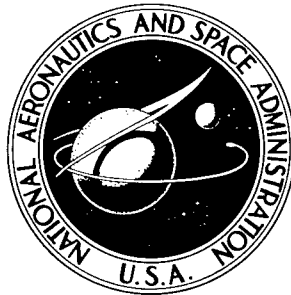


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IN ALLOYS SUITABLE FOR
ELEVATED-TEMPERATURE APPLICATIONS

by C. Michael Hudson
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STUDIES OF FATIGUE CRACK GROWTH IN ALLOYS SUITABLE FOR
ELEVATED-TEMPERATURE APPLICATIONS

By C. Michael Hudson
Langley Research Center

SUMMARY

Constant-amplitude axial-load fatigue-crack-propagation tests were conducted on 8-inch (20.3-cm) wide sheet specimens made of AM 350 (CRT) and AM 367 stainless steels, two thicknesses of Ti-8Al-1Mo-1V (duplex annealed) titanium alloy, 2020-T6, 2024-T81 (clad), and RR-58 (clad) aluminum alloys, and Inconel 718 superalloy. Tests were conducted at room, elevated, and cryogenic temperatures to determine the effect of temperature on crack propagation in each material.

The fatigue-crack-growth resistance of the materials was determined and compared with materials tested similarly in a previous investigation. At elevated temperature, the 0.050-inch (1.27-mm) thick titanium alloy, Ti-8Al-1Mo-1V, in either the duplex- or triplex-annealed condition showed the greatest resistance to crack growth. At the room and cryogenic temperatures, the superalloy Inconel 718 appeared to be the most resistant. The AM 367 stainless steel showed good resistance to crack growth at all temperatures but only a limited number of tests were conducted on this material.

INTRODUCTION

A study of the fatigue-crack-growth characteristics of nine materials having potential use in supersonic aircraft is reported in reference 1 which is extended herein to include seven additional materials. Axial-load fatigue tests were conducted at positive mean stresses on 8-inch (20.3-cm) wide sheet specimens. Identical tests were conducted at elevated, room, and cryogenic temperatures to determine the effect of temperature on fatigue crack growth.

The experimental results of this study are presented in this paper. The effects of temperature on crack propagation in each material were determined. In addition, the crack-growth characteristics of the seven materials tested are compared with the characteristics of the most resistant materials tested in the previous investigation (ref. 1) to provide a comprehensive ranking of each material with respect to resistance to fatigue crack propagation.

SYMBOLS

The units used for the physical quantities defined in this paper are given both in the U.S. Customary Units and in the International System of Units (SI). Factors relating the two systems are given in reference 2.

a	one-half of the total length of a central symmetrical crack, inches or centimeters (cm)
N	number of cycles
S _a	alternating stress amplitude, ksi or meganewton/meter ² (MN/m ²)
S _m	mean stress, ksi or meganewtons/meter ² (MN/m ²)
t	specimen thickness, inch or millimeters (mm)

TESTS

Specimens

The materials tested in this investigation are listed in the following table:

Material	Condition	Thickness	
		in.	mm
Stainless steel	AM 350 (CRT)	0.050	1.27
	AM 367	.050	1.27
Aluminum alloy	2020-T6	.050	1.27
Aluminum alloy	2024-T81 (clad)	.063	1.61
Aluminum alloy	RR-58 (clad)	.063	1.61
Titanium alloy	Ti-8Al-1Mo-1V (duplex annealed)	.050	1.27
Titanium alloy	Ti-8Al-1Mo-1V (duplex annealed)	.250	6.35
Superalloy	Inconel 718	.050	1.27

All the specimens for each alloy were obtained from the same mill heat. The tensile properties of each material tested are listed in table I and the nominal chemical compositions, in table II.

The general configuration of the specimens may be seen in figure 1. The specimens were 24 inches (61 cm) long and 8 inches (20.3 cm) wide. All specimens were made with the longitudinal axis of the specimens parallel to the

grain of the sheet. A 0.1-inch (0.254-cm) notch was cut into the center of each specimen by means of an electrical discharge process. Very localized heating occurs in making notches in this manner. Thus, virtually all of the material through which the fatigue crack propagates is unaltered by the cutting process.

Prior to shearing the specimen blanks, the sheet materials were covered with tape to protect the surfaces. Following shearing, all specimens were chemically cleaned. Those specimens requiring heat treatment were then heat treated according to the procedures outlined in table III.

A reference grid (fig. 2) was photographically printed on the specimen surfaces to define intervals along the crack path. This photographic method produces no mechanical defects in the specimen surface, and, consequently, no stress concentrations are introduced. Metallographic examination and tensile tests conducted on specimens bearing the grid indicate that the grid had no detrimental effects upon the materials tested.

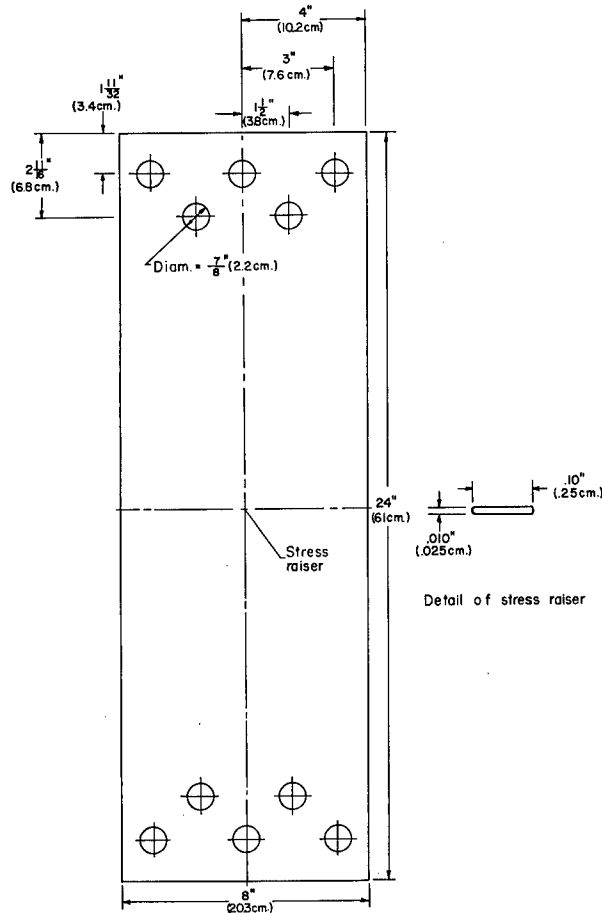


Figure 1.- Specimen configuration for crack propagation studies.

Testing Equipment

Three axial-load fatigue testing machines were employed in this investigation. A 20 000-pound (89-kN) capacity subresonant fatigue machine (ref. 3) having an operating frequency of 1800 cpm (30 Hz) was used for tests expected to last more than 1 000 000 cycles. A 100 000-pound (445-kN) capacity hydraulic fatigue machine which applied loads at a rate of 1200 cpm (20 Hz) was employed in tests expected to last from 10 000 to 1 000 000 cycles. A combination hydraulic and subresonant fatigue testing machine (ref. 4) capable of applying loads up to 132 000 pounds (587 kN) hydraulically or 110 000 pounds (489 kN) subresonantly was used as the needs for testing dictated. The operating frequencies were 40 to 60 cpm (0.7 to 1 Hz) for the hydraulic unit, and approximately 820 cpm (14 Hz) for the subresonant unit.

In all tests, loads were monitored by measuring the output of a bridge circuit whose active elements were wire-resistance strain gages. These gages were fixed to weigh bars through which the load was transmitted to a specimen. Monitoring precision was approximately ± 1 percent.

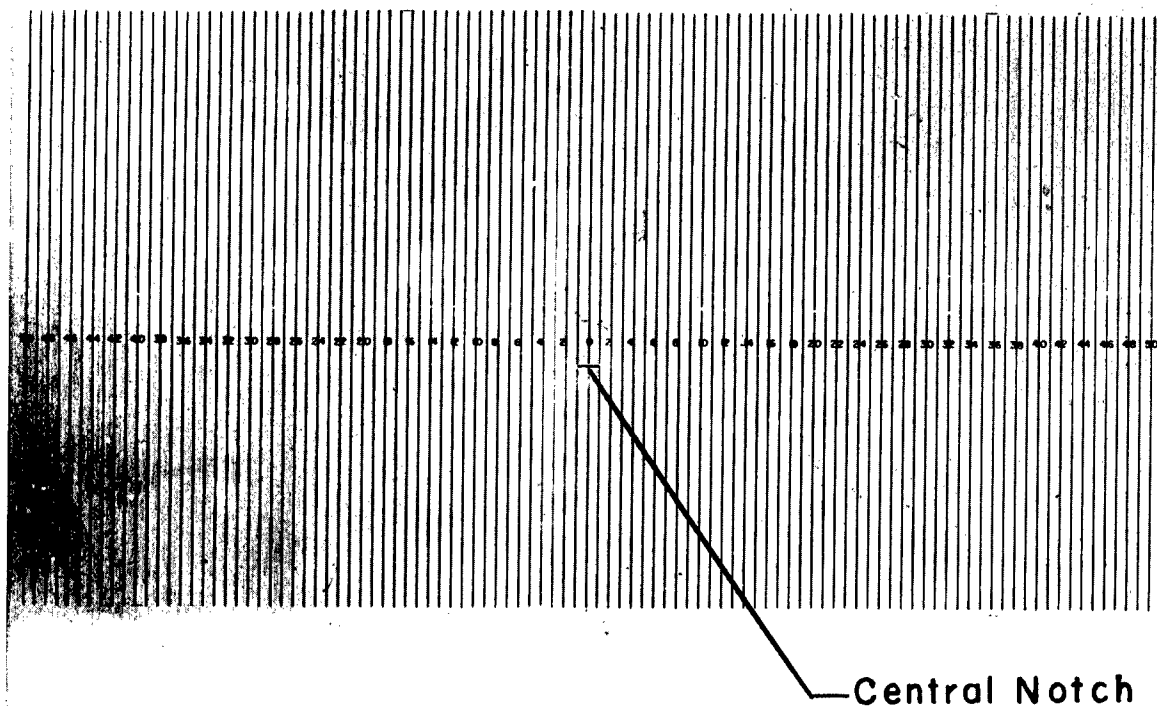
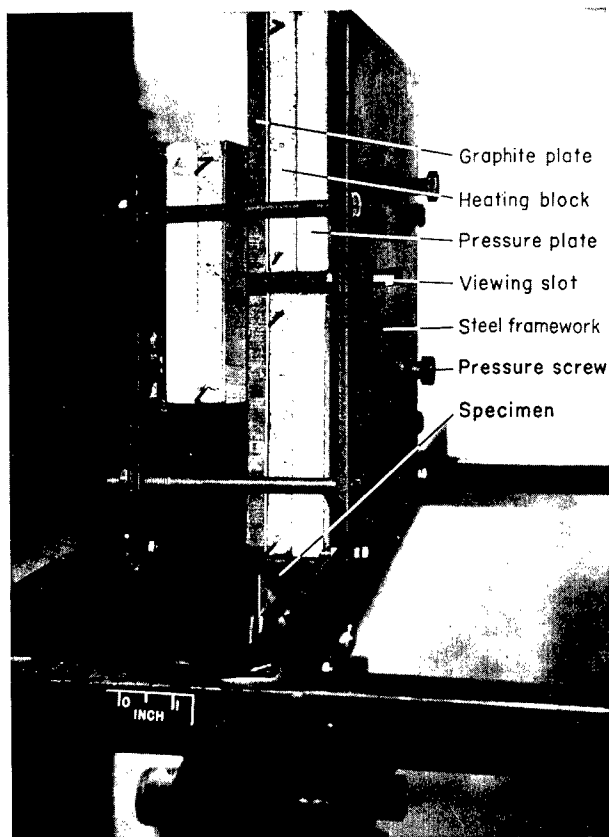


Figure 2.- Grid used to mark intervals in crack path. Grid spacing is 0.05 inch (1.27 mm). L-63-4299.1

The apparatus used in the elevated-temperature tests (fig. 3) consisted of three heating units and a steel framework which held the heating units in contact with the specimen. The heating units were composed of a 1/2-inch (1.27-cm) thick graphite plate, a ceramic block containing wire resistance heaters, and an insulating pressure plate. A machine screw was jammed against the insulating pressure plate to hold the heating unit in contact with the specimen surface. The screws were carefully tightened to insure thermal contact without introducing significant frictional forces. Two heating units were placed on the observation side of the specimen; one above and the other below the region of crack growth. A 1/2-inch (1.27-cm) gap was provided to insure an unobstructed view of the propagating crack. The third unit was located on the opposite surface immediately opposite the crack-growth region.

