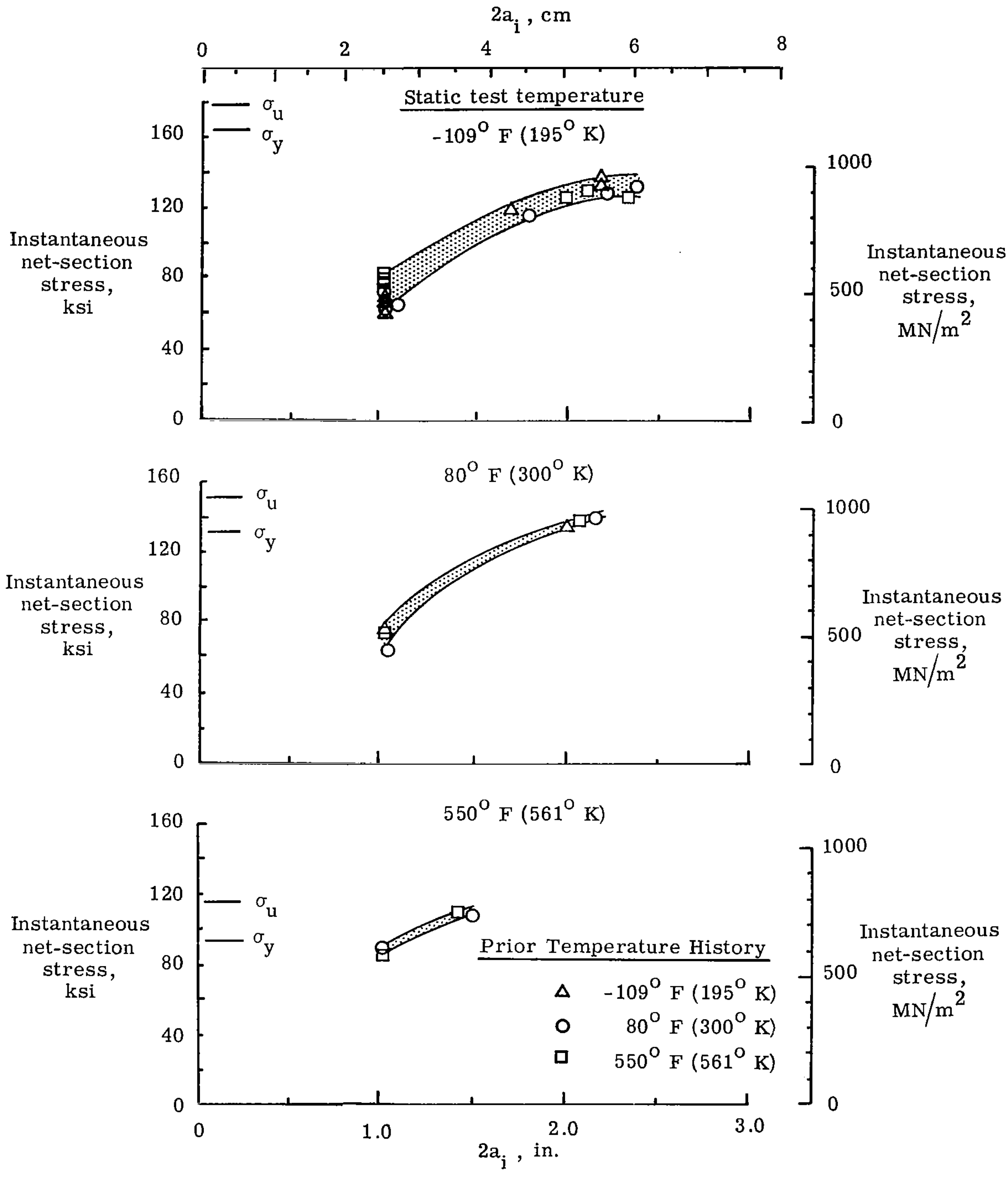


Figure 8.- Effect of prior temperature history on slow crack growth of 8-inch-wide (20.3-cm) Ti-8Al-1Mo-1V (duplex-annealed) specimens. t = 0.050 inch (1.27 mm); longitudinal grain. Data at left indicate initiation of slow crack growth; data at right indicate critical conditions; scatterband indicates trend of slow-crack-growth data.

