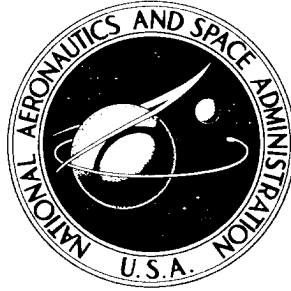


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**THE FATIGUE BEHAVIOR
OF MATERIALS FOR THE
SUPERSONIC TRANSPORT**

*by M. S. Healy, C. W. Marschall,
F. C. Holden, and W. S. Hyler*

Prepared under Contract No. NASr-100-(01) by
BATTELLE MEMORIAL INSTITUTE
Columbus, Ohio
for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • APRIL 1965

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ABSTRACT

Tests were conducted on sheet specimens of two materials, Ti-8Al-1Mo-1V and AM350 CRT to determine the fatigue lives, rates of fatigue-crack propagation, and residual static strengths at three temperatures, 550°F, -110°F, and room temperature. The effects of prior exposure to 550°F for up to 10 000 hours on the same properties were also studied.

Neither material was significantly degraded by the elevated temperature soak. The fatigue characteristics were found to be comparable to those of contemporary aluminum alloys.

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THE FATIGUE BEHAVIOR OF MATERIALS FOR THE SUPERSONIC TRANSPORT

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SUMMARY

This report describes an investigation of the fatigue behavior of two materials considered as skin materials for the supersonic transport. The materials are AM-350 CRT stainless steel and triplex-annealed Ti-8Al-1Mo-1V alloy.

The three aspects of the program are (1) crack propagation behavior, (2) residual static strength, and (3) the base fatigue strength of the two materials. In each case, many variables have been evaluated that are related to the operating conditions of the supersonic transport. This report describes the research accomplished during the second year of the program. However, included in the discussion is information from the first year. This was done so that an over-all view of the results of the program could be obtained.

Based on this investigation it appears that the fatigue behaviors of the two materials are not too different from those of materials currently used in subsonic aircraft. In addition, the studies of the effect of prior stressed exposure on fatigue behavior of the two materials showed that neither material exhibited a significant tendency toward metal-lurgy instability at an exposure temperature of 550 F after a stressed exposure of about 10,000 hours. This observation agrees with the results of other programs currently in progress at NASA and other organizations on the same materials.

INTRODUCTION

The National Aeronautics and Space Administration is engaged in research programs directed toward the solution of the myriad problems associated with the development of the supersonic transport. One of these problem areas is the selection of suitable skin materials. As with all aircraft, the supersonic transport structure will experience cyclic stresses due to gust and maneuver loads, heating, noise, and other variable loads; thus the fatigue behavior of potential skin materials is an important factor in design considerations.

The skin of the supersonic transport will be subjected to temperatures ranging from well below freezing to approximately 550 F. Actually, a major portion of the flight

profile is at cruise condition. Consequently, the skin will be subjected to elevated temperature for appreciable periods of time. It is because of this stressed exposure at elevated temperature over a long period of time that the present program included an evaluation of possible metallurgical instability which could affect static or dynamic behavior of the materials.

This Battelle program has been concerned with the fatigue behavior of two possible skin materials, AM-350 CRT stainless steel and triplex-annealed Ti-8Al-1Mo-1V alloy. The base fatigue and fatigue crack-propagation behavior of these materials, as well as residual static strength, has been examined with respect to the temperatures and stressed exposure to which the supersonic transport skin will be subjected.

Because of the large scope of this research effort, some of the variables were explored to a very limited extent. These studies were intended to cover a wide range of potential problem areas in order to determine those that require further detailed study.

Since the program has covered a 2-year period, generally only experimental data obtained during the second year's research are reported. The data from the first year is presented in NASA CR-28, April 1964 [Reference (1)]. In the discussion and conclusions reference is made to the results of both programs.

EXPERIMENTAL DETAILS

Materials

Three sheets of AM-350 CRT stainless steel and of triplex-annealed Ti-8Al-1Mo-1V alloy were provided by Langley Research Center from a large quantity of material specifically obtained for NASA programs. ^{see also in the report} Manufacturer's chemical-analysis and mechanical-property data appear in Appendix A. During the first year of the Battelle program, tensile data were obtained from specimens of each of the three sheets of each material that were provided. A discussion of the results and the detailed data appear in Reference (1). The data are summarized in Table 1, together with tensile data on edge-notched specimens of the same design as the fatigue specimens.


Specimen Design

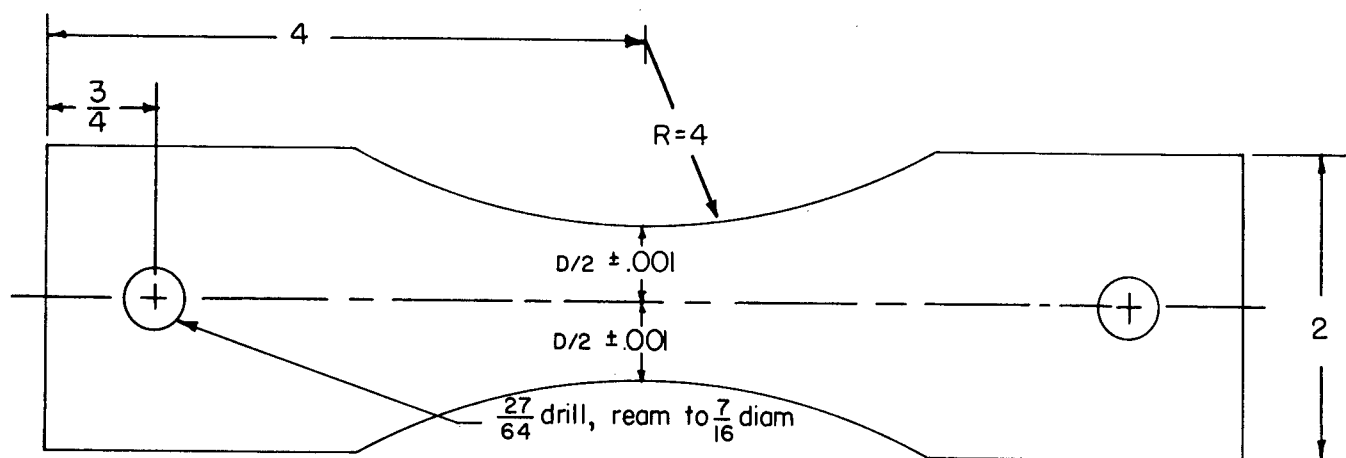
Four types of specimens were employed in the program. These specimens include an unnotched specimen, an edge-notched specimen, a 2-inch-wide center-notched specimen, and a 4-inch-wide center-notched specimen. The latter specimen was made only from the titanium alloy; only a few specimens were made. Drawings of each specimen are shown in Figure 1. Details concerning the fabrication of the specimens are given in Reference (1).

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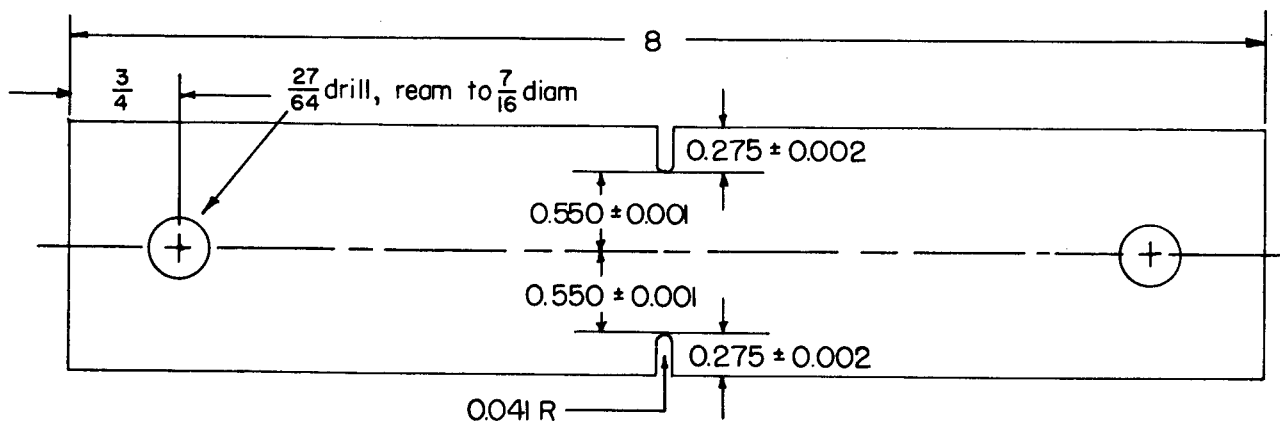
TABLE 1. SUMMARY OF TENSILE DATA FOR AM-350 CRT AND TRIPLEX-ANNEALED Ti-8Al-1Mo-1V SHEET SPECIMENS

| Temperature, F | Orientation | 0.2 Per Cent Offset Yield Strength, ksi | Ultimate Tensile Strength, ksi | Elongation in 2 Inches, per cent | Modulus of Elasticity, 10 ⁶ psi |
|---|-------------|--|--|--|--|
| <u>Unnotched-Specimen Data</u> | | | | | |
| <u>AM-350 CRT</u> | | | | | |
| -100 | L | 221 | 273 | 20.2 | 28.1 |
| RT | L | 221 | 233 | 21.1 | 27.8 |
| | T | 201 | 236 | 13.1 | 29.5 |
| 550 | L | 184 | 201 | 3.7 | 25.2 |
| <u>Ti-8Al-1Mo-1V</u> | | | | | |
| -100 | L | 166 | 179 | 12.0 | 20.0 |
| RT | L | 140 | 152 | 12.9 | 18.8 |
| | T | 132 | 144 | 11.8 | 17.4 |
| 550 | L | 98 | 125 | 9.5 | 16.7 |
| <u>Notched-Specimen Data, k_t = 4.0</u> | | | | | |
| | | | <u>Notched Tensile Strength, ksi</u> | | |
| <u>AM-350 CRT</u> | | | | | |
| RT | L | -- | 242 | -- | -- |
| 550 | L | -- | 200 | -- | -- |
| <u>Ti-8Al-1Mo-1V</u> | | | | | |
| RT | L | -- | 166 | -- | -- |
| 550 | L | -- | 125 | -- | -- |


 3 → 1/24/10



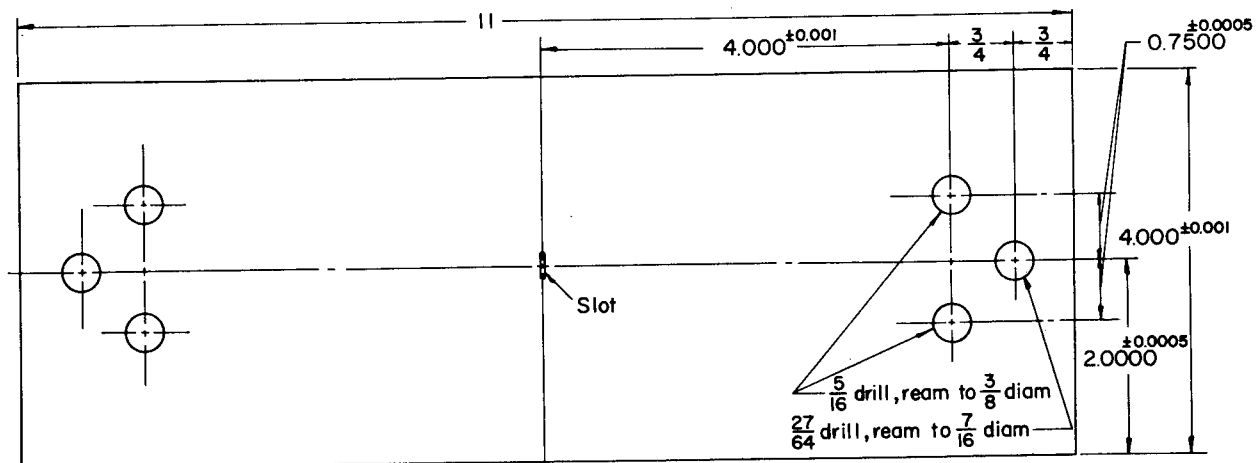
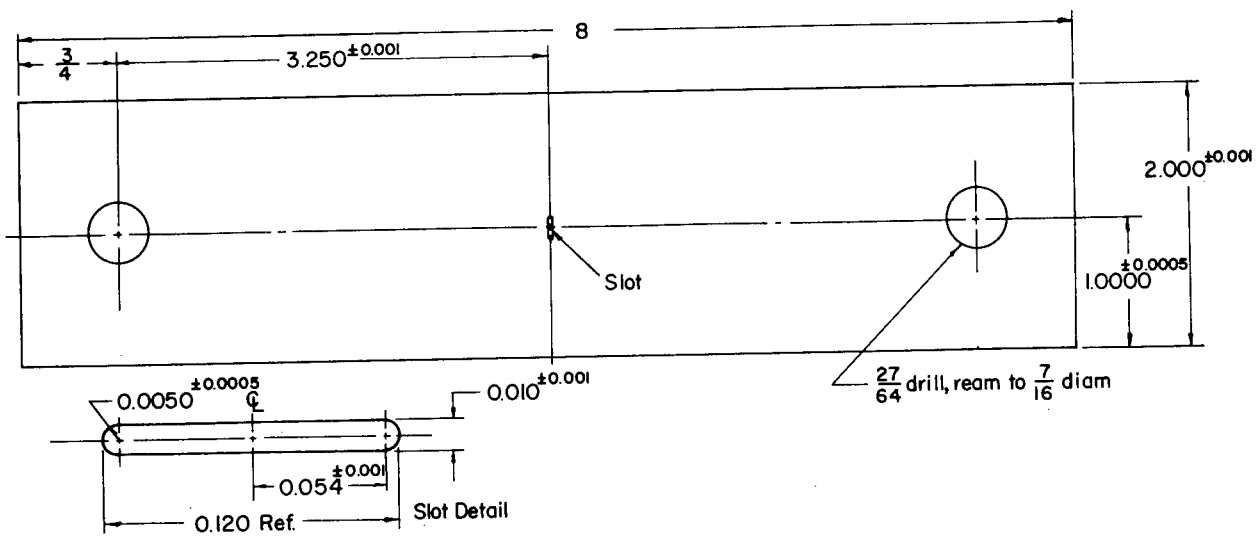
a. Unnotched specimen



b. Edge-notched specimen

C-45377

FIGURE 1. FATIGUE SPECIMENS



c. Center-Notched Specimens

A - 48096

FIGURE 1. (CONTINUED)