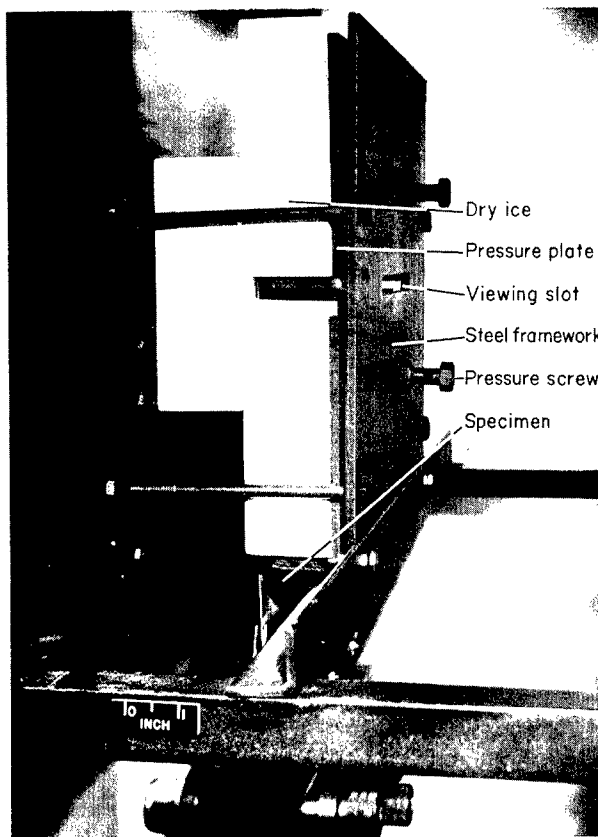
A control thermocouple was fixed in the expected crack path near the edge of the specimen. By using an edge control point, the temperature was found to vary $\pm 5^{\circ}$ F ($\pm 3^{\circ}$ K) across the specimen width. The temperature at a given point was found to vary $\pm 2^{\circ}$ F ($\pm 1^{\circ}$ K) during the course of the test. Temperature control was maintained in the elevated-temperature tests by a controller-recorder which regulated current flow through a saturable reactor. The controller operated at 208 volts using 60-cycle single-phase ac power.

The equipment used in the -109° F (195° K) tests (fig. 4) consisted of three blocks of dry ice, the same steel framework used for the furnace, and an insulating cover box. The dry ice blocks were mounted in the steel framework



L-63-9528.2

Figure 3.- Elevated-temperature-test apparatus.



L-63-9529.2

Figure 4.- Cryogenic-temperature-test apparatus.

and held in contact with the specimen surface in the same manner as the heating units. Test temperature was governed by the sublimation temperature of the dry ice and was found to vary less than 5° F (3° K).

The entire cooling apparatus was isolated from circulating air drafts by the insulating cover box. This isolation was necessary in order to control the sublimation rate of the dry ice satisfactorily. The specimen surfaces were periodically sprayed with ethyl alcohol to prevent frost buildup in the crack-growth region.

Specimens were clamped between $3/8$ -inch (0.95-cm) thick aluminum guides (ref. 5) to prevent buckling and out-of-plane vibrations in all the room-temperature tests. Guides were also used in the elevated- and cryogenic-temperature tests in which compressive loadings were applied. In these latter tests, the heating or cooling units were placed directly against the guide plates and the specimen was heated or cooled by heat conduction through the guides. Good temperature control was maintained throughout these tests.

Specimen surfaces were lubricated with light oil in the room- and cryogenic-temperature tests and with dry molybdenum disulfide in the elevated-temperature tests. One side of the guide contained a 1/2-inch (1.27-cm) cutout across its width to allow visual observation of the crack path. A transparent plate was fitted into the guide cutout to prevent buckling of the specimen.

Test Procedure

Constant-amplitude axial-load fatigue tests were conducted at positive mean stresses of 40 ksi (276 MN/m²) for AM 350, AM 367, and Inconel 718; 25 ksi (173 MN/m²) for Ti-8Al-1Mo-1V; and 15 ksi (104 MN/m²) for 2020-T6, RR-58 (clad), and 2024-T81 (clad). All stresses mentioned herein refer to the original net area of the specimen. Alternating stresses ranged from ± 60 to ± 5 ksi (± 414 to ± 30 MN/m²) for AM 350, AM 367, and Inconel 718; ± 25 to ± 2 ksi (± 173 to ± 14 MN/m²) for Ti-8Al-1Mo-1V; and ± 15 to ± 2 ksi (± 104 to ± 14 MN/m²) for 2020-T6, RR-58 (clad), and 2024-T81 (clad). Mean and alternating loads were kept constant throughout each test.

Tests were conducted at 80° F (300° K) and -109° F (195° K) on all materials, at 550° F (561° K) on the stainless steels, titanium alloys, and the superalloy, and at 250° F (394° K) on the aluminum alloys. Specimens were tested at the same stress levels at all test temperatures in order to evaluate the effect of temperature on crack propagation.

The test data were obtained by observing the crack growth through 30 power microscopes while illuminating the specimen with stroboscopic light. The number of cycles required to propagate the crack to each grid line was recorded so that the rate of crack propagation could be determined. Tests were terminated when the cracks reached a predetermined crack length, and the specimens were reserved for the subsequent residual static-strength investigation reported in reference 6.

RESULTS AND DISCUSSION

The crack-propagation-test results are presented in table IV which gives the number of cycles required to propagate a crack from a half length a of 0.15 inch (0.38 cm). The number of cycles given in table IV, and in figures 5 to 12, is the mean number of cycles required to grow cracks of equal length on both sides of the central starter notch. The numbers of cycles are referenced from a half crack length of 0.15 inch (0.38 cm) because at this length the fatigue crack growth is no longer influenced by the starter notch (ref. 7).

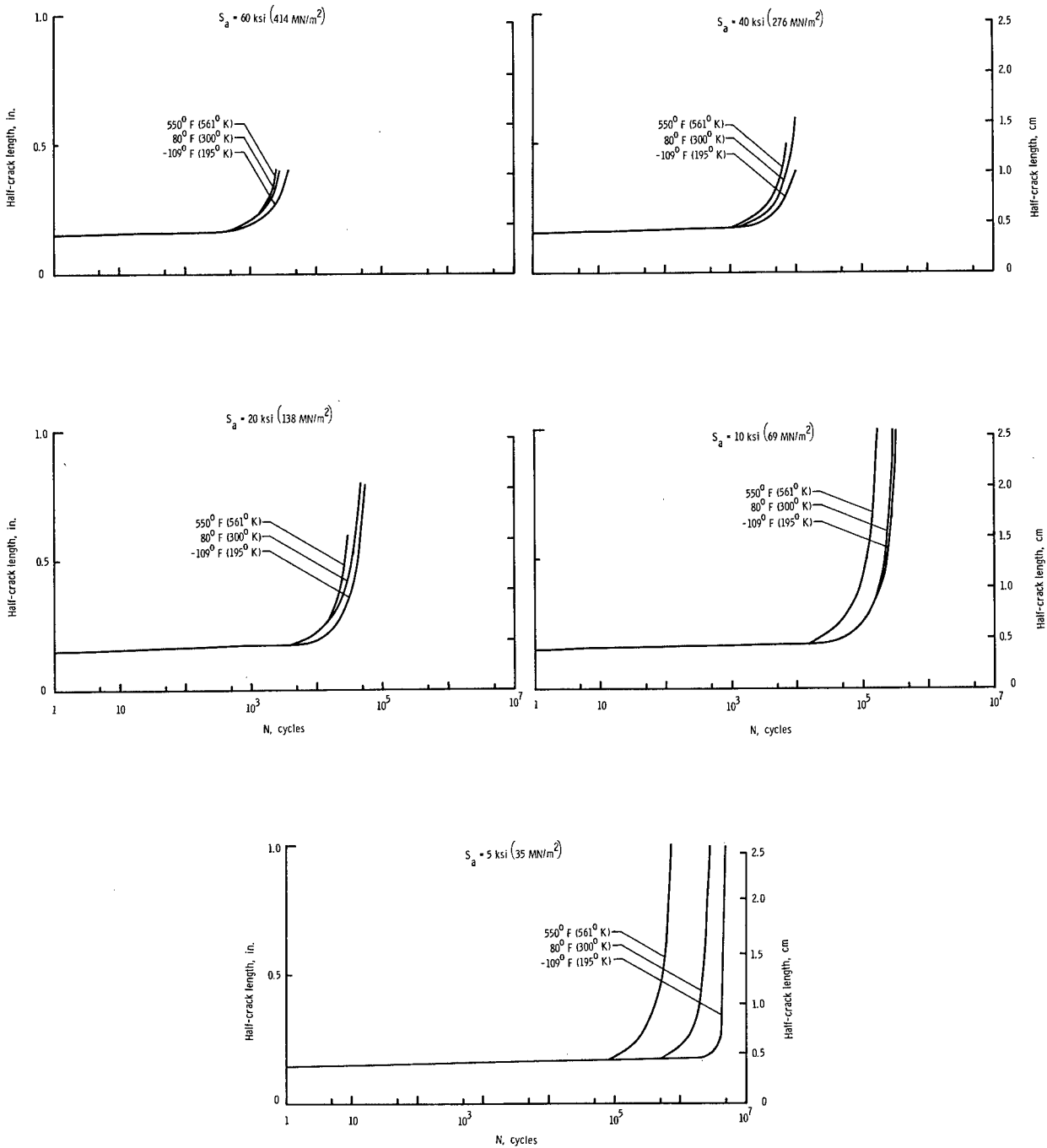


Figure 5.- Fatigue-crack-propagation curves for Inconel 718. $S_m = 40 \text{ ksi (276 MN/m}^2\text{)}$.