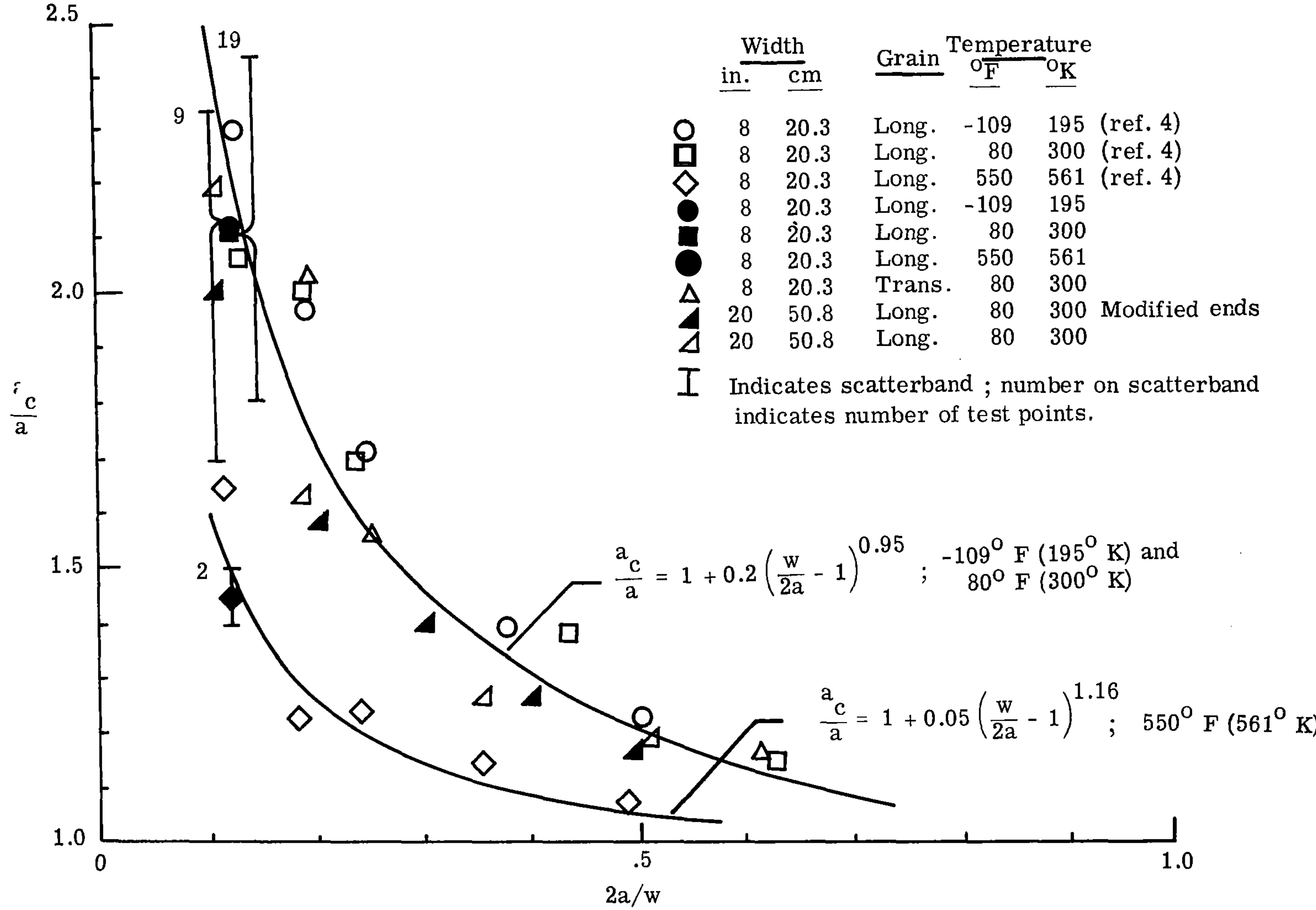


Figure 9.- Summary plot of slow-crack-growth behavior as a function of 2a/w at various temperatures.

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