Examination of the finished notches showed them to be uniformly good. The edge notches had radii of 0.041 ± 0.002 inch; the center notches had radii of 0.0045 inch and lengths of 0.125 ± 0.005 inch. The theoretical stress-concentration factor for the edge-notched specimen is 4.0, which is the same notch severity as that used in several Battelle and NASA programs. (2,3) Using the relations of Inglis⁽⁴⁾ and Dixon⁽⁵⁾, as reported by Gerard⁽⁶⁾, the stress-concentration factor for the 2-inch-wide center-notched specimens is approximately 7.9. Similarly, K_t is about 8.1 for the 4-inch-wide center-notched specimens.

Equipment

All fatigue testing was conducted in Krouse direct-stress fatigue machines of 5,000 or 10,000-pound capacity. These machines operate at 1725 and 1200 cpm, respectively. The smaller capacity machines are equipped with automatic hydraulic load maintainers that monitor test loads on each specimen. Accuracy of load setting and maintenance is about 3 per cent of the maximum test load.

For specimens that were stressed in compression for a portion of the cycle, anti-buckling jigs, similar in design to those used at Langley Research Center, were employed. These jigs consist of graphite plates held in contact with the specimen by steel pressure plates and pressure screws mounted in a rigid frame.

The means of heating the elevated-temperature fatigue specimens has been modified as a consequence of some difficulties experienced occasionally with the antibuckling jig-heater method described in Reference (1). The present equipment consists of two nickel-chromium coiled resistance-wire heating units fixed to opposite sides of a closed section of asbestos pipe. This furnace type of heater encloses the antibuckling jig and specimen grips. The specimen temperature is indicated by a Chromel-Alumel thermocouple located in a hole in the graphite plate of the antibuckling jig. The hole is drilled in the graphite plate on the side away from the specimen. The thermocouple is inserted into this hole to within about 1/32 inch of the specimen surface. The thermocouple is connected to a potentiometer controller which regulates the electrical power to the heating units.

The manner in which the fatigue specimens are cooled to -110 F and the equipment for stress-elevated temperature exposures are discussed in Reference (1).

CRACK PROPAGATION AND RESIDUAL STATIC STRENGTH

The flight profile of the supersonic transport indicates that there are a number of environmental factors that may influence both the manner in which a fatigue crack will propagate and the strength of a structural element that contains a fatigue crack. As a result, a wide variety of variables were studied to determine which ones may have a significant effect upon the crack-propagation behavior and residual static strength of the two materials. The factors that were explored were the following: alternating stress amplitude, cyclic frequency, specimen orientation with respect to principal rolling direction, temperature, and prior stressed exposure at elevated temperature. The studies

reported in Reference (1) were devoted to the AM-350 stainless steel. The work that is reported here is primarily concerned with the titanium alloy; however, the behavior of exposed stainless steel specimens has also been examined and is included in this report.

Crack-Propagation Studies

^{SS, Ti}
The fatigue-crack propagation studies were conducted in conjunction with the residual-strength investigations. In the latter effort, fatigue-cracked specimens with nominal tip-to-tip crack lengths of 3/16-, 3/8-, 3/4-, and 1-inch were evaluated. Crack-propagation data were obtained from those specimens cracked to 3/4- and 1-inch crack lengths in addition to several specimens in which the cracks were propagated until specimen failure occurred. All of the residual-strength tests were conducted on the 2-inch-wide specimens and therefore the majority of crack-propagation information pertains to the 2-inch-wide specimens. A very limited number of 4-inch-wide Ti-8Al-1Mo-1V specimens were also employed in the crack-propagation studies. Data on the crack-propagation behavior of the titanium alloy were obtained at a mean stress of 25 ksi, and the data for the AM-350 were obtained at a mean stress of 40 ksi. - 728

All of the stainless steel specimens were cracked in a 10,000-pound Krouse fatigue machine at a cyclic rate of 1200 cpm. The titanium-alloy specimens were cracked in a 5000-pound Krouse machine at frequencies of 1725 cpm and 34 cpm; however, the largest stress amplitude employed in the program necessitated the use of the 10,000-pound machine. During cracking, the net-section stresses were held essentially constant with an allowable variation of ± 10 per cent for the steel [as in Reference (1)] and 0 to +10 per cent for the Ti-8Al-1Mo-1V alloy. The net-section stresses are based on the uncracked portion, regardless of whether the specimen went into compression or not. A few titanium-alloy specimens were cracked at constant gross-section stress for purposes of comparison with the data obtained under constant net-section stress. Crack-propagation measurements were made by stopping the machine and measuring crack length with a measuring microscope mounted on a traverse. Measurements were taken with the specimen subjected to the maximum stress of the particular test. At -110 F and 550 F, the data were obtained in the same manner by observing the crack through a window in the enclosure.

From the experimental data, total crack length was plotted against total number of cycles. As was indicated in Reference (1), the effect of the ± 10 per cent variation in stress is readily apparent in these plots for the steel; however, there seems to be little evidence of the 0 to +10 per cent stress variation in similar curves for the titanium alloy.

In order to determine the effects of the several variables in terms of the crack-propagation behavior, curves were drawn on the crack length versus cycles plots to minimize the small effect of the load changes required to maintain a constant nominal net-section stress. Crack-propagation rates were determined by evaluating the slope of the curves at specific crack lengths of 0.250, 0.350, 0.500, 0.625, 0.750, and 0.950 inch. For purposes of this investigation, "initiation" has been defined as a total crack length of 0.150 inch for the titanium and 0.130 inch for the steel. Although most of the specimen tests were stopped at nominal crack lengths of 3/4 and 1 inch, two specimens, under each set of conditions, were tested to failure from a nominal crack length of 1 inch without further adjustment of the net-section stress. The propagation

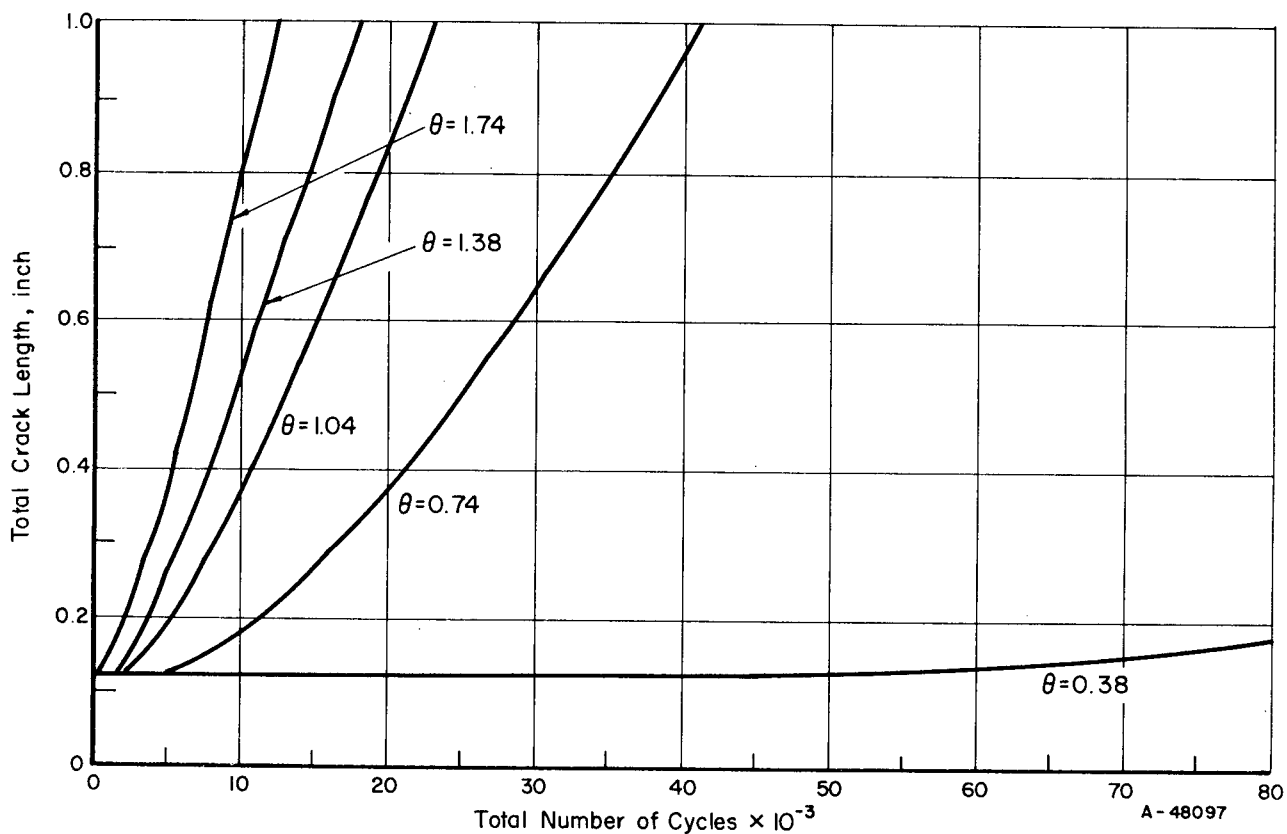


FIGURE 2. TYPICAL FATIGUE-CRACK PROPAGATION CURVES FOR UNEXPOSED, LONGITUDINAL 2-INCH-WIDE Ti-8Al-1Mo-1V ALLOY SHEET SPECIMENS AT ROOM TEMPERATURE AND 1200-1725 CPM

Net-section stresses maintained within 0 to +10 per cent of nominal values.

rates and total number of cycles to propagate a crack to the indicated crack lengths are given in detail in Appendix B. The data from tests of 2-inch-wide titanium alloy specimens at constant net-section stress are summarized in Table 2.

The effects of the variables examined, on crack propagation behavior, are presented and discussed in the following subsections.

Effect of Alternating Stress Amplitude

Alternating stress amplitude has been expressed in Table 2 and in subsequent tables and figures as the ratio, θ , of alternating stress amplitude to 1-g mean stress. The effect of θ is illustrated by conditions A, B, G, K, N, and Q in Table 2.

As would be expected, θ does have a significant influence upon crack propagation behavior. Figure 3, on which are stress-lifetime curves for various crack-length criteria, shows how the number of cycles to a given crack length is affected by θ . Figure 4 illustrates the increase in crack-propagation rates with increasing θ for three values of crack length. Figure 2 and Table 2 show that following initiation, crack-propagation rate increases with increasing crack length for an initial portion of total crack growth. After this portion of crack growth has taken place, the propagation rate becomes virtually constant with a further increase in crack length, to a nominal 1-inch crack length. This appears to be consistent with other observations(7,8) of crack propagation behavior under constant net-section stresses.

As a guide to determine the value of θ at which a crack will not initiate in the starter notch in 10^7 cycles, a specimen was tested at a θ of 0.25. After the specimen had accumulated 10^6 cycles without any visible sign of a crack, the test was continued on the same specimen at $\theta = 0.30$. Following a period of crack initiation and growth at $\theta = 0.30$, it was decided to determine the value of θ at which the crack would cease to propagate. The value of θ was decreased successively in steps with sufficient cycles added at each θ to insure that crack growth occurred and that some measure of the propagation rate was obtained. The results from this test appear in Table 3. As is indicated, the test was stopped after a crack failed to propagate at $\theta = 0.05$ in 80,000 cycles.