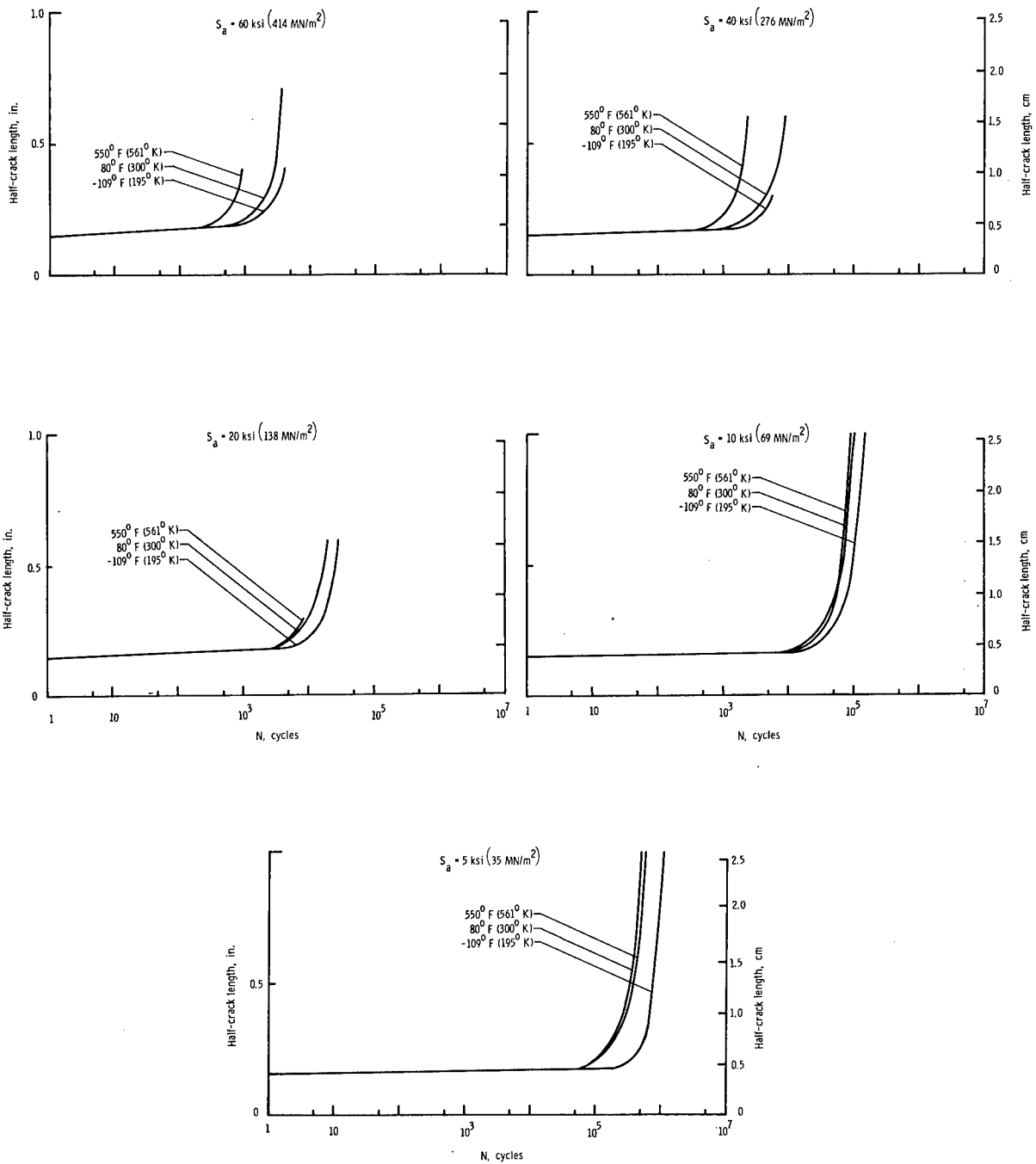


Figure 6.- Fatigue-crack-propagation curves for AM 350 (CRT). $S_m = 40 \text{ ksi (276 MN/m}^2\text{)}$.

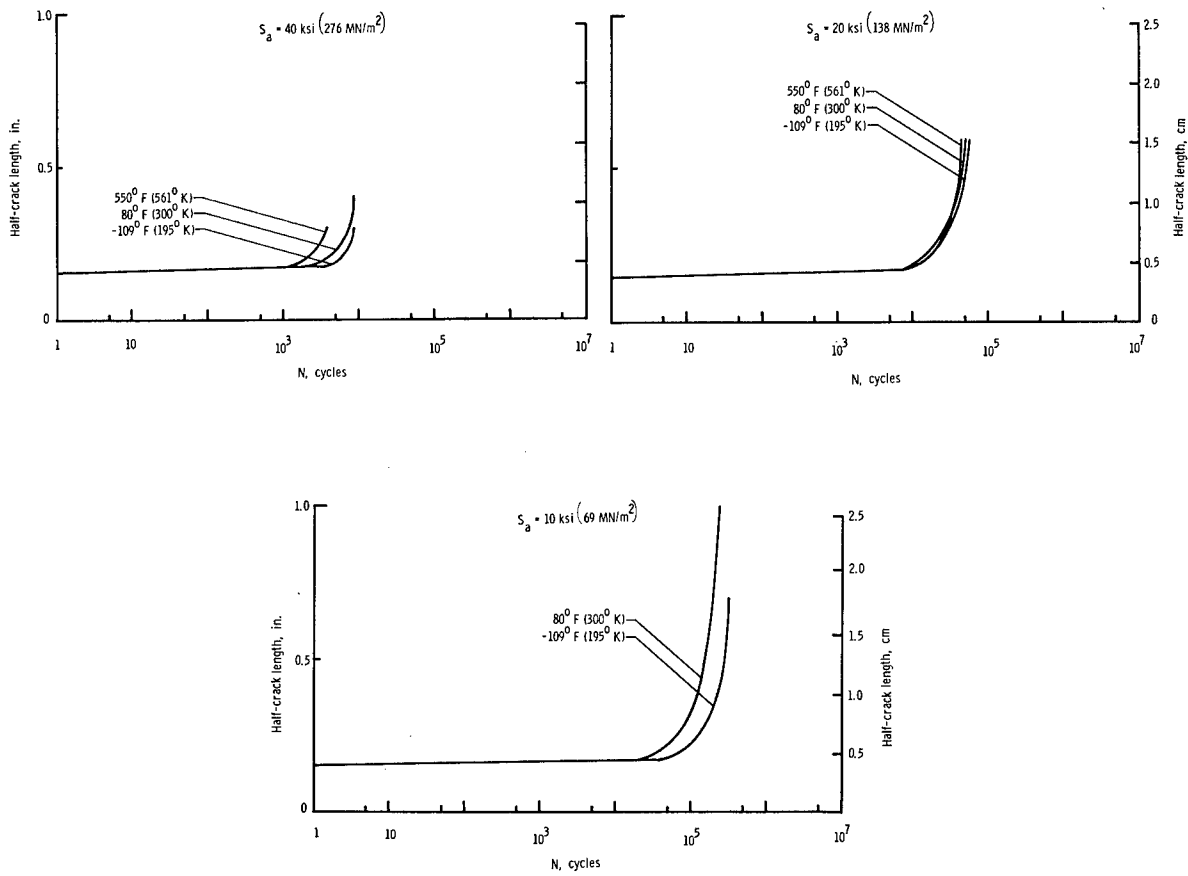


Figure 7.- Fatigue-crack-propagation curves for AM 367. $S_m = 40 \text{ ksi (276 MN/m}^2\text{)}$.

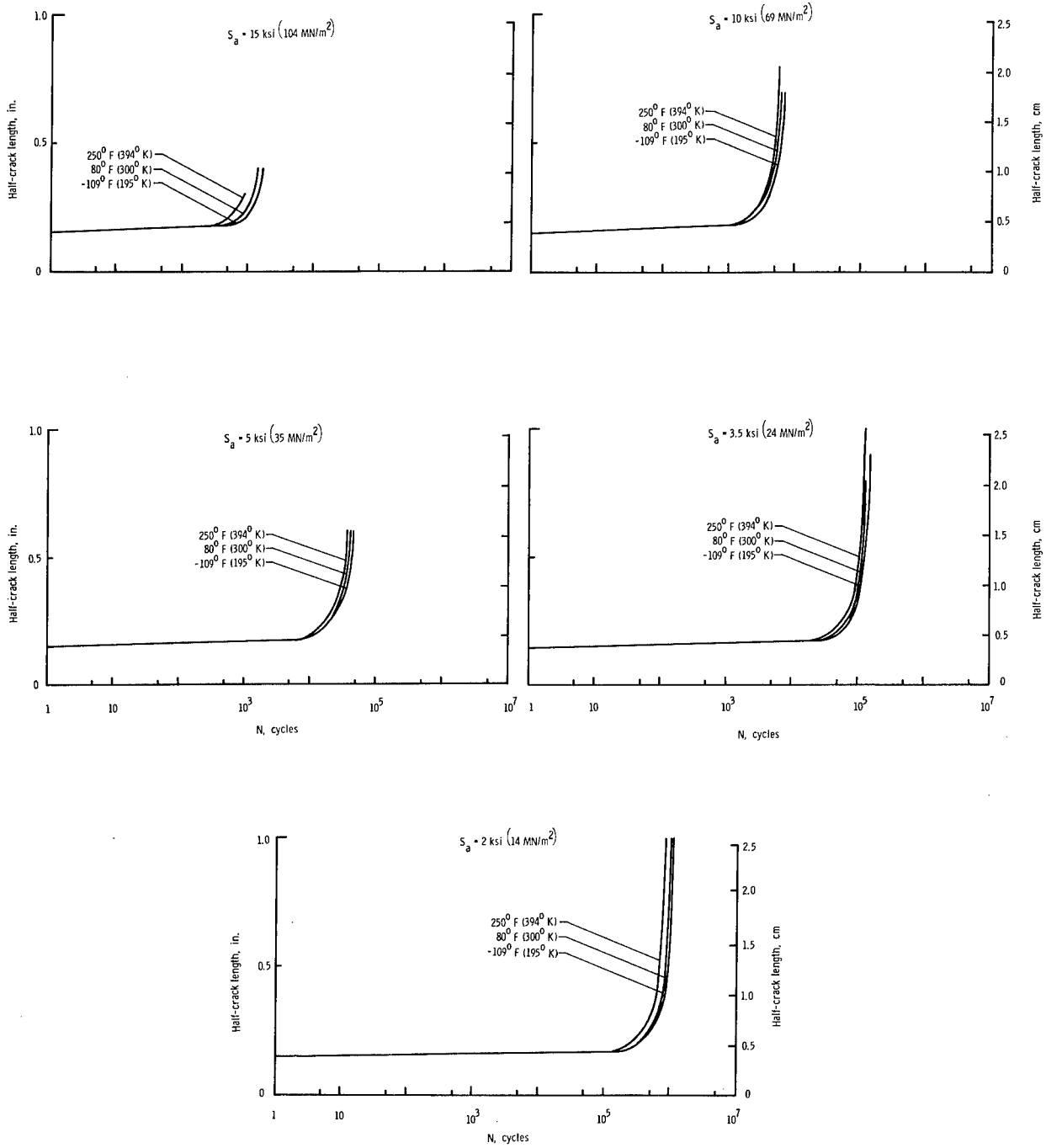


Figure 8.- Fatigue-crack-propagation curves for 2024-T81 (clad). $S_m = 15 \text{ ksi (104 MN/m}^2\text{)}$.

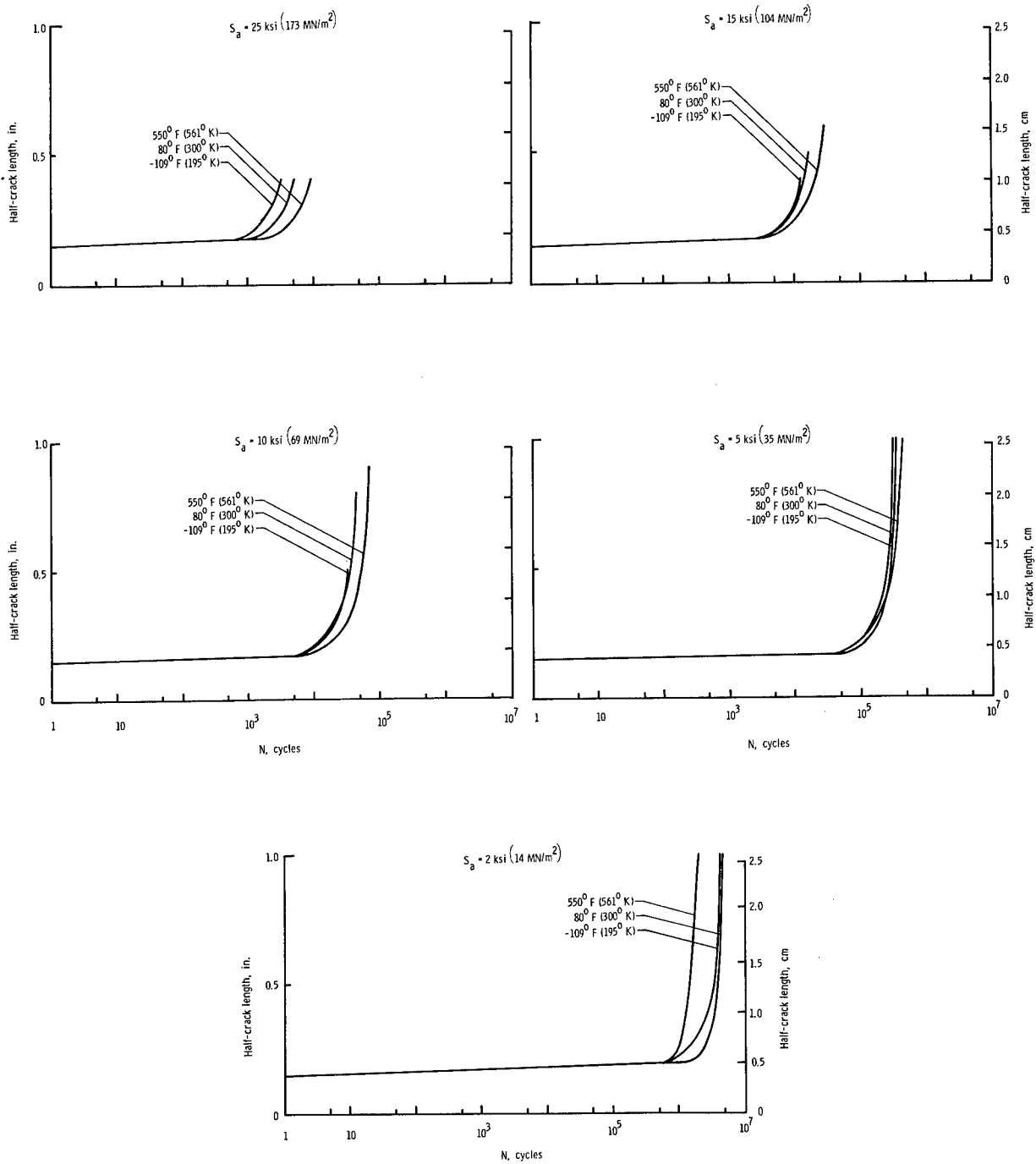


Figure 9.- Fatigue-crack-propagation curves for Ti-8Al-1Mo-1V (duplex annealed).
 $t = 0.050 \text{ inch (1.270 mm)}$; $S_m = 25 \text{ ksi (173 MN/m}^2\text{)}$.

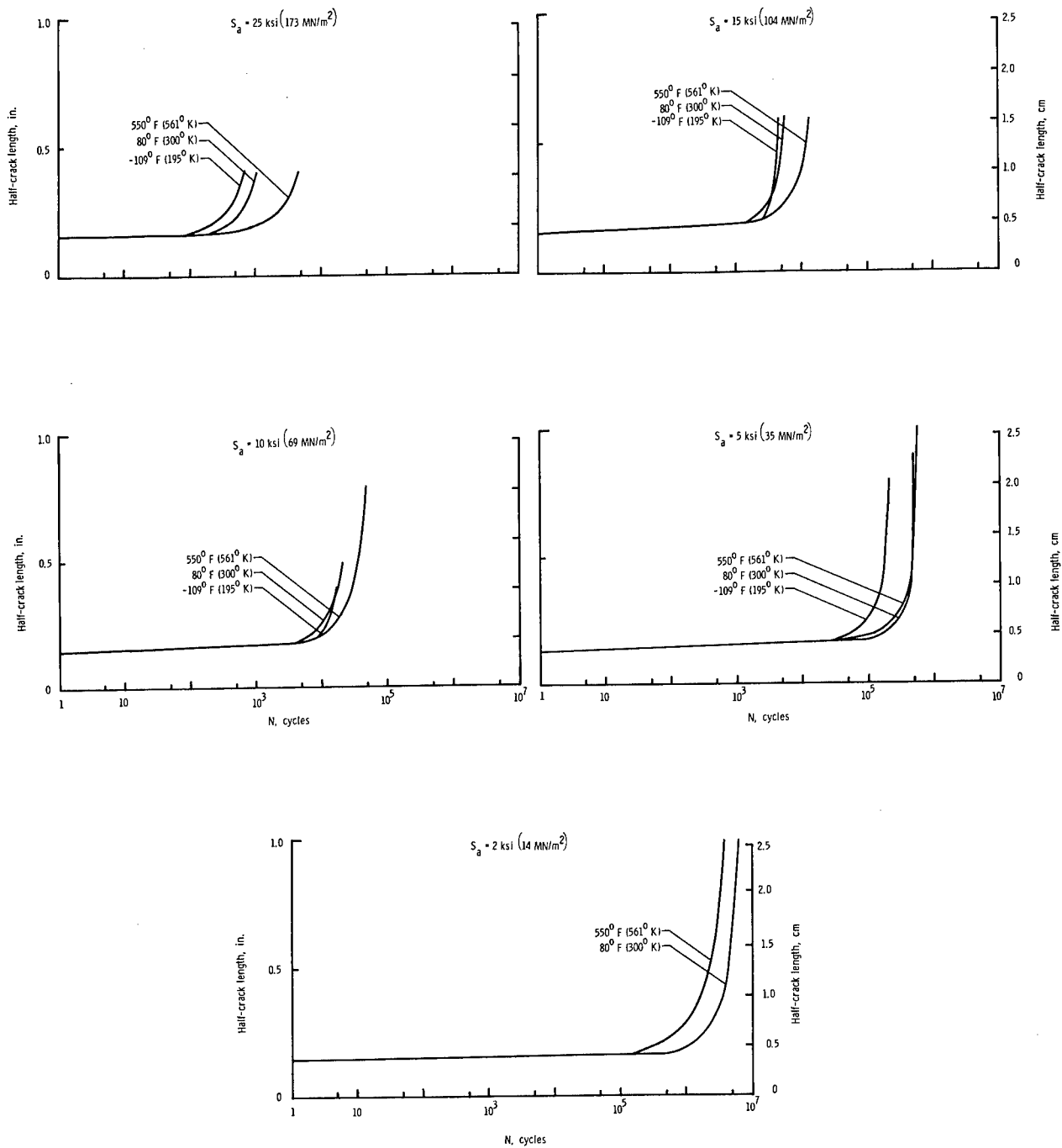


Figure 10.- Fatigue-crack-propagation curves for Ti-8Al-1Mo-1V (duplex annealed).
 $t = 0.250 \text{ inch } (6.350 \text{ mm})$; $S_m = 25 \text{ ksi } (173 \text{ MN/m}^2)$.

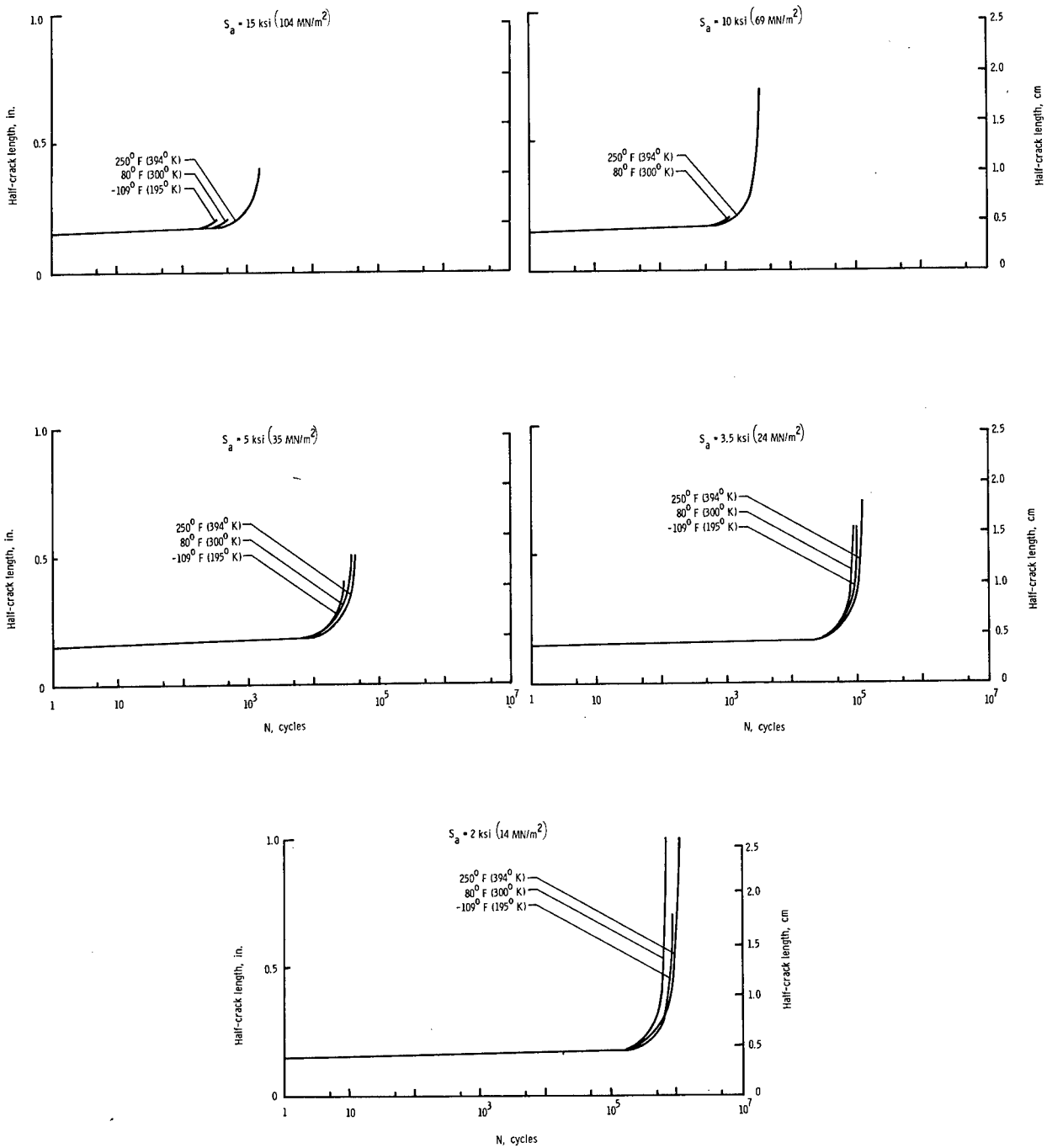


Figure 11.- Fatigue-crack-propagation curves for 2020-T6. S_m = 15 ksi (10⁴ MN/m²).

Temperature Effect

The effect of temperature on crack growth was determined by comparison of the crack propagation curves from tests at room, elevated, and cryogenic temperatures. The crack-growth curves for Inconel 718, AM 350, AM 367, and 2024-T81 (clad) (figs. 5, 6, 7, and 8, respectively) show almost without exception that the higher the temperature, the more rapidly fatigue cracks propagated. A similar change of crack-growth resistance with temperature was found for the stainless steels and a superalloy tested in the previous crack-growth investigation (ref. 1). The loss of resistance to fatigue crack growth with increasing temperature may be attributed to the normal deterioration of properties at elevated temperature.