The initiation curve in Figure 3 indicates that the fatigue limit, at 10^7 cycles, for a 2-inch-wide center-notched Ti-8Al-1Mo-1V alloy specimen, with a K_t of approximately 7.9, will be at a θ of about 0.20. However, the data from the single specimen points out that once a crack has initiated, cracks will propagate at values of θ which are considerably lower than the fatigue limit for the starter notch. It is recognized(9,10,11) that the θ at which a fatigue crack will cease propagating also is a function of the crack length, but the results of this test illustrate that a crack will propagate at stresses below the fatigue limit. This adds to the complexity of cumulative damage assessment since both initiation and propagation behavior of a crack must be accounted for, and some of the lower stresses for propagation should be included in an analysis. To provide comparable information for both materials, a similar test was conducted on a single specimen of AM-350 stainless steel. During this test the same values of θ were employed, and every effort was made to have initial and final crack lengths for each condition identical to those in the titanium specimen test. The results are given in Table 4. From a comparison of the two sets of data, it is apparent that the same observations apply to the behavior of the stainless steel.

TABLE 2. SUMMARY OF DATA FROM CRACK-PROPAGATION TESTS OF 2-INCH-WIDE Ti-8Al-1Mo-IV ALLOY SHEET SPECIMENS AT CONSTANT NET-SECTION STRESS

Center-notched, triplex-annealed specimens.
Constant net-section mean stress of 25 ksi.

| Condition | Test Series Value | Number Tested | Crack-Propagation Rate, μ in./cycle, at Indicated Crack Length(a), inch | | | | | Total Thousands of Cycles to Indicated Crack Length(a), inch | | | | | | | | | | Failure(b) |
|--|-------------------|---------------|---|-------|-------|-------|-------|--|--------------------|------|------|------|------|------|---------|---------|------|------------|
| | | | 0.250 | 0.350 | 0.500 | 0.625 | 0.750 | 0.950 | 0.150 (Initiation) | | | | | | | | | |
| A | Minimum | | 1.3 | 2.2 | 2.8 | 3.3 | 3.4 | 3.4 | 635 | 853 | 915 | 973 | 1013 | 1045 | 1095 | 1107 | 1181 | |
| | Mean | 2 | 1.4 | 2.2 | 2.9 | 3.4 | 3.7 | 3.7 | 858 | 1041 | 1103 | 1161 | 1199 | 1234 | 1289 | 1300 | 1380 | |
| | Maximum | | 1.4 | 2.2 | 2.9 | 3.4 | 4.0 | 4.0 | 1080 | 1229 | 1291 | 1349 | 1385 | 1422 | 1481 | 1492 | 1578 | |
| $\theta = 0.26$, Room Temperature, 1725 CPM, Longitudinal, Unexposed, | | | | | | | | | | | | | | | | | | |
| B | Minimum | | 4.2 | 5.3 | 7.2 | 8.1 | 8.7 | 8.7 | 53.0 | 92.5 | 105 | 127 | 141 | 156 | 177 | 181 | 228 | |
| | Mean | 5 | 4.3 | 5.8 | 8.1 | 8.8 | 9.4 | 9.0 | 61.2 | 93.7 | 115 | 136 | 151 | 165 | 186 | 192 | 234 | |
| | Maximum | | 4.5 | 6.7 | 8.6 | 9.6 | 10 | 9.6 | 67.2 | 101 | 123 | 146 | 161 | 176 | 199 | 205 | 240 | |
| $\theta = 0.38$, Room Temperature, 1725 CPM, Longitudinal, Unexposed | | | | | | | | | | | | | | | | | | |
| C | Minimum | | 3.6 | 4.5 | 5.8 | 7.4 | 7.4 | 8.0 | 77.3 | 119 | 146 | 165 | 180 | 195 | 217 | 222 | 269 | |
| | Mean | 4 | 4.0 | 4.7 | 6.4 | 7.9 | 8.1 | 8.4 | 86.6 | 129 | 153 | 178 | 196 | 212 | 236 | 241 | 291 | |
| | Maximum | | 4.5 | 4.9 | 7.2 | 8.3 | 9.2 | 9.2 | 103 | 151 | 179 | 206 | 224 | 239 | 264 | 271 | 312 | |
| $\theta = 0.38$, Room Temperature, 1725 CPM, Transverse, Unexposed | | | | | | | | | | | | | | | | | | |
| D | Minimum | | 3.0 | 3.8 | 4.6 | 5.5 | 5.2 | 5.2 | 57.3 | 90.2 | 117 | 149 | 174 | 195 | 229 | 239 | 298 | |
| | Mean | 2 | 3.4 | 3.9 | 4.8 | 5.5 | 5.7 | 5.3 | 57.4 | 99.6 | 128 | 162 | 187 | 209 | 247 | 256 | 316 | |
| | Maximum | | 3.8 | 4.0 | 4.9 | 5.5 | 6.1 | 5.3 | 57.5 | 109 | 139 | 175 | 199 | 223 | 264 | 273 | 333 | |
| $\theta = 0.38$, 550 F, 1725 CPM, Longitudinal, Unexposed | | | | | | | | | | | | | | | | | | |
| E | Minimum | | 20 | 23 | 34 | 34 | 33 | 33 | 8.3 | 14.7 | 19.1 | 24.7 | 28.0 | 31.4 | 36.2 | 37.4 | 45.9 | |
| | Mean | 4 | 22 | 24 | 36 | 36 | 37 | 38(d) | 9.2 | 15.7 | 20.0 | 25.5 | 29.0 | 32.5 | 38.2(d) | 39.6(d) | 48.3 | |
| | Maximum | | 23 | 26 | 38 | 38 | 42 | 42 | 11.1 | 17.6 | 22.0 | 27.5 | 31.1 | 34.8 | 40.1 | 41.7 | 50.7 | |
| $\theta = 0.74$, -110 F, 1725 CPM, Longitudinal, Unexposed | | | | | | | | | | | | | | | | | | |
| F | Minimum | | 19 | 26 | 33 | 36 | 36 | 38 | 6.0 | 11.7 | 15.4 | 20.3 | 23.7 | 26.9 | 32.0 | 32.9 | 39.4 | |
| | Mean | 4 | 23 | 28 | 34 | 38 | 38 | 38(d) | 6.5 | 12.3 | 16.4 | 21.3 | 24.8 | 28.1 | 32.7(d) | 33.8(d) | 41.0 | |
| | Maximum | | 24 | 29 | 35 | 40 | 40 | 39 | 7.8 | 12.9 | 16.7 | 21.9 | 25.4 | 28.9 | 33.4 | 34.7 | 42.6 | |
| $\theta = 0.74$, Room Temperature, 34 CPM, Longitudinal, Unexposed | | | | | | | | | | | | | | | | | | |
| G | Minimum | | 17 | 22 | 27 | 30 | 30 | 31 | 6.7 | 11.7 | 16.3 | 22.2 | 26.3 | 30.2 | 36.2 | 37.7 | 45.1 | |
| | Mean | 10 | 20 | 24 | 29 | 31 | 32 | 32(e) | 7.1 | 13.5 | 18.4 | 24.3 | 28.5 | 32.3 | 38.4(e) | 39.8(e) | 47.3 | |
| | Maximum | | 22 | 25 | 31 | 33 | 36 | 34 | 7.5 | 14.3 | 19.3 | 25.4 | 29.7 | 33.7 | 40.2 | 41.9 | 50.0 | |

$\theta = 0.74$, Room Temperature, 1725 CPM, Longitudinal, 8,000 Hours' Exposure

| | | | | | | | | | | | | | | | | |
|---|---------|----|----|----|----|----|-------|-----|------|------|------|------|------|---------|---------|---------|
| H | Minimum | 21 | 23 | 32 | 34 | 37 | 38 | 5.3 | 10.9 | 17.1 | 19.3 | 22.2 | 25.0 | 32.7 | 34.0 | 41.5 |
| | Mean | 23 | 28 | 34 | 38 | 39 | 38(d) | 6.5 | 11.9 | 16.8 | 21.3 | 24.1 | 27.4 | 33.7(d) | 35.0(d) | 42.3(d) |
| | Maximum | 24 | 33 | 37 | 45 | 45 | 39 | 7.7 | 13.1 | 15.0 | 22.1 | 25.9 | 29.3 | 34.6 | 36.0 | 43.0 |

$\theta = 0.74$, Room Temperature, 1725 CPM, Transverse, Unexposed

| | | | | | | | | | | | | | | | | |
|---|---------|----|----|----|----|----|-------|-----|------|------|------|------|------|---------|---------|------|
| I | Minimum | 16 | 21 | 25 | 26 | 26 | 31 | 7.3 | 14.7 | 19.2 | 25.4 | 29.9 | 33.9 | 40.0 | 41.6 | 51.1 |
| | Mean | 18 | 22 | 27 | 29 | 30 | 31(e) | 8.2 | 15.0 | 20.1 | 26.7 | 31.1 | 35.4 | 40.8(e) | 42.4(e) | 51.5 |
| | Maximum | 20 | 23 | 28 | 31 | 31 | 33 | 8.8 | 16.2 | 21.8 | 28.5 | 33.3 | 38.1 | 41.7 | 43.1 | 51.8 |

$\theta = 0.74$, 550 F, 1725 CPM, Longitudinal, Unexposed

| | | | | | | | | | | | | | | | | |
|---|---------|----|----|----|----|----|-------|-----|------|------|------|------|------|---------|---------|------|
| J | Minimum | 12 | 14 | 17 | 17 | 17 | 18 | 6.5 | 15.6 | 23.0 | 31.9 | 38.6 | 44.9 | 54.9 | 57.4 | 74.3 |
| | Mean | 13 | 15 | 18 | 18 | 18 | 19(d) | 7.6 | 17.0 | 24.4 | 33.7 | 40.6 | 47.4 | 57.4(d) | 59.8(d) | 76.5 |
| | Maximum | 14 | 17 | 19 | 20 | 20 | 20 | 8.7 | 18.0 | 25.5 | 35.0 | 42.1 | 49.2 | 59.9 | 62.2 | 78.7 |

$\theta = 1.04$, Room Temperature, 1725 CPM, Longitudinal, Unexposed

| | | | | | | | | | | | | | | | | |
|---|---------|----|----|----|----|----|----|-----|-----|------|------|------|------|------|------|------|
| K | Minimum | 35 | 36 | 43 | 47 | 47 | 47 | 3.4 | 6.8 | 9.5 | 13.2 | 15.8 | 18.3 | 22.4 | 23.4 | 30.2 |
| | Mean | 36 | 41 | 47 | 50 | 50 | 50 | 3.7 | 7.2 | 10.0 | 13.7 | 16.3 | 18.7 | 22.7 | 23.7 | 30.4 |
| | Maximum | 36 | 43 | 52 | 52 | 52 | 52 | 4.4 | 7.9 | 10.6 | 14.1 | 16.6 | 19.1 | 23.3 | 24.3 | 30.5 |

$\theta = 1.38$, -110 F, 1725 CPM, Longitudinal, Unexposed

| | | | | | | | | | | | | | | | | |
|---|---------|----|----|----|----|----|----|-----|-----|-----|-----|-----|------|------|------|------|
| L | Minimum | 57 | 63 | 82 | 82 | 82 | 82 | 1.8 | 4.2 | 5.7 | 7.6 | 9.0 | 10.4 | 12.6 | 13.1 | 15.8 |
| | Mean | 58 | 67 | 83 | 86 | 86 | 86 | 1.9 | 4.2 | 5.8 | 7.8 | 9.2 | 10.7 | 13.0 | 13.6 | 16.4 |
| | Maximum | 58 | 71 | 83 | 89 | 89 | 89 | 1.9 | 4.2 | 5.8 | 7.9 | 9.4 | 10.9 | 13.4 | 14.0 | 17.0 |

$\theta = 1.38$, Room Temperature, 34 CPM, Longitudinal, Unexposed

| | | | | | | | | | | | | | | | | |
|---|---------|----|----|----|----|----|-------|-----|-----|-----|-----|------|------|---------|---------|------|
| M | Minimum | 49 | 58 | 71 | 71 | 76 | 78 | 1.2 | 3.7 | 5.4 | 7.5 | 9.1 | 10.7 | 13.3 | 13.8 | 16.5 |
| | Mean | 54 | 62 | 77 | 77 | 78 | 77(d) | 1.4 | 3.9 | 5.7 | 7.9 | 9.5 | 11.1 | 13.7(d) | 14.2(d) | 17.0 |
| | Maximum | 56 | 63 | 79 | 79 | 79 | 76 | 1.8 | 4.3 | 6.2 | 8.5 | 10.1 | 11.7 | 14.0 | 14.6 | 17.5 |

$\theta = 1.38$, Room Temperature, 1725 CPM, Longitudinal, Unexposed

| | | | | | | | | | | | | | | | | |
|---|---------|----|----|----|----|----|----|-----|-----|-----|------|------|------|------|------|------|
| N | Minimum | 44 | 50 | 59 | 59 | 59 | 56 | 1.8 | 4.3 | 6.2 | 8.8 | 10.7 | 12.6 | 15.7 | 16.5 | 21.0 |
| | Mean | 46 | 53 | 62 | 62 | 62 | 60 | 2.2 | 4.8 | 6.9 | 9.5 | 11.6 | 13.6 | 16.9 | 17.8 | 22.3 |
| | Maximum | 50 | 56 | 64 | 64 | 64 | 64 | 2.4 | 5.3 | 7.4 | 10.1 | 12.2 | 14.2 | 17.8 | 18.8 | 23.7 |