The crack-growth curves for both thicknesses of Ti-8Al-1Mo-1V (duplex annealed) and for 2020-T6 (figs. 9, 10, and 11, respectively) indicate that fatigue cracks generally grow most slowly at elevated temperature, and most rapidly at cryogenic temperature. In most instances, however, the differences between the crack-growth curves were small. The titanium alloys tested in reference 1 were also found to be slightly more resistant to crack growth at elevated temperature.

The fatigue-crack-growth curves for the RR-58 (clad) (fig. 12) indicate no consistent variation of crack-growth resistance with temperature. At the higher stress levels the RR-58 (clad) showed the greatest resistance at room temperature, while at the lower stress levels the resistance was greatest at 250° F (394° K).

Crack-Growth Resistance of Materials

The relative crack-growth resistance of the various materials was determined by comparing plots of the rates of fatigue crack growth against the ratio of the alternating to the mean stress (i.e., the stress ratio). The lower the rate of crack growth for a given stress ratio, the greater the resistance of the material to fatigue crack growth. The crack-growth rates were determined graphically by taking the slopes of the fatigue-crack-growth curves (on a linear plot) at different crack lengths. Figures 13, 14, and 15 show the rate plotted against stress ratio for the elevated-, room-, and cryogenic-temperature tests, respectively. The rates shown in these three figures are for a half crack length a of 0.40 inch (1.02 cm). The materials generally maintained the same relative positions at other crack lengths.

The mean stresses at which the comparisons in figures 13 to 15 were made are approximately one-fifth of the ultimate tensile strength of the materials. The mean stress-density ratios for the materials are also approximately equal.

At elevated temperature (fig. 13), the thin titanium sheet showed the greatest resistance to crack growth, followed by Inconel 718, and the thick titanium plate. The results of tests on AM 367 indicate good crack-growth resistance at elevated temperature, but only a small number of tests were conducted. Fatigue-crack-growth rates in the 2020-T6, RR-58 (clad), 2024-T81 (clad), and AM 350 were relatively high.

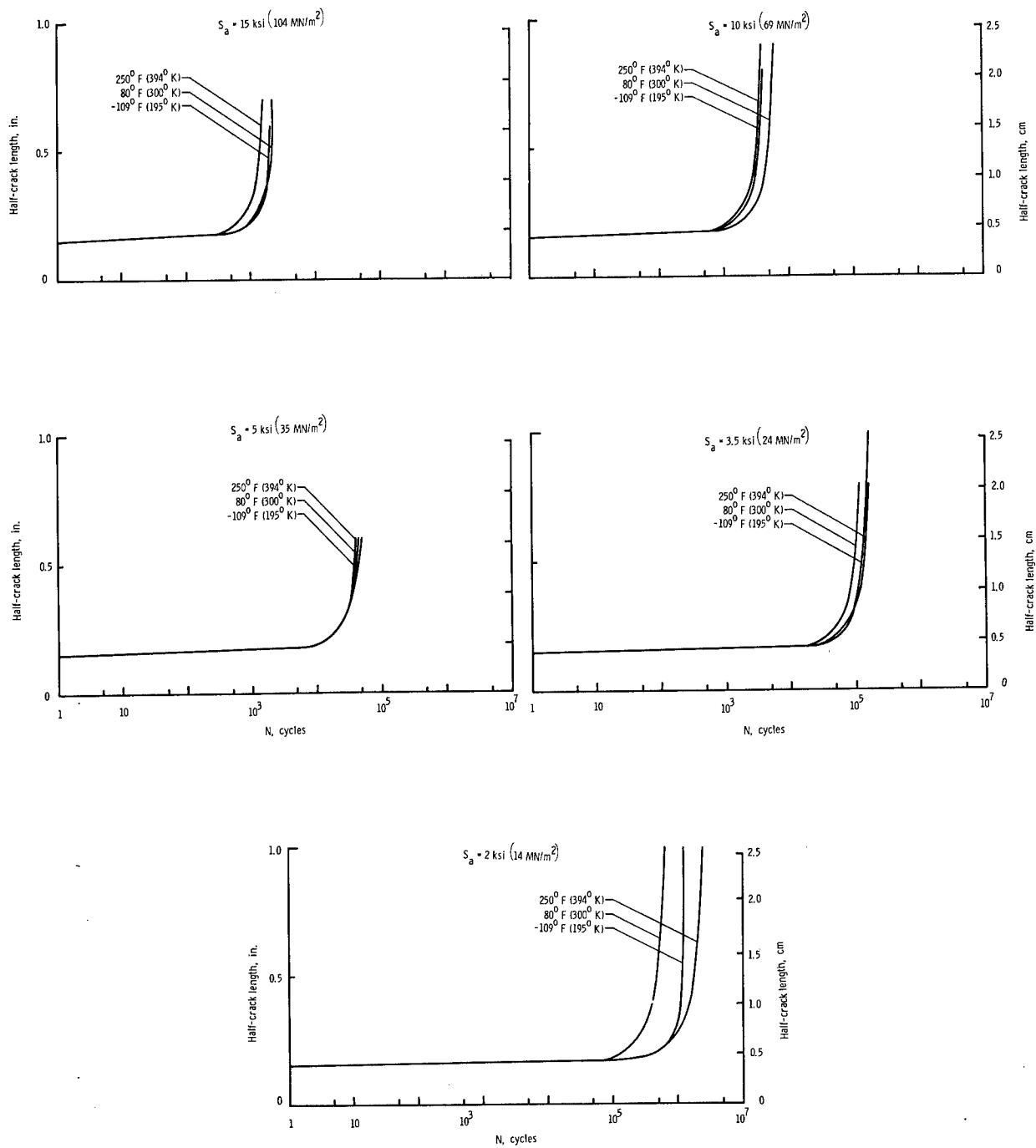


Figure 12.- Fatigue-crack-propagation curves for RR-58 (clad). $S_m = 15 \text{ ksi (104 MN/m}^2\text{)}$.

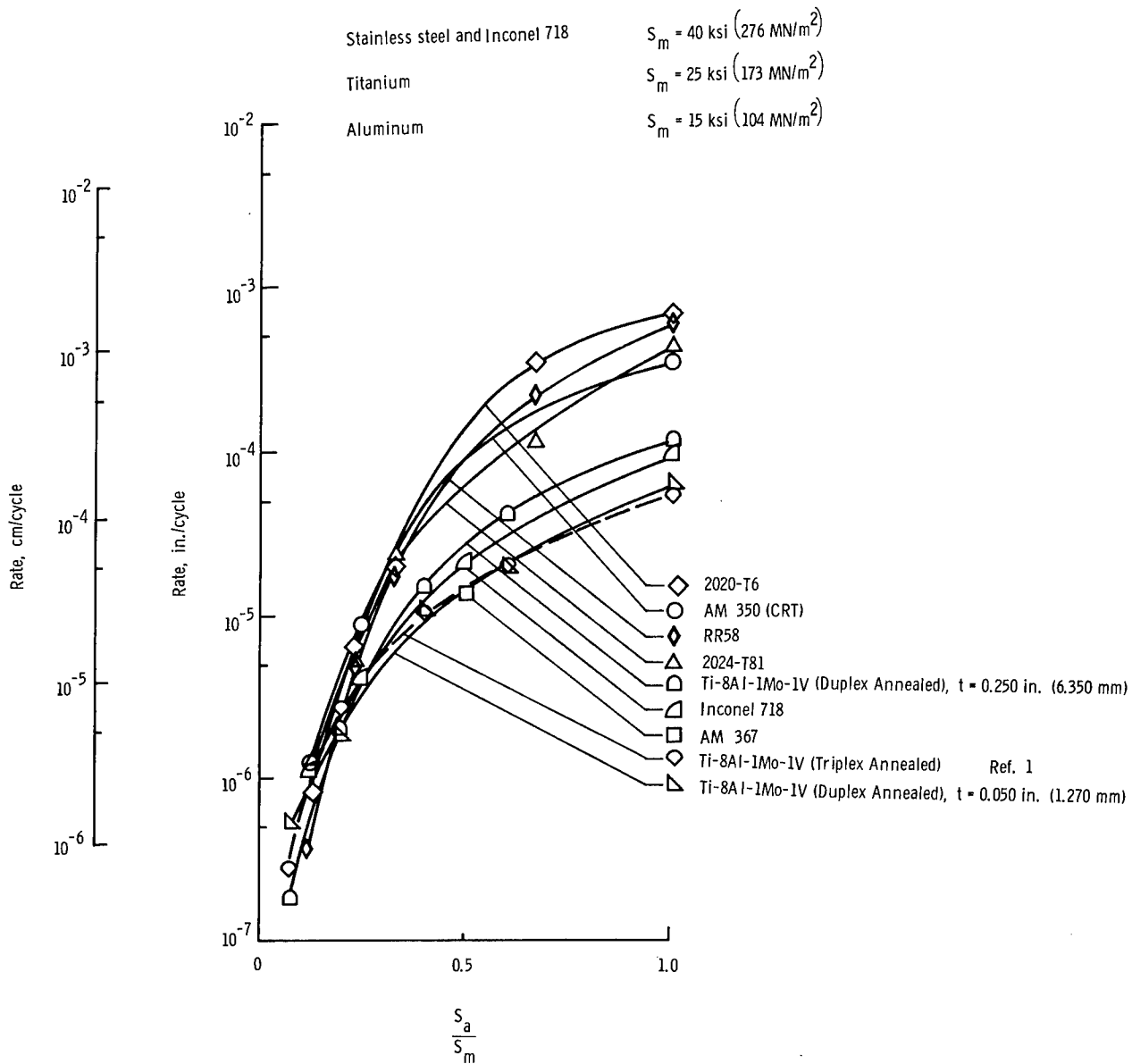


Figure 13.- Fatigue-crack-propagation rate as a function of the ratio of alternating to mean stress at elevated temperature (250° F (394° K) for the aluminums, 550° F (561° K) for all others) for a half crack length a of 0.40 inch (1.02 cm).

Data from tests at 550° F (561° K) and at 250° F (394° K) are compared directly in figure 13 in order to evaluate the relative efficiencies of the various materials at the approximate elevated temperature extremes to which the materials might be subjected in supersonic aircraft.