$\theta = 1.38$, Room Temperature, 1725 CPM, Transverse, Unexposed

| | | | | | | | | | | | | | | | | |
|---|---------|----|----|----|----|----|----|-----|-----|-----|------|------|------|------|------|------|
| O | Minimum | 38 | 46 | 52 | 52 | 52 | 50 | 1.3 | 4.7 | 7.0 | 9.9 | 12.0 | 14.2 | 17.5 | 18.3 | 22.2 |
| | Mean | 42 | 47 | 58 | 58 | 60 | 55 | 2.2 | 5.2 | 7.5 | 10.4 | 12.6 | 14.8 | 18.3 | 19.2 | 23.7 |
| | Maximum | 44 | 48 | 61 | 61 | 70 | 61 | 2.5 | 5.6 | 8.2 | 11.3 | 13.7 | 16.1 | 20.0 | 21.0 | 25.1 |

$\theta = 1.38$, 550 F, 1725 CPM, Longitudinal, Unexposed

| | | | | | | | | | | | | | | | | |
|---|---------|----|----|----|----|----|----|-----|-----|-----|------|------|------|------|------|------|
| P | Minimum | 30 | 39 | 44 | 44 | 44 | 44 | 1.6 | 5.3 | 8.4 | 11.9 | 14.7 | 17.2 | 21.6 | 22.7 | 26.0 |
| | Mean | 31 | 41 | 45 | 45 | 49 | 45 | 1.7 | 5.4 | 8.5 | 12.0 | 14.8 | 17.5 | 21.9 | 23.0 | 27.1 |
| | Maximum | 31 | 42 | 45 | 45 | 53 | 45 | 1.8 | 5.5 | 8.6 | 12.1 | 14.9 | 17.7 | 22.2 | 23.3 | 28.2 |



TABLE 2. (Continued)

| Condition | Test Series Value | Number Tested | Crack Propagation Rate, μ in./cycle, at Indicated Crack Length(a), inch | | | | | | | Total Thousands of Cycles to Indicated Crack Length(a), inch | | | | | | | | |
|-----------|-------------------|---------------|---|-------|-------|-------|-------|-------|-------|--|-------|-------|-------|-------|-------|-------|-------|------------|
| | | | 0.250 | 0.350 | 0.500 | 0.625 | 0.750 | 0.950 | 1.150 | (Initiation) | 0.250 | 0.350 | 0.500 | 0.625 | 0.750 | 0.950 | 1,000 | Failure(b) |
| Q | Minimum | | 50 | 61 | 71 | 75 | 75 | 63 | | 1.1 | 2.2 | 4.7 | 6.5 | 8.0 | 9.5 | 11.8 | 12.4 | 15.1 |
| | Mean | 4 | 57 | 68 | 81 | 82 | 82 | 75 | 1.3 | 3.3 | 5.1 | 7.2 | 8.7 | 10.3 | 12.8 | 13.5 | 16.6 | |
| | Maximum | | 61 | 71 | 85 | 85 | 83 | | 1.5 | 4.0 | 5.7 | 8.1 | 9.8 | 11.5 | 14.5 | 15.3 | 15.5 | |

$\theta = 1.74$, Room Temperature, 1200 CPM, Longitudinal, Unexposed

- (a) Tip-to-tip crack length.
- (b) Two specimens under each set of conditions cycled to failure from 1-inch nominal crack length without further adjustment of net-section stress.
- (c) θ = net-section alternating-stress amplitude/1-g mean stress of 25 ksi.
- (d) Only two specimens tested to indicated crack length.
- (e) Only four specimens tested to indicated crack length.

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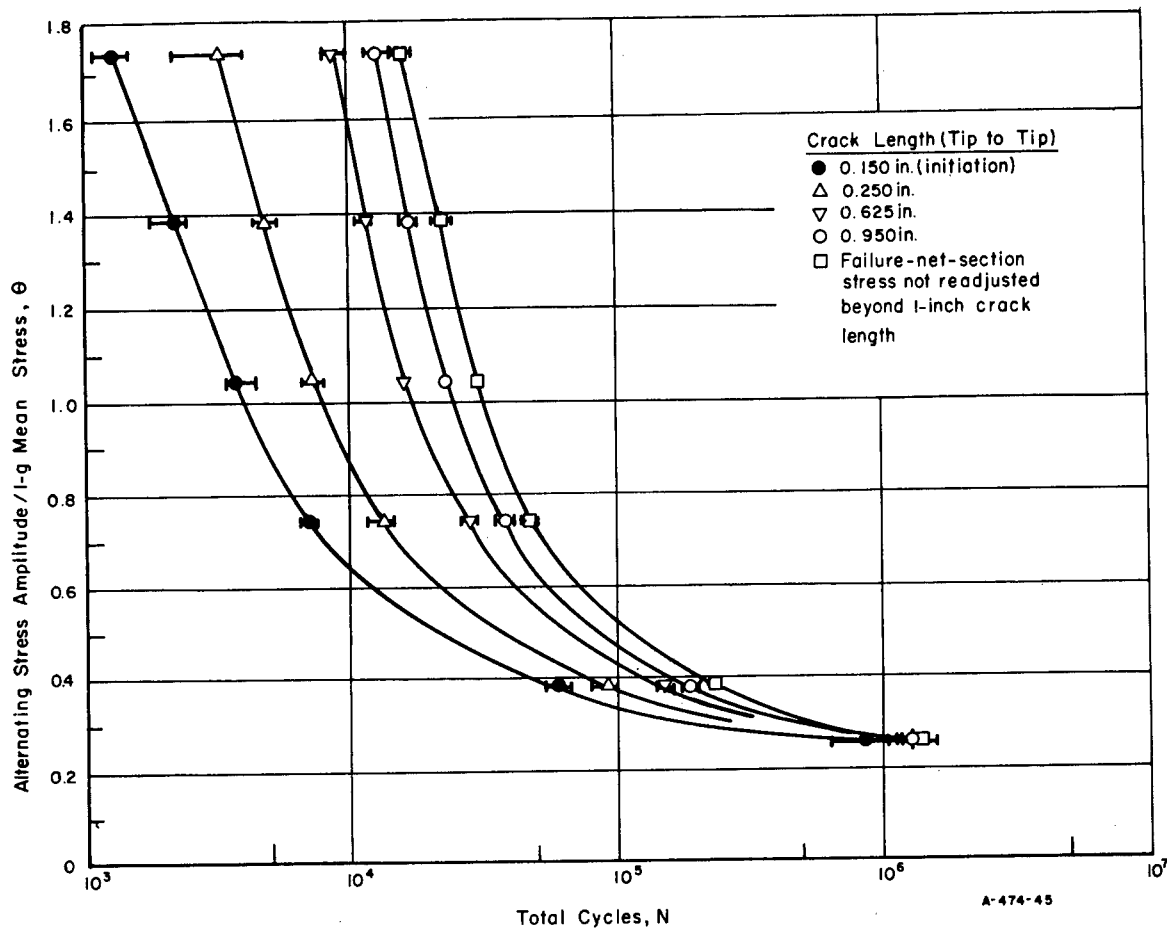


FIGURE 3. EFFECT OF THE RATIO θ ON THE CRACK-PROPAGATION BEHAVIOR OF Ti-8Al-1Mo-1V ALLOY SHEET SPECIMENS.

Specimens: Unexposed, 2 inches wide, longitudinal.

Conditions: Room temperature, 1200-1725 cpm, constant net-section 1-g mean stress of 25 ksi.

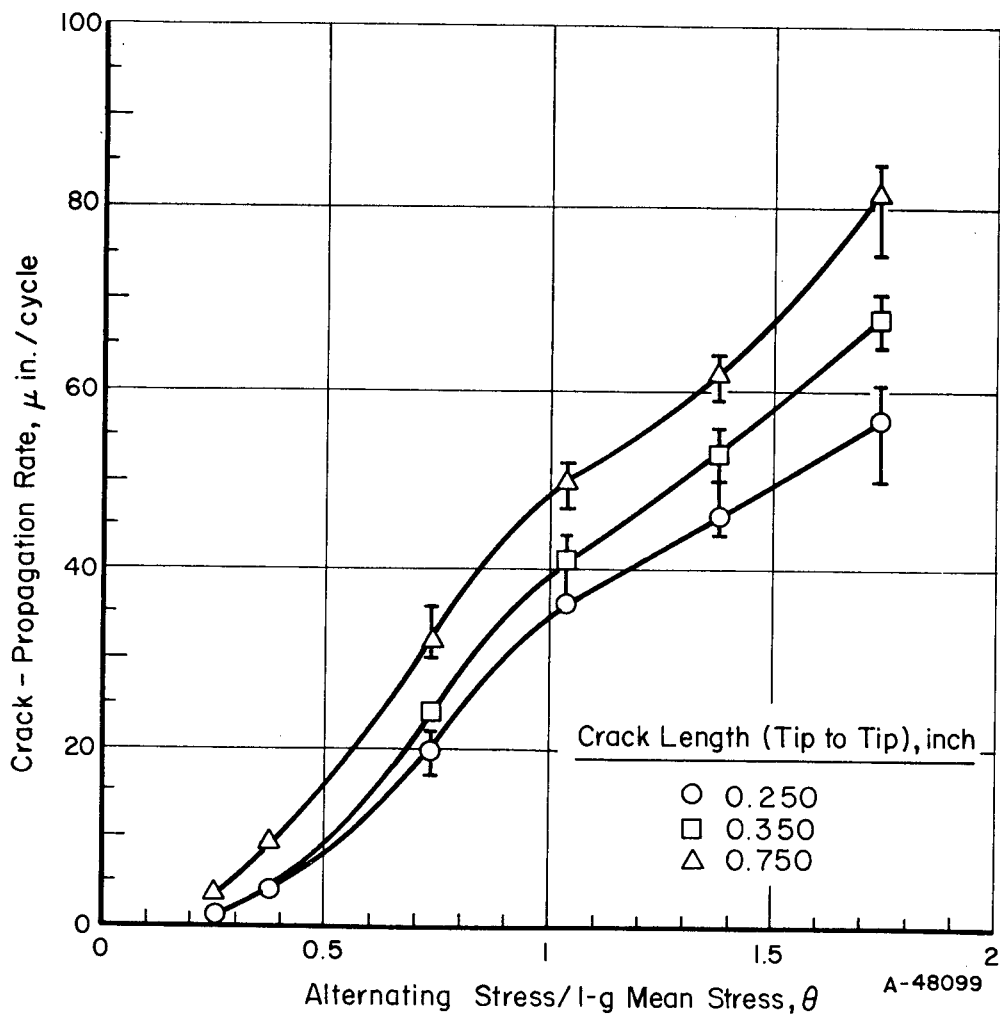


FIGURE 4. EFFECT OF THE RATIO θ ON CRACK-PROPAGATION RATE IN Ti-8Al-1Mo-1V ALLOY SHEET SPECIMENS

Specimens: Unexposed, 2 inches wide, longitudinal.

Conditions: Room temperature, 1200-1725 cpm, constant net-section stress.

TABLE 3. CRACK-PROPAGATION DATA FOR A 2-INCH-WIDE Ti-8Al-1Mo-1V ALLOY SHEET SPECIMEN AT SEVERAL ALTERNATING STRESS AMPLITUDES AND CRACK LENGTHS

25-ksi mean stress, room temperature, unexposed, longitudinal, and 1725 cpm

| Condition | ASA | θ | l_i | l_f | N | $\Delta l / \Delta N$ |
|-----------|------|----------|--------|--------|------|-----------------------|
| 1 | 6.25 | 0.25 | 0.1218 | 0.1218 | 1000 | 0 |
| 2 | 7.50 | 0.30 | 0.1218 | 0.2880 | 320 | 2.5(a) |
| 3 | 7.00 | 0.28 | 0.2880 | 0.3433 | 30 | 1.8 |
| 4 | 6.50 | 0.26 | 0.3433 | 0.3922 | 30 | 1.6 |
| 5 | 6.00 | 0.24 | 0.3922 | 0.4463 | 30 | 1.8 |
| 6 | 5.00 | 0.20 | 0.4463 | 0.4965 | 40 | 1.3 |
| 7 | 4.50 | 0.18 | 0.4965 | 0.5371 | 50 | 0.8 |
| 8 | 3.75 | 0.15 | 0.5371 | 0.5568 | 40 | 0.5 |
| 9 | 3.00 | 0.12 | 0.5568 | 0.5936 | 130 | 0.3 |
| 10 | 2.00 | 0.08 | 0.5936 | 0.6072 | 150 | 0.09 |
| 11 | 1.25 | 0.05 | 0.6072 | 0.6072 | 80 | 0.00 |

ASA - alternating stress amplitude in ksi.

θ - alternating stress amplitude/mean stress.

l_i - initial tip-to-tip crack length at indicated condition.

l_f - final tip-to-tip crack length at indicated condition.

N - number of cycles ($\times 10^{-3}$) under given condition.

$\Delta l / \Delta N$ - average crack propagation rate, μ in./cycle.