At room temperature (fig. 14), Inconel 718 and AM 367 exhibited the lowest fatigue-crack-growth rates followed by AM 350 and the thin titanium sheet. The crack-growth rates again were quite high for the three aluminum alloys and also

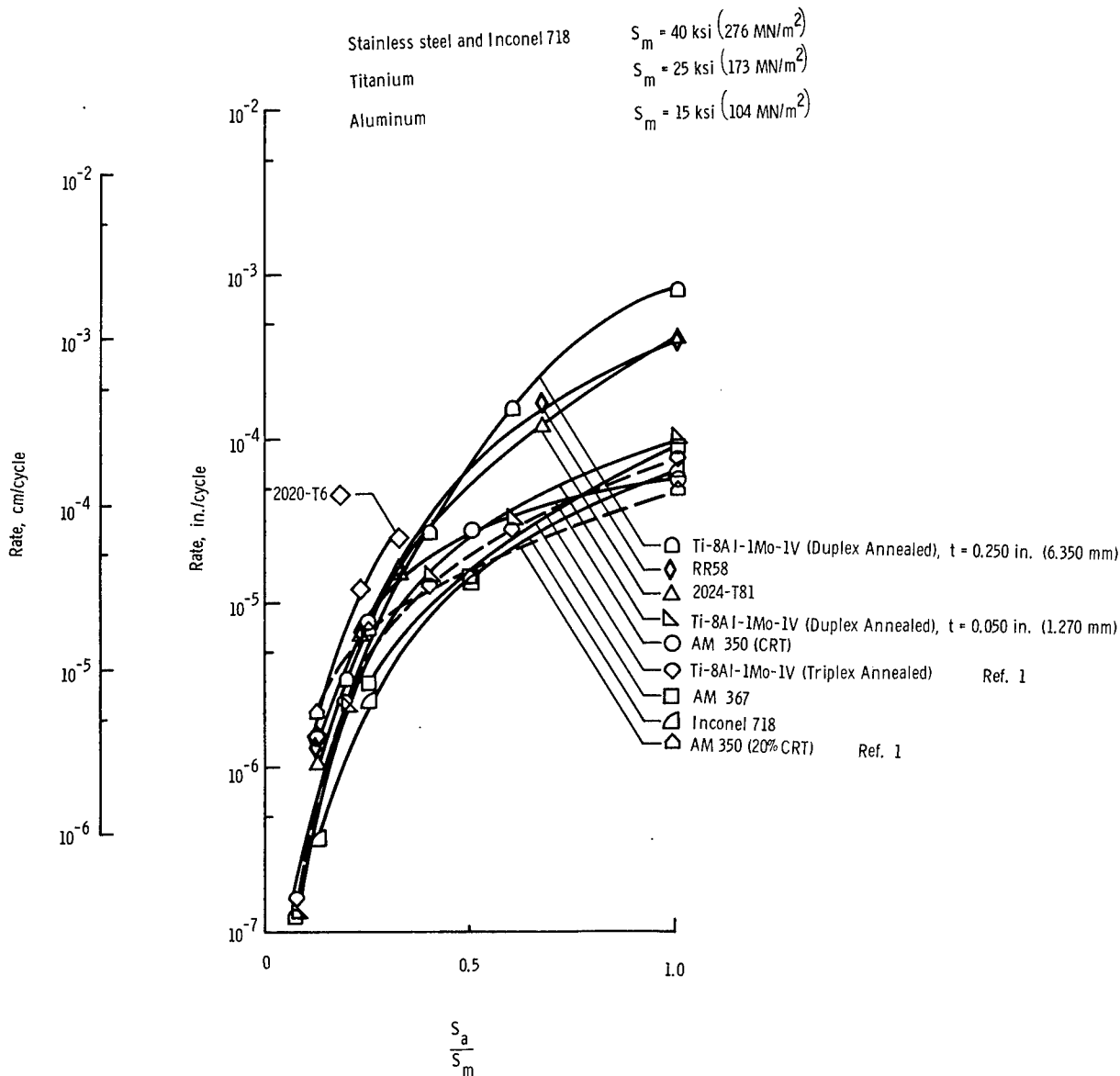


Figure 14.- Fatigue-crack-propagation rate as a function of the ratio of alternating to mean stress at 80° F (300° K) for a half crack length a of 0.40 inch (1.02 cm).

for the thick titanium plate. The AM 367 and Inconel 718 (fig. 15) also showed the greatest resistance to fatigue crack growth at cryogenic temperature. The AM 350 and the thin titanium sheet followed. The three aluminum alloys and the thick titanium plate were once again the least resistant materials tested.

Thus, it appears that over the temperature range of the investigation, the Inconel 718 and the AM 367 exhibited the greatest overall resistance to fatigue crack growth. It should be remembered, however, that a somewhat smaller quantity of data was obtained on the AM 367. It further appears that the crack-growth resistance of the thick titanium plate is considerably lower than the resistance of the thin sheet. This lower crack-growth resistance may result

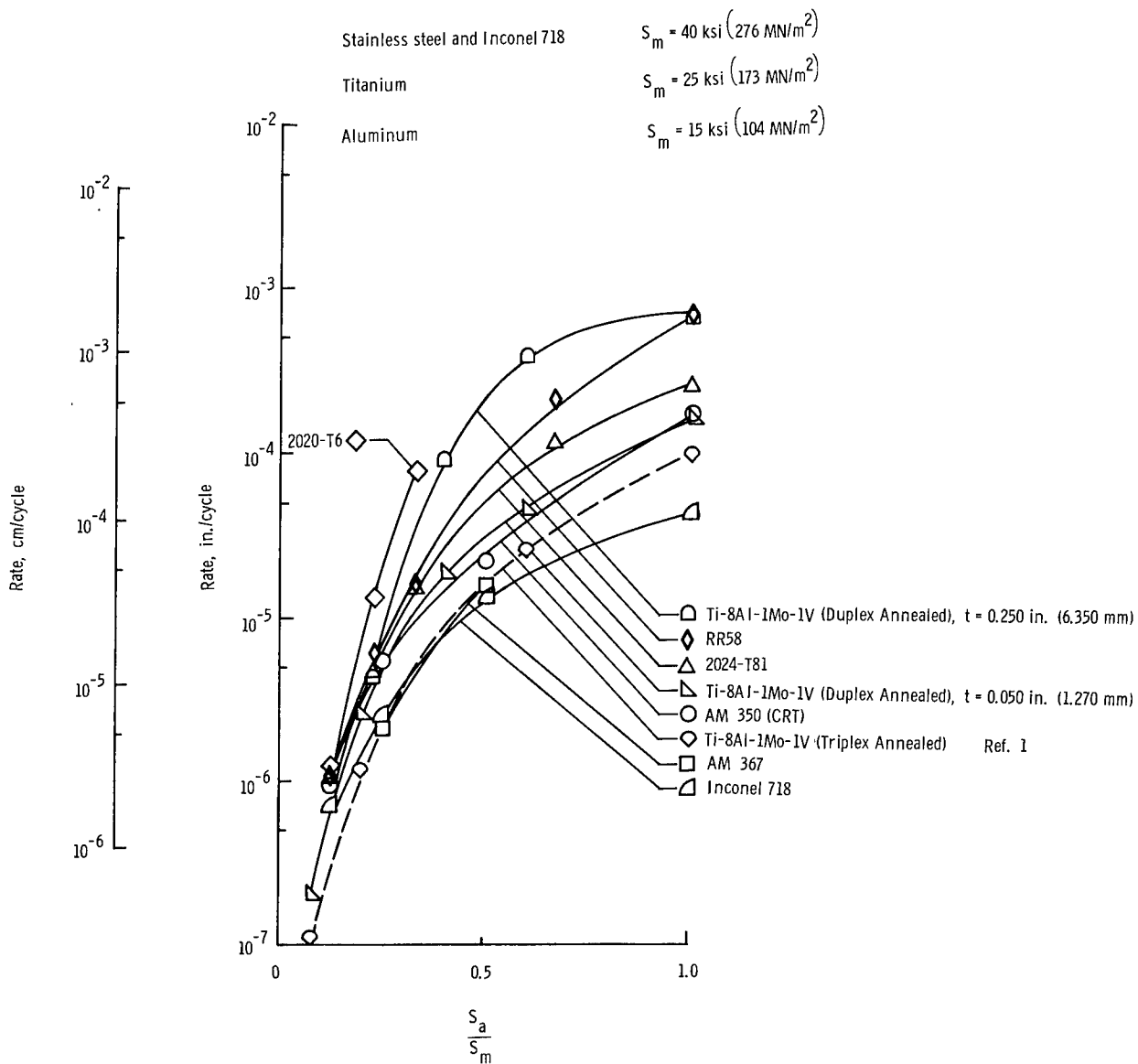


Figure 15.- Fatigue-crack-propagation rate as a function of the ratio of alternating to mean stress at $-109^\circ \text{ F } (195^\circ \text{ K})$ for a half crack length a of 0.40 inch (1.02 cm).

from a tri-axial stress state inherent in the thicker material. In this state, the plastic deformation in the material ahead of the crack tip is partially restrained by the large bulk of elastic material surrounding the plastic zone. This restraint of plastic flow causes the stresses in this plastic zone to increase to a higher level than would be possible if plastic flow could occur readily, as in thin sheet materials. These higher stresses could promote a faster rate of fatigue crack growth. The difference between crack-growth resistance of the thick and the thin titanium material also have resulted from the different amounts of working to which the material was subjected in processing.

For purposes of comparison, the crack-growth-rate against stress-ratio curves for sheet Ti-8Al-1Mo-1V (triplex annealed) titanium alloy, and AM 350 (20% CRT) stainless steel, which showed the greatest crack-growth resistance in the previous investigation (ref. 1), have been included (dashed curves) with the test data reported herein. Inspection of figures 13, 14, and 15 indicates that for the entire spectrum of materials tested, the sheet Ti-8Al-1Mo-1V titanium alloy in either the duplex- or triplex-annealed condition has the greatest resistance to fatigue crack growth at elevated temperature. At the room and cryogenic temperatures, Inconel 718 generally appeared to be most resistant. The AM 367 also exhibited relatively good crack-growth characteristics at all three test temperatures.

The data for the triplex-annealed titanium alloy has been included at all three test temperatures to show the effect of the different annealing processes on the crack-growth resistance. The curves indicate that at elevated temperature the crack-growth characteristics of the triplex-annealed alloy are approximately equal to those of the duplex-annealed alloy. At the room and cryogenic temperatures, the triplex-annealed alloy is generally more resistant to crack growth than is the duplex-annealed alloy.

CONCLUSIONS

The following conclusions were drawn from the investigation of the fatigue-crack-growth characteristics of seven materials considered for structural applications in supersonic aircraft design. Tests were conducted at temperatures of -109° F (195° K), 80° F (300° K), and either 550° F (561° K) or 250° F (394° K) depending upon the material.

1. The higher the temperature the more rapidly fatigue cracks propagated in AM 350 (CRT) and AM 367 stainless steel, Inconel 718 superalloy, and 2024-T81 (clad) aluminum alloy. Cracks were found to grow more rapidly as the temperature decreased in the Ti-8Al-1Mo-1V (duplex annealed) titanium alloy and the 2020-T6 aluminum alloy. These conclusions concur in general with those presented in NASA Technical Note D-2331. The RR-58 (clad) aluminum alloy exhibited no consistent variation of crack-growth resistance with temperature. 0.20

2. The superalloy Inconel 718 exhibited the greatest overall resistance to fatigue crack growth. The 0.050-inch (1.27-mm) thick Ti-8Al-1Mo-1V (duplex annealed) sheet material was the most resistant to crack growth at elevated temperature followed by Inconel 718. The Inconel 718 showed the greatest resistance to crack propagation at room and cryogenic temperatures. A limited number of tests on AM 367 indicated this material has good resistance to crack growth, but only a small number of tests were conducted.

3. The fatigue-crack-growth resistance of the 0.250-inch (6.35-mm) thick Ti-8Al-1Mo-1V (duplex annealed) titanium alloy was considerably lower than the resistance of the 0.050-inch (1.27-mm) thick material. This lower resistance in the thicker material may result from a tri-axial stress state, or from a difference in the cold working.

4. For the test conditions used, the crack-growth resistance of the 2020-T6, RR-58 (clad), and 2024-T81 (clad) aluminum alloys was relatively poor over the entire temperature range.

5. Comparison of the crack-growth-rate with stress-ratio curves for the sheet Ti-8Al-1Mo-1V (duplex annealed) with similar curves for sheet Ti-8Al-1Mo-1V (triplex annealed) obtained in a previous investigation (TN D-2331), shows that crack-growth characteristics are quite similar at elevated temperature. However, at the room and cryogenic temperatures the triplex-annealed alloy was generally more crack-growth resistant than the duplex-annealed alloy.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., January 6, 1965.