(a) Represents average crack-propagation rate over the final portion of this condition.

TABLE 4. CRACK-PROPAGATION DATA FOR A 2-INCH-WIDE AM-350 STAINLESS STEEL SHEET SPECIMEN AT SEVERAL ALTERNATING STRESS AMPLITUDES AND CRACK LENGTHS

40 ksi mean stress, room temperature, unexposed, longitudinal, and 1725 cpm

| Condition | ASA | θ | l_i | l_f | N | $\Delta l / \Delta N$ |
|-----------|------|----------|--------|--------|------|-----------------------|
| 1 | 10.0 | 0.25 | 0.1234 | 0.1234 | 1000 | 0 |
| 2 | 12.0 | 0.30 | 0.1234 | 0.287 | 84 | 5.0(a) |
| 3 | 11.2 | 0.28 | 0.287 | 0.363 | 16 | 4.7 |
| 4 | 10.4 | 0.26 | 0.363 | 0.390 | 6 | 4.5 |
| 5 | 9.6 | 0.24 | 0.390 | 0.445 | 14 | 3.9 |
| 6 | 8.0 | 0.20 | 0.445 | 0.4935 | 17.5 | 2.8 |
| 7 | 7.2 | 0.18 | 0.4935 | 0.542 | 22.5 | 2.2 |
| 8 | 6.0 | 0.15 | 0.542 | 0.554 | 10 | 1.2 |
| 9 | 4.8 | 0.12 | 0.554 | 0.594 | 45 | 0.9 |
| 10 | 3.2 | 0.08 | 0.594 | 0.612 | 67 | 0.3 |
| 11 | 2.0 | 0.05 | 0.612 | 0.6205 | 108 | 0.08 |
| 12 | 1.2 | 0.03 | 0.6205 | 0.6205 | 110 | 0.00 |

ASA - alternating stress amplitude in ksi.

θ - alternating stress amplitude/mean stress.

l_i - initial tip-to-tip crack length at indicated condition.

l_f - final tip-to-tip crack length at indicated condition.

N - number of cycles ($\times 10^{-3}$) under given condition.

$\Delta l / \Delta N$ - average crack propagation rate, μ in./cycle.

(a) Represents average crack-propagation rate over the final portion of this condition.

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A very limited study was made of the differences in crack-propagation behavior of the titanium alloy between tests conducted under constant net-section stress and those under constant gross-section stress. One specimen under the latter stress condition was tested at each value of θ employed in the program. The crack-propagation behavior of the material under the two stress conditions is illustrated in Figures 5 and 6.

It has been proposed that the rate at which a crack propagates under constant gross-section stress is given by

$$\frac{d\ell}{dN} = c \ell^m S_G^n ,$$

where

ℓ = total crack length

S_G = gross section stress amplitude

c , m , and n are constants.

In the analysis of the present data, the exponent m was taken equal to 1.0, after Frost and Dugdale⁽¹²⁾ and Liu⁽¹³⁾. This assumption implies a linear relationship between $\log \ell$ and N over a limited range. The exponent n was found to be 1.7 from Figure 5 for these specimens tested at $S_{\text{mean}} = 25$ ksi. From Figure 6 it can be seen that the linear relationship between $\log \ell$ and N did exist for ℓ/w values up to at least 0.4 for the constant gross-section stress tests. On much wider specimens than used in the present program, this linear relation was reported by Frost and Dugdale to be valid for ℓ/w values of 0.125 or less, with the exponent $n = 3.0$ for all materials that they tested.

Figures 5 and 6 show that specimens tested with constant net-section stress do not follow the above expression. Careful examination of Figure 5 and Table 2 shows for specimens tested in this manner, that the rate of crack propagation became almost constant at some crack length in the range 0.500 to 1.000 inch. In some cases the propagation rate decreased after reaching some maximum value. In this respect, there was a major difference in the two types of crack-propagation tests.

Another way of considering the data is by means of the form suggested by McEvily and Illg,⁽¹⁴⁾ as shown in Figure 7.

In this figure, the parameter, $K_N S_{\text{net}}$, was evaluated for the constant gross-section stress tests by using the simplifying assumption that the effective crack-tip radius, ρ_e , was approximately equal to the Neuber constant, ρ' , and thus

$$K_N = [1 + 1/2 (K_H - 1) (\ell/2\rho')^{1/2}] ,$$

where

ℓ = total crack length

K_H = theoretical stress-concentration factor for a hole of diameter ℓ .

The value of ρ' was evaluated from Figure 5c of Reference (15) and was found to be approximately equal to 0.0049 inch. The term S_{net} is defined as the maximum nominal net-section stress to which the remaining uncracked area of the specimen is subjected.

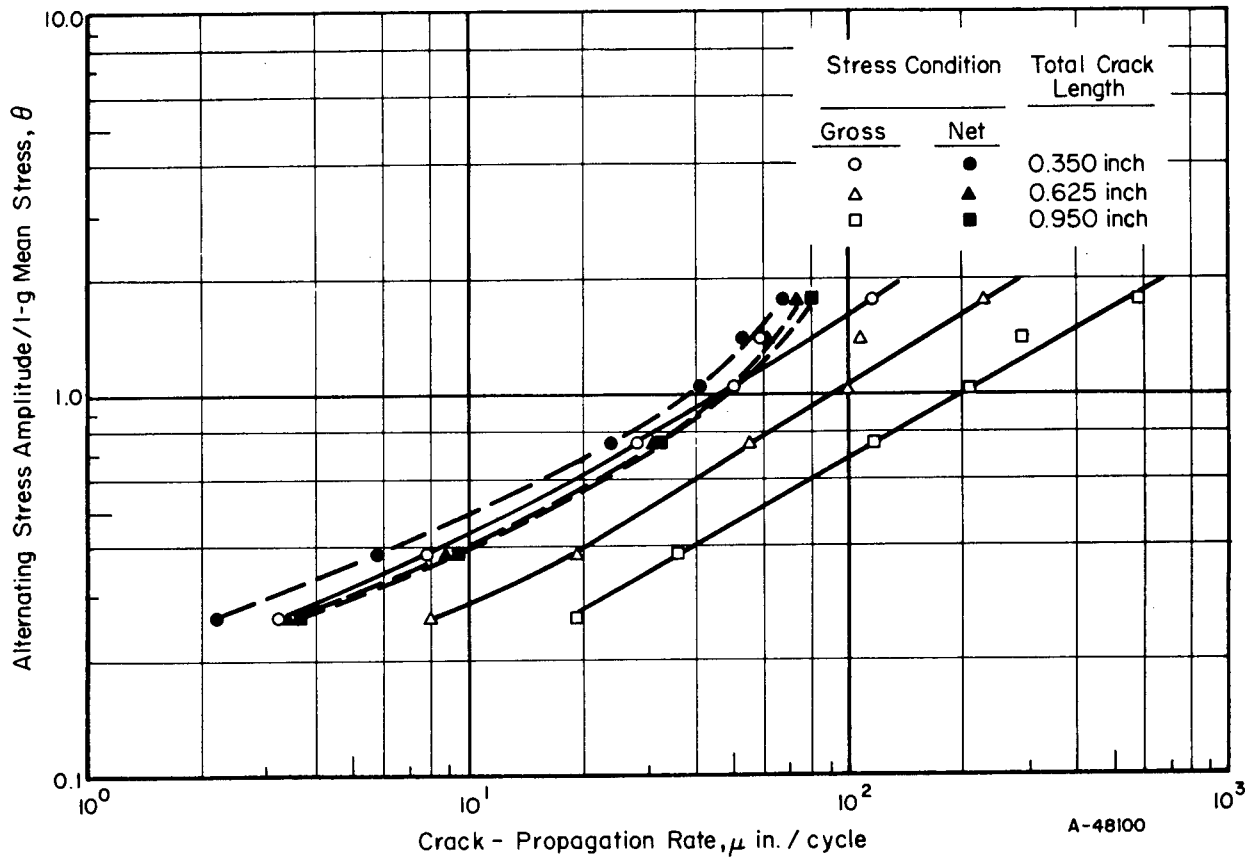


FIGURE 5. EFFECT OF STRESS CONDITION ON CRACK-PROPAGATION RATE IN 2-INCH-WIDE, LONGITUDINAL Ti-8Al-1Mo-1V ALLOY SHEET SPECIMENS

Room temperature, 1200-1725 cpm, and 25-ksi mean stress.

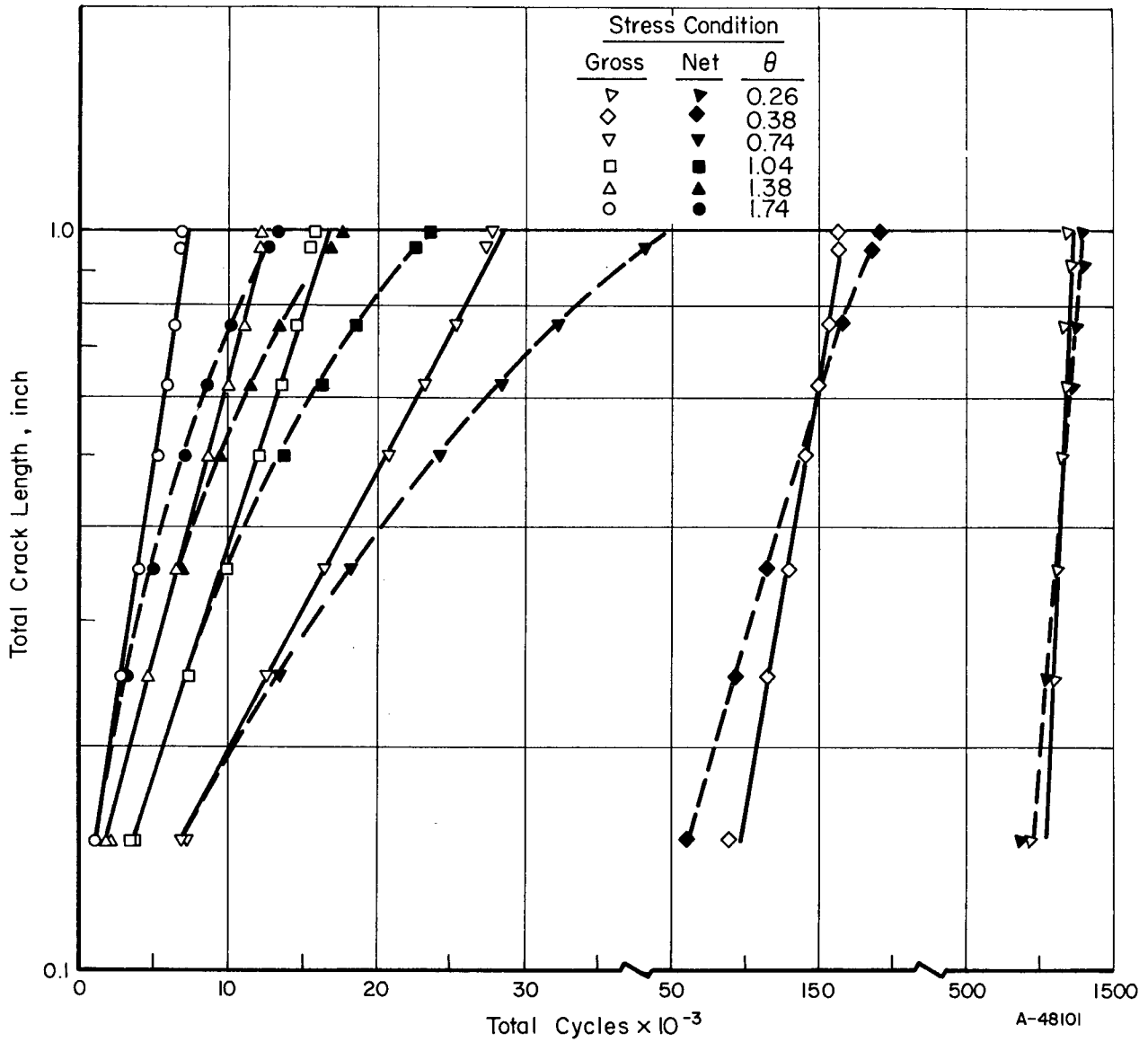


FIGURE 6. EFFECT OF STRESS CONDITION ON THE NUMBERS OF CYCLES TO A PARTICULAR CRACK LENGTH IN 2-INCH-WIDE, LONGITUDINAL Ti-8Al-1Mo-1V ALLOY SHEET SPECIMENS

Room temperature, 1200-1725 cpm, and 25-ksi mean stress.