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TABLE I.- AVERAGE TENSILE PROPERTIES OF MATERIALS TESTED

[Grain direction longitudinal]

Temperature		Ultimate tensile strength		Yield strength (0.2% offset)		Modulus of elasticity		Elongation, percent 2-in. (5.08-cm) gage length	Number of tests
°F	°K	ksi	MN/m ²	ksi	MN/m ²	ksi	GN/m ²		
AM 367									
-109	195	266.0	1835	263.7	1820	31.4 × 10 ³	217	5.0	3
80	300	243.4	1680	242.0	1670	30.7	212	4.2	3
550	561	206.1	1422	201.3	1389	20.1	139	3.8	3
AM 350 (CRT)									
-109	195	266.3	1838	222.0	1532	28.6 × 10 ³	197	20.7	3
80	300	223.4	1542	217.5	1501	27.8	192	16.2	3
550	561	197.8	1365	184.5	1273	22.5	155	3.0	3
Inconel 718									
-109	195	195.0	1346	161.2	1112	27.8 × 10 ³	192	28.0	3
80	300	193.7	1337	162.2	1119	27.8	192	23.3	3
550	561	172.1	1187	144.7	998	26.8	185	19.0	4
Ti-8Al-1Mo-1V (duplex annealed); t = 0.050 inch (1.27 mm)									
-109	195	178.0	1228	162.7	1123	17.7 × 10 ³	121	15.3	3
80	300	152.0	1049	133.6	922	18.3	126	12.5	3
550	561	115.5	797	93.7	647	14.1	97	12.0	3
Ti-8Al-1Mo-1V (duplex annealed); t = 0.250 inch (6.35 mm)									
-109	195	157.5	1087	145.6	1005	16.9 × 10 ³	117	11.0	3
80	300	137.4	948	120.0	828	14.8	102	17.3	3
550	561	113.8	785	85.8	592	13.3	92	16.5	2
2020-T6									
-109	195	88.3	609	82.4	569	12.4 × 10 ³	86	7.7	3
80	300	81.8	564	77.5	535	11.3	78	8.8	4
250	394	68.8	475	64.0	442	9.7	67	9.0	3
2024-T81 (clad)									
-109	195	69.0	476	62.2	429	8.8 × 10 ³	61	7.0	3
80	300	63.2	436	57.6	397	9.5	66	7.2	3
250	394	59.3	409	53.3	368	8.4	58	7.5	3
RR-58 (clad)									
-109	195	64.6	445	58.8	405	10.4 × 10 ³	72	8.3	3
80	300	59.2	408	54.6	377	10.0	69	7.0	3
250	394	54.0	372	51.3	354	10.5	72	7.3	3

TABLE II.-- NOMINAL CHEMICAL COMPOSITION OF MATERIALS TESTED

Element	AM 367, percent	AM 350, percent	Inconel 718, percent	Ti-8Al-1Mo-1V, percent	2020-T6, percent	2024-T81 (clad), percent	RR-58 (clad), percent
C	0.021	0.08 to 0.12	0.10 max	0.08 max	0.30 to 0.80	0.30 to 0.90	
Mn	0.024	0.50 to 1.25	0.50 max				
P	0.002	0.040 max					
S	0.009	0.030 max			0.40 max	0.50 max	
Si	0.080	0.50 max	0.75 max				1.2
Ni	3.40	4.00 to 5.00	50.0 to 55.0				
Cr	14.25	16.00 to 17.00	17.0 to 21.0			0.10 max	
Mo	1.99	2.50 to 3.25	2.80 to 3.30				
V				0.75 to 1.25			
Al	0.03	0.07 to 0.13	0.20 to 1.00	0.75 to 1.25	Balance	Balance	Balance
N				7.50 to 8.50			
H				0.05 max			
Ti	0.35		0.30 to 1.30	0.015 max	0.10 max		0.1
Fe	Balance	Balance	Balance	Balance	0.40 max	0.50 max	1.0
Co	15.44			0.30 max			
Cu					4.0 to 5.0	3.8 to 4.9	2.5
Cb + Ta			4.50 to 5.75				
Li					0.9 to 1.7		
Mg					0.03 max	1.2 to 1.8	1.5
Zn					0.25 max	0.25 max	
Cd					0.10 to 0.35		

TABLE III.- MATERIAL HEAT TREATMENTS

Material	Condition	Heat treatment
AM 367	-----	Annealed 1400° F (1033° K), quench to -100° F (200° K) for 16 hr, aged 8 hr at 850° F (727° K), air cool
AM 350	CRT	20% cold rolled, tempered 3 to 5 min at 930° F (772° K), air cool
Inconel 718	-----	Annealed 1325° F (993° K) for 8 hr, furnace cool 20° F/hr to 1150° F (894° K), air cool
Ti-8Al-1Mo-1V	Duplex annealed	1450° F (1061° K) for 8 hr, furnace cool, 1450° F (1061° K) for 15 min, air cool
RR-58 (clad)	Fully heat treated to specification DTD 5070 A	5 min to 1 hr at 525° C to 530° C (798° K to 803° K), depending on gage, quench in cold water, 10 to 30 hr at 190° C ± 5° C (463° K ± 5° K)
2020	T6	See reference 8
2024 (clad)	T81	See reference 8

TABLE IV.- MEAN NUMBER OF CYCLES REQUIRED TO EXTEND CRACKS FROM A HALF-LENGTH OF 0.15 INCH (0.38 cm)

Temperature °F	Sa ksi	Number of cycles required to propagate a crack from a half length a of 0.15 inch (0.38 cm) to a length a of -														
		0.20 in. (0.508 cm)	0.30 in. (0.762 cm)	0.40 in. (1.016 cm)	0.50 in. (1.270 cm)	0.60 in. (1.524 cm)	0.70 in. (1.778 cm)	0.80 in. (2.032 cm)	0.90 in. (2.286 cm)	1.00 in. (2.540 cm)	1.20 in. (3.048 cm)	1.40 in. (3.556 cm)	1.60 in. (4.064 cm)	1.80 in. (4.572 cm)		
AM 350 (CRM); S _m = 40 ksi (276 MN/m ²)																
80	60	424	780	2 000	2 650	3 050	3 500	3 525	3 650	3 725	3 800	3 875	3 950	4 025	4 100	4 175
80	300	40 276	1 500	4 250	6 350	7 800	8 775	9 750	10 725	11 700	12 675	13 650	14 625	15 600	16 575	17 550
80	300	10 69	3 600	9 400	13 800	17 100	19 800	22 500	25 200	27 900	30 600	33 300	36 000	38 700	41 400	44 100
80	300	10 35	80 000	175 000	320 000	465 000	610 000	755 000	900 000	1 045 000	1 190 000	1 335 000	1 480 000	1 625 000	1 770 000	1 915 000
550	60	414	315	710	890	1 075	1 260	1 445	1 630	1 815	2 000	2 185	2 370	2 555	2 740	2 925
550	300	40 276	3 900	8 750	14 000	19 250	24 500	29 750	35 000	40 250	45 500	50 750	56 000	61 250	66 500	71 750
550	300	10 138	20 500	44 000	77 500	111 000	144 500	178 000	211 500	245 000	278 500	312 000	345 500	379 000	412 500	446 000
550	300	10 35	85 000	205 000	370 000	535 000	700 000	865 000	1 030 000	1 195 000	1 360 000	1 525 000	1 690 000	1 855 000	2 020 000	2 185 000
-109	195	40 276	2 500	5 650	9 800	13 950	18 100	22 250	26 400	30 550	34 700	38 850	43 000	47 150	51 300	55 450
-109	195	20 138	6 250	14 750	24 750	34 750	44 750	54 750	64 750	74 750	84 750	94 750	104 750	114 750	124 750	134 750
-109	195	10 69	28 000	61 000	111 000	161 000	211 000	261 000	311 000	361 000	411 000	461 000	511 000	561 000	611 000	661 000
-109	195	10 35	320 000	575 000	710 000	800 000	865 000	920 000	985 000	1 040 000	1 095 000	1 150 000	1 205 000	1 260 000	1 315 000	1 370 000
AM 357; S _m = 40 ksi (276 MN/m ²)																
80	40	276	3 500	7 500	8 400	9 300	10 200	11 100	12 000	12 900	13 800	14 700	15 600	16 500	17 400	18 300
80	300	20 138	11 000	25 500	34 500	43 500	52 500	61 500	70 500	79 500	88 500	97 500	106 500	115 500	124 500	133 500
80	300	10 69	35 000	82 000	120 000	157 000	194 000	231 000	268 000	305 000	342 000	379 000	416 000	453 000	490 000	527 000
550	60	414	2 100	3 900	4 500	5 100	5 700	6 300	6 900	7 500	8 100	8 700	9 300	9 900	10 500	11 100
550	300	20 138	13 000	28 000	35 000	42 000	49 000	56 000	63 000	70 000	77 000	84 000	91 000	98 000	105 000	112 000
-109	195	40 276	5 500	13 500	18 000	22 500	27 000	31 500	36 000	40 500	45 000	49 500	54 000	58 500	63 000	67 500
-109	195	20 138	10 700	27 700	39 000	50 300	61 600	72 900	84 200	95 500	106 800	118 100	129 400	140 700	152 000	163 300
-109	195	10 69	71 000	157 000	214 000	258 000	298 000	342 000	386 000	430 000	474 000	518 000	562 000	606 000	650 000	694 000
Inconel 718; S _m = 40 ksi (276 MN/m ²)																
80	60	414	940	2 060	2 650	3 240	3 830	4 420	5 010	5 600	6 190	6 780	7 370	7 960	8 550	9 140
80	300	40 276	2 400	5 600	7 500	9 400	11 300	13 200	15 100	17 000	18 900	20 800	22 700	24 600	26 500	28 400
80	300	10 138	7 000	18 500	28 000	37 500	47 000	56 500	66 000	75 500	85 000	94 500	104 000	113 500	123 000	132 500
80	300	10 35	80 000	170 000	260 000	350 000	440 000	530 000	620 000	710 000	800 000	890 000	980 000	1 070 000	1 160 000	1 250 000
550	60	414	960	2 000	2 560	3 120	3 680	4 240	4 800	5 360	5 920	6 480	7 040	7 600	8 160	8 720
550	300	40 276	1 850	4 650	6 100	7 550	9 000	10 450	11 900	13 350	14 800	16 250	17 700	19 150	20 600	22 050
550	300	10 138	7 500	17 000	23 000	29 000	35 000	41 000	47 000	53 000	59 000	65 000	71 000	77 000	83 000	89 000
550	300	10 35	25 000	62 000	81 000	100 000	119 000	138 000	157 000	176 000	195 000	214 000	233 000	252 000	271 000	290 000
-109	195	40 276	1 400	3 600	4 900	6 200	7 500	8 800	10 100	11 400	12 700	14 000	15 300	16 600	17 900	19 200
-109	195	20 138	3 100	7 700	10 400	13 100	15 800	18 500	21 200	23 900	26 600	29 300	32 000	34 700	37 400	40 100
-109	195	10 69	58 000	135 000	181 000	227 000	273 000	319 000	365 000	411 000	457 000	503 000	549 000	595 000	641 000	687 000
-109	195	10 35	3 410 000	3 874 000	4 060 000	4 246 000	4 432 000	4 618 000	4 804 000	4 990 000	5 176 000	5 362 000	5 548 000	5 734 000	5 920 000	6 106 000
Ti-6Al-4V; duplex annealed; t = 0.250 in. (6.350 mm); S _m = 25 ksi (173 MN/m ²)																
80	300	25 173	780	2 060	2 650	3 240	3 830	4 420	5 010	5 600	6 190	6 780	7 370	7 960	8 550	9 140
80	300	15 104	1 900	3 730	4 650	5 570	6 490	7 410	8 330	9 250	10 170	11 090	12 010	12 930	13 850	14 770
80	300	5 35	5 800	12 200	17 000	21 800	26 600	31 400	36 200	41 000	45 800	50 600	55 400	60 200	65 000	69 800
80	300	10 35	1 250 000	2 775 000	3 675 000	4 575 000	5 475 000	6 375 000	7 275 000	8 175 000	9 075 000	9 975 000	10 875 000	11 775 000	12 675 000	13 575 000
550	60	414	1 340	3 290	4 450	5 610	6 770	7 930	9 090	10 250	11 410	12 570	13 730	14 890	16 050	17 210
550	300	20 138	2 650	7 450	10 850	14 250	17 650	21 050	24 450	27 850	31 250	34 650	38 050	41 450	44 850	48 250
550	300	10 69	8 500	20 000	28 000	36 000	44 000	52 000	60 000	68 000	76 000	84 000	92 000	100 000	108 000	116 000
550	300	10 35	130 000	312 000	425 000	538 000	651 000	764 000	877 000	990 000	1 103 000	1 216 000	1 329 000	1 442 000	1 555 000	1 668 000
-109	195	25 173	220	475	662	849	1 036	1 223	1 410	1 597	1 784	1 971	2 158	2 345	2 532	2 719
-109	195	15 104	2 550	3 680	4 810	5 940	7 070	8 200	9 330	10 460	11 590	12 720	13 850	14 980	16 110	17 240
-109	195	5 35	8 000	16 500	21 500	26 500	31 500	36 500	41 500	46 500	51 500	56 500	61 500	66 500	71 500	76 500
-109	195	10 35	54 000	114 500	150 000	189 000	228 000	267 000	306 000	345 000	384 000	423 000	462 000	501 000	540 000	579 000
No data available																

^aCrack initiated at S_a of 10 ksi (69 MN/m²) to expedite testing.
^bCrack initiated at S_a of 5 ksi (35 MN/m²) to expedite testing.

TABLE IV.- MEAN NUMBER OF CYCLES REQUIRED TO EXTEND CRACKS FROM A HALF-LENGTH OF 0.15 INCH (0.38 cm) - Concluded

Temperature of	Ks ksi	Sa MM/√in ²	Number of cycles required to propagate a crack from a half length a of 0.15 inch (0.38 cm) to a length a of -												
			0.20 in. (0.508 cm)	0.30 in. (0.762 cm)	0.40 in. (1.016 cm)	0.50 in. (1.270 cm)	0.60 in. (1.524 cm)	0.70 in. (1.778 cm)	0.80 in. (2.032 cm)	0.90 in. (2.286 cm)	1.00 in. (2.540 cm)	1.20 in. (3.048 cm)	1.40 in. (3.556 cm)	1.60 in. (4.064 cm)	1.80 in. (4.572 cm)
T1-8A1-1M0-1V; duplex annealed; t = 0.050 in. (1.270 mm)															
80	300	25	1 750	3 700	4 900	38 500	42 000	45 000	310 000	320 000	330 000	4 900 000	4 900 000	4 900 000	5 050 000
80	300	10	4 300	14 300	14 300	34 000	285 000	285 000	4 280 000	4 280 000	4 770 000	4 900 000	4 900 000	4 900 000	5 050 000
80	300	10	8 000	19 500	28 000	34 000	265 000	265 000	4 280 000	4 280 000	4 770 000	4 900 000	4 900 000	4 900 000	5 050 000
80	300	10	660 000	1 800 000	2 640 000	3 280 000	3 700 000	3 700 000	4 280 000	4 280 000	4 770 000	4 900 000	4 900 000	4 900 000	5 050 000
550	561	25	2 900	6 500	8 900	29 400	29 400	29 400	69 500	69 500	74 000	1 123 000	1 123 000	1 123 000	2 193 000
550	561	15	6 200	14 900	20 900	51 000	51 000	51 000	367 000	367 000	409 000	454 000	454 000	454 000	2 193 000
550	561	10	13 500	31 500	42 500	104 000	104 000	104 000	965 000	965 000	1 070 000	1 070 000	1 070 000	1 070 000	2 193 000
550	561	5	74 000	184 000	252 000	300 000	300 000	300 000	1 768 000	1 768 000	1 943 000	2 048 000	2 048 000	2 048 000	2 193 000
550	561	b2	708 000	1 018 000	1 298 000	1 428 000	1 563 000	1 685 000	3 119 000	3 119 000	3 400 000	3 560 000	3 560 000	3 560 000	4 572 000
-109	195	25	1 075	2 275	3 025	32 600	32 600	32 600	396 000	396 000	422 000	447 000	447 000	447 000	4 572 000
-109	195	15	4 900	10 500	13 500	282 000	282 000	282 000	3 962 000	3 962 000	4 312 000	4 472 000	4 472 000	4 472 000	4 572 000
-109	195	10	9 800	21 000	28 000	574 000	574 000	574 000	7 924 000	7 924 000	8 624 000	9 084 000	9 084 000	9 084 000	9 084 000
-109	195	5	97 000	195 000	249 000	3 742 000	3 742 000	3 742 000	50 000	50 000	55 000	58 000	58 000	58 000	58 000
-109	195	b2	1 502 000	2 752 000	3 372 000	3 742 000	3 742 000	3 742 000	50 000	50 000	55 000	58 000	58 000	58 000	58 000
2020-26; S _m = 15 ksi (104 MM/√in ²)															
80	300	15	500	27 500	33 000	89 500	89 500	89 500	673 000	673 000	673 000	673 000	673 000	673 000	673 000
80	300	10	1 250	67 500	70 000	160 000	160 000	160 000	1 250 000	1 250 000	1 250 000	1 250 000	1 250 000	1 250 000	1 250 000
80	300	5	48 000	146 000	160 000	3 200	3 200	3 200	124 000	124 000	129 000	1 030 000	1 030 000	1 030 000	1 075 000
80	300	b2	228 000	1 200	1 450	3 200	3 200	3 200	920 000	920 000	965 000	990 000	990 000	990 000	1 075 000
250	300	15	104	69	69	340	340	340	27 900	27 900	27 900	27 900	27 900	27 900	27 900
250	300	10	69	35	35	176 000	176 000	176 000	90 000	90 000	90 000	90 000	90 000	90 000	90 000
250	300	5	35	14	14	635 000	635 000	635 000	635 000	635 000	635 000	635 000	635 000	635 000	635 000
250	300	b2	228 000	1 200	1 450	3 200	3 200	3 200	920 000	920 000	965 000	990 000	990 000	990 000	1 075 000
250	300	15	104	69	69	340	340	340	27 900	27 900	27 900	27 900	27 900	27 900	27 900
250	300	10	69	35	35	176 000	176 000	176 000	90 000	90 000	90 000	90 000	90 000	90 000	90 000
250	300	5	35	14	14	635 000	635 000	635 000	635 000	635 000	635 000	635 000	635 000	635 000	635 000
250	300	b2	228 000	1 200	1 450	3 200	3 200	3 200	920 000	920 000	965 000	990 000	990 000	990 000	1 075 000
250	300	15	104	69	69	340	340	340	27 900	27 900	27 900	27 900	27 900	27 900	27 900
250	300	10	69	35	35	176 000	176 000	176 000	90 000	90 000	90 000	90 000	90 000	90 000	90 000
250	300	5	35	14	14	635 000	635 000	635 000	635 000	635 000	635 000	635 000	635 000	635 000	635 000
250	300	b2	228 000	1 200	1 450	3 200	3 200	3 200	920 000	920 000	965 000	990 000	990 000	990 000	1 075 000
250	300	15	104	69	69	340	340	340	27 900	27 900	27 900	27 900	27 900	27 900	27 900
250	300	10	69	35	35	176 000	176 000	176 000	90 000	90 000	90 000	90 000	90 000	90 000	90 000
250	300	5	35	14	14	635 000	635 000	635 000	635 000	635 000	635 000	635 000	635 000	635 000	635 000
250	300	b2	228 000	1 200	1 450	3 200	3 200	3 200	920 000	920 000	965 000	990 000	990 000	990 000	1 075 000
250	300	15	104	69	69	340	340	340	27 900	27 900	27 900	27 900	27 900	27 900	27 900
250	300	10	69	35	35	176 000	176 000	176 000	90 000	90 000	90 000	90 000	90 000	90 000	90 000
250	300	5	35	14	14	635 000	635 000	635 000	635 000	635 000	635 000	635 000	635 000	635 000	635 000
250	300	b2	228 000	1 200	1 450	3 200	3 200	3 200	920 000	920 000	965 000	990 000	990 000	990 000	1 075 000
250	300	15	104	69	69	340	340	340	27 900	27 900	27 900	27 900	27 900	27 900	27 900
250	300	10	69	35	35	176 000	176 000	176 000	90 000	90 000	90 000	90 000	90 000	90 000	90 000
250	300	5	35	14	14	635 000	635 000	635 000	635 000	635 000	635 000	635 000	635 000	635 000	635 000
250	300	b2	228 000	1 200	1 450	3 200	3 200	3 200	920 000	920 000	965 000	990 000	990 000	990 000	1 075 000
250	300	15	104	69	69	340	340	340	27 900	27 900	27 900	27 900	27 900	27 900	27 900
250	300	10	69	35	35	176 000	176 000	176 000	90 000	90 000	90 000	90 000	90 000	90 000	90 000
250	300	5	35	14	14	635 000	635 000	635 000	635 000	635 000	635 000	635 000	635 000	635 000	635 000
250	300	b2	228 000	1 200	1 450	3 200	3 200	3 200	920 000	920 000	965 000	990 000	990 000	990 000	1 075 000
250	300	15	104	69	69	340	340	340	27 900	27 900	27 900	27 900	27 900	27 900	27 900
250	300	10	69	35	35	176 000	176 000	176 000	90 000	90 000	90 000	90 000	90 000	90 000	90 000
250	300	5	35	14	14	635 000	635 000	635 000	635 000	635 000	635 000	635 000	635 000	635 000	635 000
250	300	b2	228 000	1 200	1 450	3 200	3 200	3 200	920 000	920 000	965 000	990 000	990 000	990 000	1 075 000
250	300	15	104	69	69	340	340	340	27 900	27 900	27 900	27 900	27 900	27 900	27 900
250	300	10	69	35	35	176 000	176 000	176 000	90 000	90 000	90 000	90 000	90 000	90 000	90 000
250	300	5	35	14	14	635 000	635 000	635 000	635 000	635 000	635 000	635 000	635 000	635 000	635 000
250	300	b2	228 000	1 200	1 450	3 200	3 200	3 200	920 000	920 000	965 000	990 000	990 000	990 000	1 075 000
250	300	15	104	69	69	340	340	340	27 900	27 900	27 900	27 900	27 900	27 900	27 900
250	300	10	69	35	35	176 000	176 000	176 000	90 000	90 000	90 000	90 000	90 000	90 000	90 000
250	300	5	35	14	14	635 000	635 000	635 000	635 000	635 000	635 000	635 000	635 000	635 000	635 000
250	300	b2	228 000	1 200	1 450	3 200	3 200	3 200	920 000	920 000	965 000	990 000	990 000	990 000	1 075 000
250	300	15	104	69	69	340	340	340	27 900	27 900	27 900	27 900	27 900	27 900	27 900
250	300	10	69	35	35	176 000	176 000	176 000	90 000	90 000	90 000	90 000	90 000	90 000	90 000
250	300	5	35	14	14	635 000	635 000	635 000	635 000	635 000	635 000	635 000	635 000	635 000	635 000
250	300	b2	228 000	1 200	1 450	3 200	3 200	3 200	920 000	920 000	965 000	990 000	990 000	990 000	1 075 000
250	300	15	104	69	69										

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