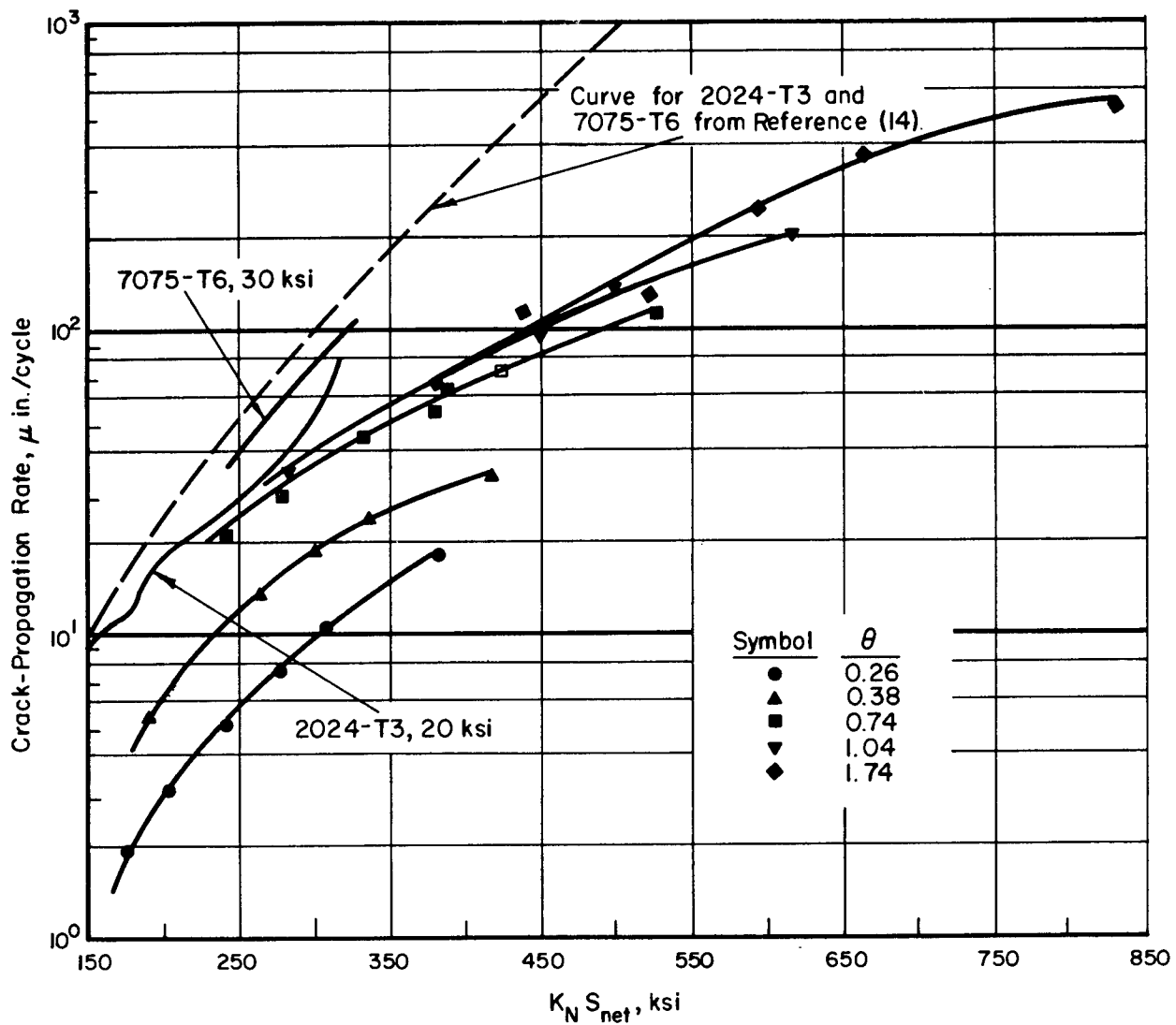


FIGURE 7. CRACK-PROPAGATION RATE AS A FUNCTION OF $K_N S_{net}$ FOR 2-INCH-WIDE, LONGITUDINAL Ti-8Al-1Mo-1V ALLOY SHEET SPECIMENS TESTED UNDER CONSTANT GROSS-SECTION STRESS CONDITION

Room temperature, 1200-1725 cpm, and 25-ksi mean stress.

Also shown on the figure are three additional curves from Reference (14). The dashed curve is plotted from an empirical expression relating crack-propagation rate with $K_{NS_{net}}$ for 2- and 12-inch-wide center-cracked specimens of 2024-T3 and 7075-T6 aluminum alloys. All tests were run essentially at $R = 0$, and the dashed curve fit all of the data reasonably well. To provide for a comparison of the results from the tests on Ti-8Al-1Mo-1V alloy and the aluminum alloys, two individual curves were singled out (one for each alloy) and are plotted in Figure 7. These were selected because the ratio of the mean test stress to tensile strength of each aluminum alloy was about equivalent to that of the titanium alloy. Thus, the latter two curves can be compared with the curve for titanium for $\theta = 1.04$. This limited comparison showed that for equal values of $K_{NS_{net}}$, the rate of crack propagation of the titanium was less than that of the aluminum alloys.

Also shown in Figure 7 is the fact that the titanium data cannot be represented conveniently by a single curve. Further evaluation, particularly at low θ values, would be required to establish a functional relationship between crack-propagation rate, R or A and $K_{NS_{net}}$.

Another limited study concerned the manner in which specimen width affects the propagation behavior of a cracked titanium specimen. Two 4-inch-wide specimens were cracked at each of two values of θ under constant net-section stress. The results are summarized in Table 5 and are illustrated in Figure 8. In general, the number of cycles to propagate a crack to a particular length and the rate of crack propagation at a particular crack length are markedly different for the two specimen widths at the same value of θ . These effects of specimen width are similar to those observed by McEvily and Illg(16), Rolfe and Munse(8), and Weibull(7). Again employing the parameter $K_{NS_{net}}$, Figure 9 shows that the difference between the propagation rates for the two specimen widths seems to be reasonably accounted for for crack lengths up to an l/ω of about 0.30.

TABLE 5. DATA ON CRACK-PROPAGATION BEHAVIOR OF LONGITUDINAL Ti-8Al-1Mo-1V ALLOY AT ROOM TEMPERATURE AND 1725 GPM FOR TWO SPECIMEN WIDTHS AND TWO STRESS AMPLITUDES

| Total Crack Length, inch | Mean Crack-Propagation Rate, μ in./cycle, for Indicated Specimen Width | |
|--------------------------|--|----------|
| | 2 Inches | 4 Inches |
| $\theta = 0.38$ | | |
| 0.250 | 4.3 | 5.9 |
| 0.350 | 5.8 | 8.8 |
| 0.500 | 8.1 | 13 |
| 0.625 | 8.8 | 16 |
| 0.750 | 9.4 | 17 |
| 0.950 | 9.0 | 21 |
| 1.250 | -- | 23 |
| 1.500 | -- | 23 |
| 1.750 | -- | 23 |
| 1.900 | -- | 23 |
| $\theta = 0.74$ | | |
| 0.250 | 20 | 24 |
| 0.350 | 24 | 32 |
| 0.500 | 29 | 39 |
| 0.625 | 31 | 45 |
| 0.750 | 32 | 51 |
| 0.950 | 32 | 60 |
| 1.250 | -- | 66 |
| 1.500 | -- | 68 |
| 1.750 | -- | 68 |
| 1.900 | -- | 68 |

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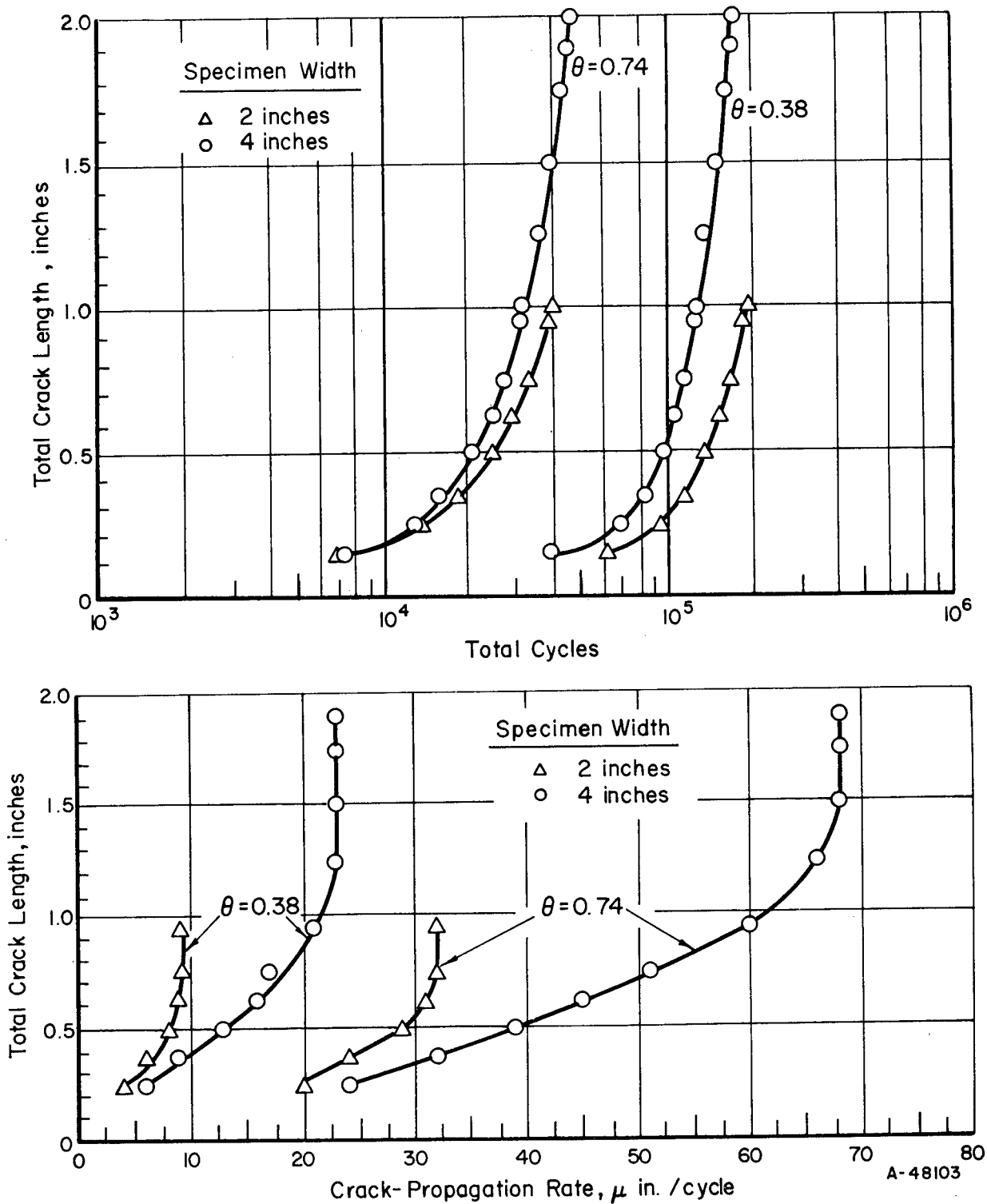


FIGURE 8. EFFECT OF SPECIMEN WIDTH ON THE CRACK-PROPAGATION BEHAVIOR OF LONGITUDINAL Ti-8Al-1Mo-1V ALLOY SHEET SPECIMENS UNDER CONSTANT NET-SECTION STRESS

Room temperature, 1200-1725 cpm, and 25-ksi mean stress.

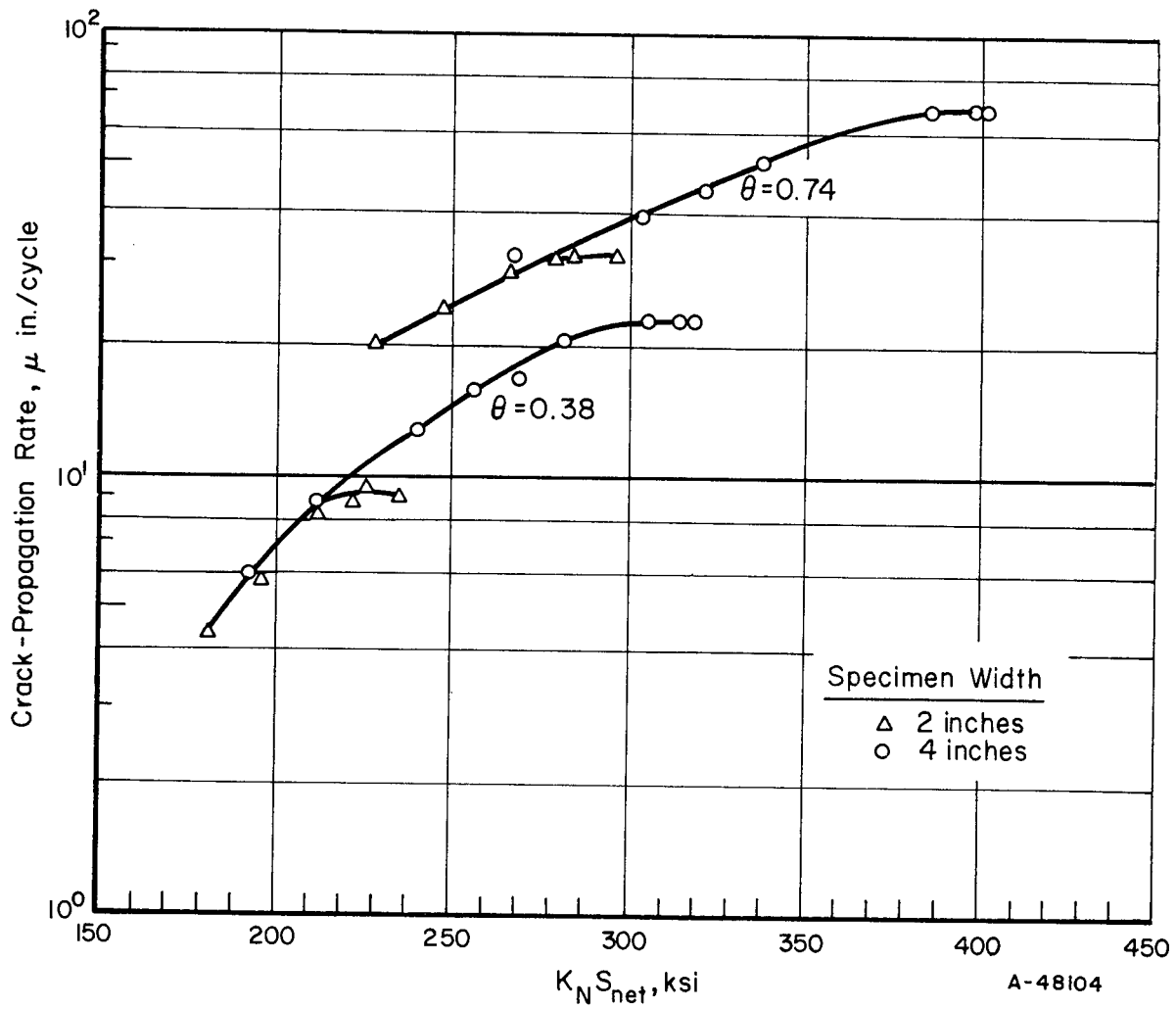


FIGURE 9. CRACK-PROPAGATION RATE AS A FUNCTION OF $K_N S_{net}$ FOR TWO SHEET SPECIMEN WIDTHS OF LONGITUDINAL Ti-8Al-1Mo-1V ALLOY UNDER CONSTANT NET-SECTION STRESS

Room temperature, 1200-1725 cpm, and 25-ksi mean stress.

Effect of Orientation

The effect of the orientation of the specimen with respect to principal rolling direction is summarized in Table 6. Represented here are data from Table 2, Conditions B, C, G, I, N and O. There appears to be some difference between propagation rates of the longitudinal and transverse specimens at θ values of 0.38, 0.74, and 1.38. These differences are consistent with the lifetime-to-failure data indicated in Table 6. In each comparison, the total lifetime-to-failure and the crack-propagation-rate data suggest that longitudinal specimens have slightly faster crack-growth characteristics than do transverse specimens.

TABLE 6. DATA ON CRACK-PROPAGATION BEHAVIOR AT THREE ALTERNATING STRESS AMPLITUDES FOR 2-INCH-WIDE Ti-8Al-1Mo-1V ALLOY SHEET SPECIMENS

Room temperature and 1725 cpm

| Total Crack Length, inch | Mean Crack-Propagation Rate, $\mu\text{in.}/\text{cycle}$, for Indicated Specimen Orientation | |
|-----------------------------------|--|------------|
| | Longitudinal | Transverse |
| <u>$\theta = 0.38$</u> | | |
| 0.250 | 4.3 | 4.0 |
| 0.350 | 5.8 | 4.7 |
| 0.500 | 8.1 | 6.4 |
| 0.625 | 8.8 | 7.9 |
| 0.750 | 9.4 | 8.1 |
| 0.950 | 9.0 | 8.4 |
| Failure (cycles) | 234,000 | 291,000 |
| <u>$\theta = 0.74$</u> | | |
| 0.250 | 20 | 18 |
| 0.350 | 24 | 22 |
| 0.500 | 29 | 27 |
| 0.625 | 31 | 29 |
| 0.750 | 32 | 30 |
| 0.950 | 32 | 31 |
| Failure (cycles) | 47,300 | 51,500 |
| <u>$\theta = 1.38$</u> | | |
| 0.250 | 46 | 42 |
| 0.350 | 53 | 47 |
| 0.500 | 62 | 58 |
| 0.625 | 62 | 58 |
| 0.750 | 62 | 60 |
| 0.950 | 60 | 55 |
| Failure (cycles) | 22,400 | 23,700 |

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Effect of Cyclic Rates

Data illustrating the effect of cyclic rate on crack propagation were obtained at θ values of 0.74 and 1.38. The testing frequencies evaluated were 34 and 1725 cpm. These data are listed in Table 2 and include conditions F, G, M, and N. Figure 10 shows that if the cyclic rate decreases there is an increase in the rate of crack propagation. In this figure data are illustrated for specimens with crack lengths of 0.250 inch and 0.750 inch. On the basis of the data, it appears that there is a small but significant effect of cycling rate on the rate of crack propagation and that this effect appears more important at high values of alternating stress amplitude and for longer cracks. For the limited conditions evaluated, increases in crack-propagation rate in the range 15 to 25 per cent were observed when testing speed was reduced from 1725 cpm to 34 cpm.

Effect of Temperature

To examine the effects of temperature on crack growth in the titanium alloy, specimens were tested at several values of θ at -110 F and at 550 F. The behavior of these specimens was compared with the behavior of specimens evaluated at room temperature. The high- and low-temperature data correspond to Conditions D, E, J, L, and P in Table 2. Figure 11 shows the influence of temperature on the rate of crack propagation at a crack length of 0.750 inch. Similar observations apply to shorter cracks. From this figure it is seen that at a given alternating stress the crack growth is more rapid the lower the temperature. Table 7 contains a summary of lifetime data for the points in Figure 11. The lifetime values for $\theta = 0.38$ can be considered to be on S-N curves for the starter notch at the three temperatures in the vicinity of the fatigue limit. From the data in Table 7, the S-N curves would be ordered in the long-life region as were the S-N curves for notched specimens with $K_t = 4.0$ [Figure 21 in Reference (1)].

Effect of Prior Stressed Exposure

Specimens of AM-350 CRT stainless steel and triplex-annealed Ti-8Al-1Mo-1V alloy were statically subjected to the appropriate 1-g mean stress while the specimens were at 550 F. The steel specimens were exposed at 40 ksi for 10,000 hours; the titanium specimens at 25 ksi for 8,000 hours. The specimens then were fatigue cracked, and crack-growth measurements were made. Table 8 is a summary of data obtained on exposed and unexposed specimens. Two cases are illustrated: (1) where the starter crack has grown to 0.250 inch and (2) where the crack has grown to 0.625 inch. The summary for stainless steel shows that the rate of crack propagation is not affected by 10,000 hours of stressed exposure. This is consistent with observations made at 1000 hours' exposure. The titanium specimens show some increase in propagation rate with exposure.

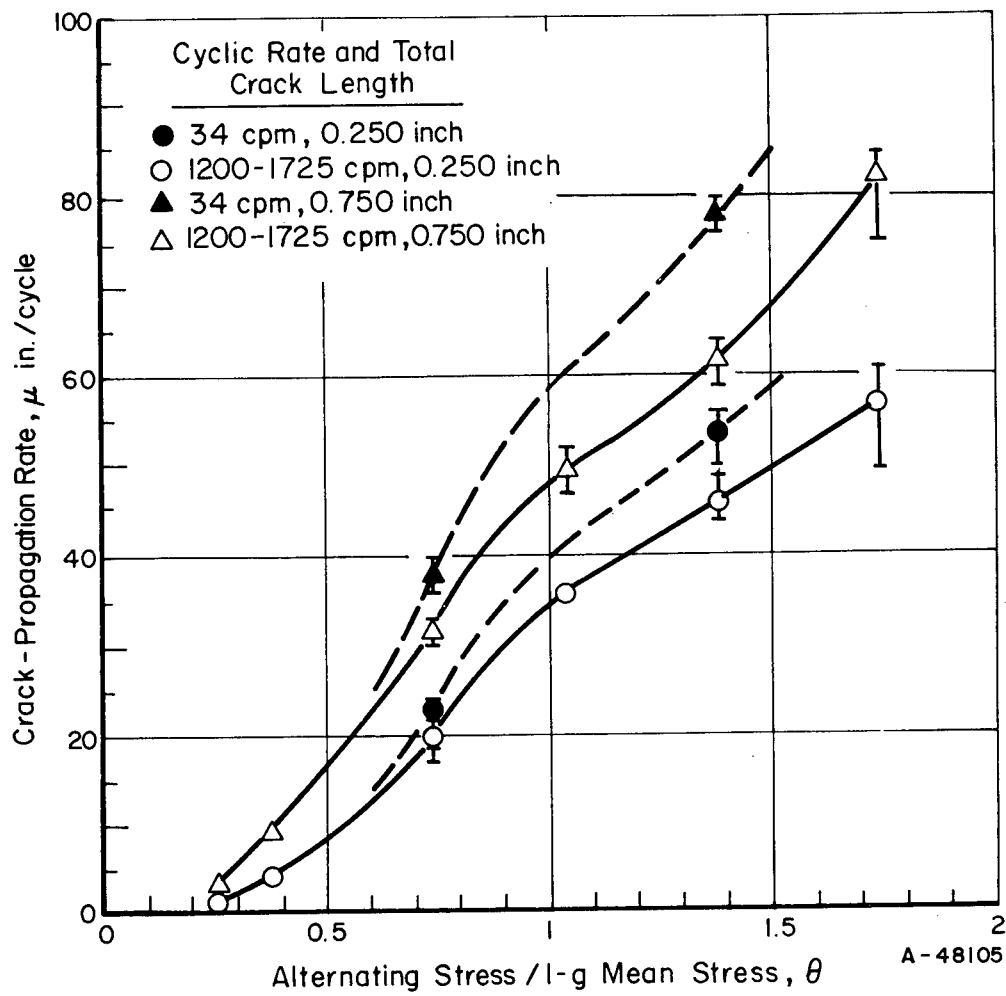


FIGURE 10. EFFECT OF CYCLIC RATE ON CRACK-PROPAGATION RATE IN 2-INCH-WIDE, LONGITUDINAL Ti-8Al-1Mo-1V ALLOY SHEET SPECIMENS AT ROOM TEMPERATURE

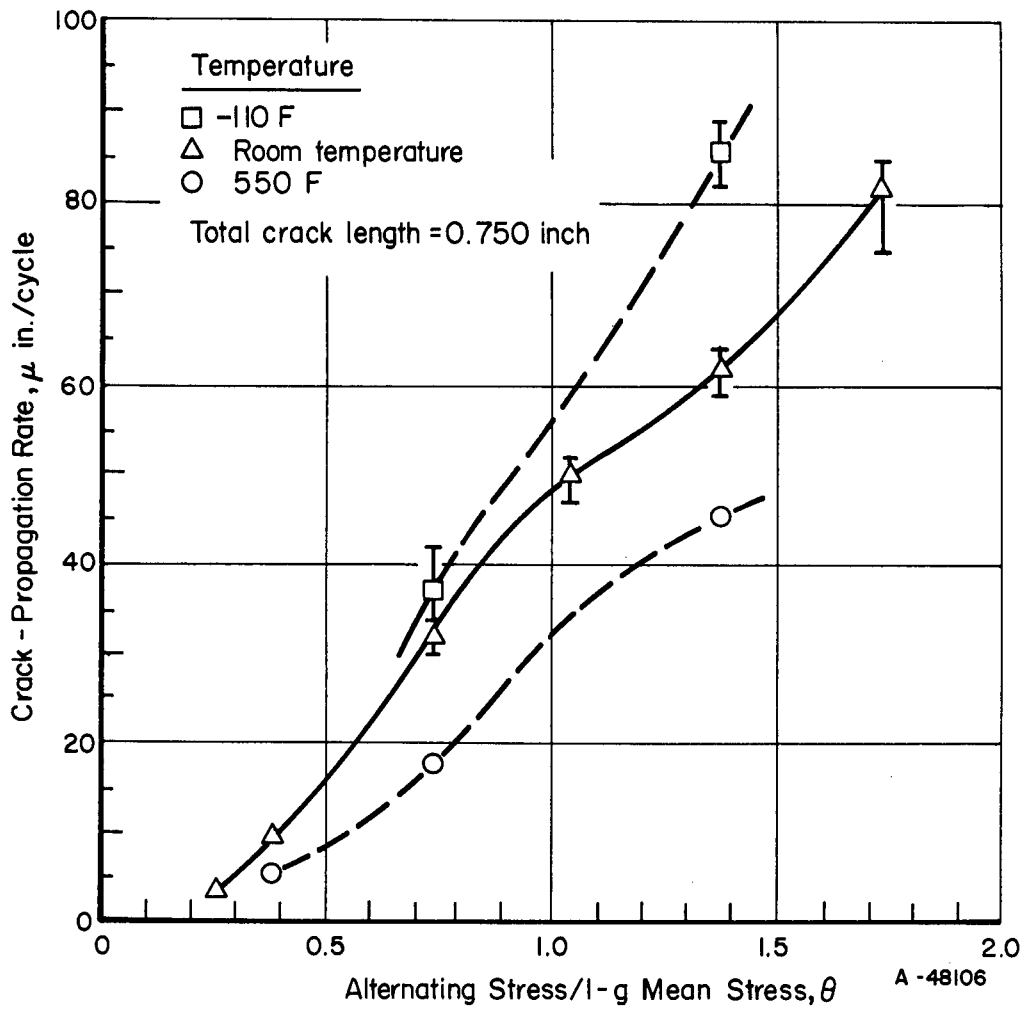


FIGURE 11. EFFECT OF TEMPERATURE ON CRACK-PROPAGATION RATE IN 2-INCH-WIDE, LONGITUDINAL Ti-8Al-1Mo-1V ALLOY SHEET

Specimens at 1200-1725 cpm.

TABLE 7. DATA ON CRACK-PROPAGATION BEHAVIOR AT THREE ALTERNATING STRESS AMPLITUDES AND THREE TEMPERATURES FOR Ti-8Al-1Mo-1V ALLOY SHEET

2-inch-wide longitudinal specimens at 1725 cpm.

| Temperature, F | Mean Total Cycles to Indicated Crack Length x 10 ⁻³ | |
|-----------------------------------|--|---------|
| | 0.150 Inch (Initiation) | Failure |
| <u>$\theta = 0.38$</u> | | |
| -110 | No initiation in 750,000 cycles | -- |
| RT | 61.2 | 234 |
| 550 | 57.4 | 315 |
| <u>$\theta = 0.74$</u> | | |
| -110 | 9.2 | 48.3 |
| RT | 7.1 | 47.3 |
| 550 | 7.6 | 76.5 |
| <u>$\theta = 1.38$</u> | | |
| -110 | 1.9 | 16.4 |
| RT | 2.2 | 22.4 |
| 550 | 1.7 | 27.1 |

TABLE 8. DATA ON CRACK-PROPAGATION BEHAVIOR OF AM-350 STAINLESS STEEL AND Ti-8Al-1Mo-1V ALLOY SHEET AT ROOM TEMPERATURE SUBJECTED TO PRIOR STRESSED EXPOSURE

2-inch-wide longitudinal specimens at 1200-1725 cpm.

| Total Crack Length, inch | | Crack-Propagation Rate, μ in./cycle, for Indicated Exposure Time | | |
|--|---------|---|-------------|--------------|
| | | Zero | 8,000 Hours | 10,000 Hours |
| <u>AM-350 at $\theta = 0.75$</u> | | | | |
| 0.250 | Minimum | 14 | -- | 19 |
| | Mean | 21 | -- | 20 |
| | Maximum | 29 | -- | 20 |
| 0.625 | Minimum | 30 | -- | 29 |
| | Mean | 36 | -- | 34 |
| | Maximum | 40 | -- | 38 |
| <u>Ti-8Al-1Mo-1V at $\theta = 0.74$</u> | | | | |
| 0.250 | Minimum | 17 | 21 | -- |
| | Mean | 20 | 23 | -- |
| | Maximum | 22 | 24 | -- |
| 0.625 | Minimum | 30 | 34 | -- |
| | Mean | 31 | 38 | -- |
| | Maximum | 33 | 45 | -- |

Residual-Static-Strength Studies

Procedures and Equipment

To determine the residual static strength and its dependence on several variables, center-cracked sheet specimens, 2 inches wide by 8 inches long, were tested in tension. The specimen geometry was identical to that employed in fatigue crack-propagation experiments (see Figure 1), except for slight modifications in the grip section. To alleviate difficulty with failures near the loading pin, stiffeners were spot welded to the grip section of the specimen and 3/4-inch-diameter loading-pin holes were drilled.

In conducting the tension tests, a constant head speed of approximately 0.02 inch/minute was used. Low-temperature tests were conducted in a mixture of dry ice and alcohol with the specimen completely immersed. Tests at 550 F were conducted in a cylindrical furnace that completely enclosed the specimen. Test temperatures were measured by thermocouples in contact with the specimen near the center crack.

The variables investigated for their effect on the residual static strength of Ti-8Al-1Mo-1V were crack length, test temperature, orientation with respect to the rolling direction, fatigue conditions employed to introduce the crack, and prior exposure to 1-g stress at 550 F.

In addition, the effect at 10,000 hours' exposure was examined for the AM-350 stainless steel. The residual-strength studies of unexposed steel and the steel after intermediate exposure are given in Reference 1.

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Effect of Crack Length

Nominal crack lengths of 3/16, 3/8, 3/4, and 1 inch were examined for their effect on residual static strength. In Figure 12, residual strength at three test temperatures is shown as a function of crack length; Table 9 contains all the pertinent data.

The data presented in Figure 12 and Table 9 show that the residual strength (both net section and gross section) decreases with increasing crack length, with one exception: specimens having crack lengths of 3/4 inch, when tested at 550 F, exhibited greater net-section strengths than those having crack lengths of 3/16 or 3/8 inch. At room temperature and -110 F, residual strength decreases continuously with increasing crack length.

Effect of Test Temperature

Residual strength was determined at test temperatures of -110, 75, and 550 F. In Figure 13 residual strength is shown as a function of test temperature for various crack lengths. Included for comparison is a curve showing the variation of the ultimate tensile strength with temperature.

Examination of Figure 13 and Table 9 shows that the residual strength decreases continuously with increasing test temperature for all the crack lengths investigated. However, the decrease in strength between room temperature and 550 F of specimens containing 3/4-inch cracks is considerably less than that of specimens with smaller cracks.

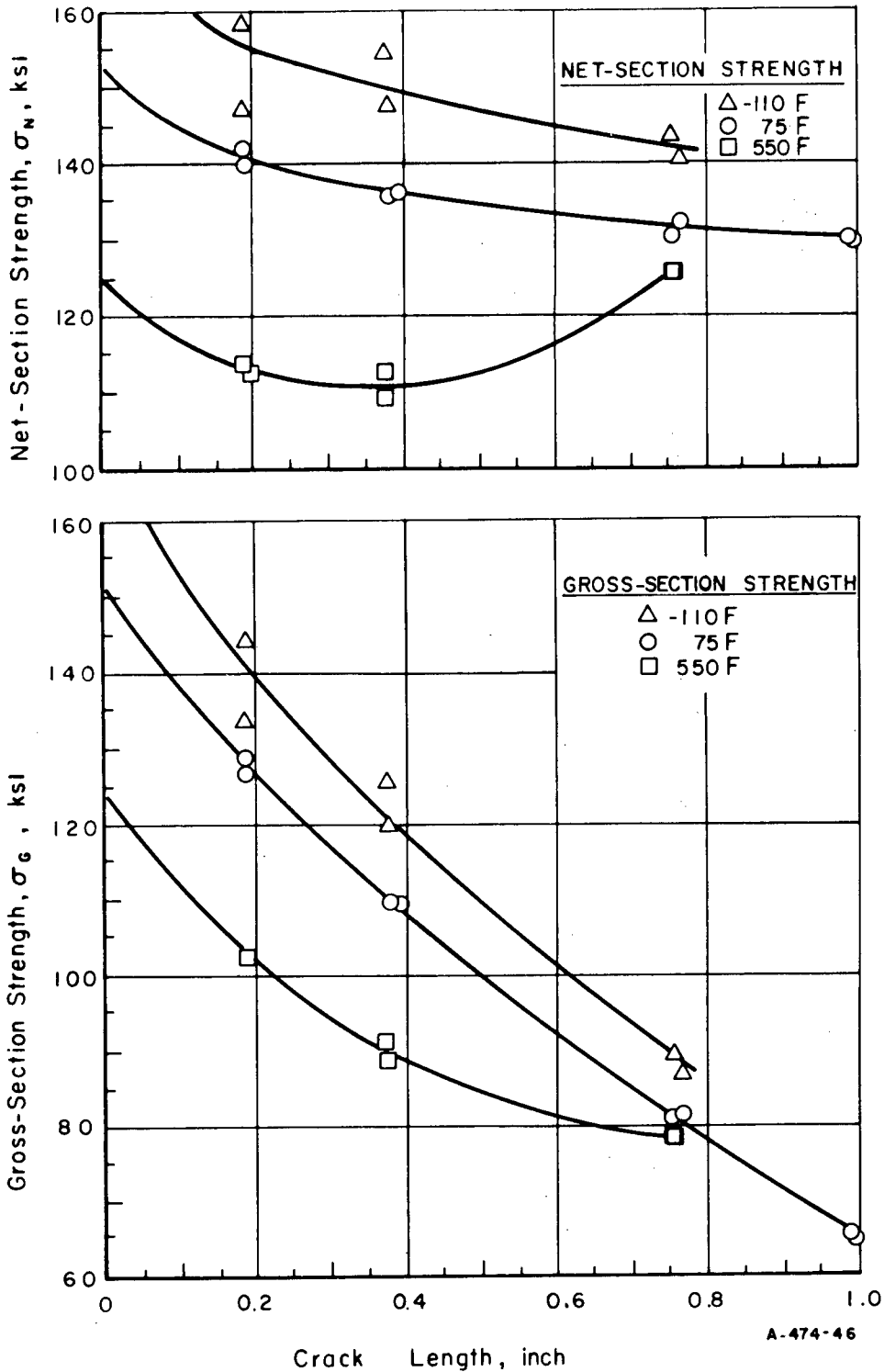


FIGURE 12. EFFECT OF CRACK LENGTH, AT THREE TEST TEMPERATURES, ON NET-SECTION STRENGTH AND GROSS-SECTION STRENGTH OF CENTER-CRACKED Ti-8Al-1Mo-1V SHEET SPECIMENS

Longitudinal specimens, 2 inches wide.

TABLE 9. RESULTS OF TENSILE TESTS ON CENTER-CRACKED Ti-8Al-1Mo-1V SHEET SPECIMENS FATIGUE CRACKED AT ROOM TEMPERATURE

2-inch-wide specimens 25-ksi mean stress, 18.5-ksi alternating stress amplitude ($\theta = 0.74$) and 1725 cpm.

| Specimen | Orientation | Test Temperature, F | Initial Crack Length, inches | Thickness, inches | $\sigma_N^{(a)}$, ksi | $\sigma_G^{(b)}$, ksi |
|----------|-------------|---------------------|------------------------------|-------------------|------------------------|------------------------|
| 8325 | L | 75 | 0.188 | 0.042 | 139.9 | 126.9 |
| 6345 | L | 75 | 0.186 | 0.047 | 142.2 | 129.0 |
| 6348 | L | 75 | 0.379 | 0.047 | 135.9 | 110.1 |
| 8169 | L | 75 | 0.390 | 0.042 | 136.2 | 109.6 |
| 7338 | L | 75 | 0.754 | 0.0445 | 130.4 | 81.2 |
| 8175 | L | 75 | 0.767 | 0.0405 | 132.2 | 81.5 |
| 8328 | L | 75 | 0.959 | 0.0433 | 130.1 | 65.7 |
| 7337 | L | 75 | 0.997 | 0.044 | 130.0 | 65.3 |
| 7329 | L | -110 | 0.186 | 0.044 | 158.6 | 143.8 |
| 7326 | L | -110 | 0.186 | 0.045 | 147.1 | 133.3 |
| 8176 | L | -110 | 0.372 | 0.040 | 154.2 | 125.6 |
| 7349 | L | -110 | 0.376 | 0.0442 | 147.7 | 119.9 |
| 6335 | L | -110 | 0.763 | 0.0465 | 140.5 | 86.9 |
| 8167 | L | -110 | 0.752 | 0.042 | 143.6 | 89.6 |
| 6351 | L | 550 | 0.191 | 0.0465 | 113.0 | 102.3 |
| 8170 | L | 550 | 0.188 | 0.0417 | 113.6 | 102.9 |
| 7331 | L | 550 | 0.371 | 0.0435 | 112.6 | 91.5 |
| 6338 | L | 550 | 0.374 | 0.0465 | 109.3 | 88.8 |
| 7333 | L | 550 | 0.752 | 0.0435 | 125.8 | 78.5 |
| 6337 | L | 550 | 0.752 | 0.0465 | 125.9 | 78.5 |
| 8229 | T | 75 | 0.195 | 0.0425 | 132.3 | 119.4 |
| 6206 | T | 75 | 0.198 | 0.048 | 130.1 | 117.2 |
| 6208 | T | 75 | 0.373 | 0.0475 | 126.2 | 102.6 |
| 8228 | T | 75 | 0.370 | 0.0425 | 128.5 | 104.7 |
| 6209 | T | 75 | 0.753 | 0.0475 | 121.6 | 75.8 |
| 8227 | T | 75 | 0.752 | 0.0415 | 123.1 | 76.8 |
| 8225 | T | 75 | 1.000 | 0.042 | 121.5 | 60.7 |
| 7227 | T | 75 | 1.001 | 0.043 | 123.8 | 61.9 |

(a) Net-section strength: $\sigma_N = \frac{\text{maximum load}}{\text{thickness} \times (\text{width} - \text{crack length})}$

(b) Gross-section strength: $\sigma_G = \frac{\text{maximum load}}{\text{thickness} \times \text{width}}$

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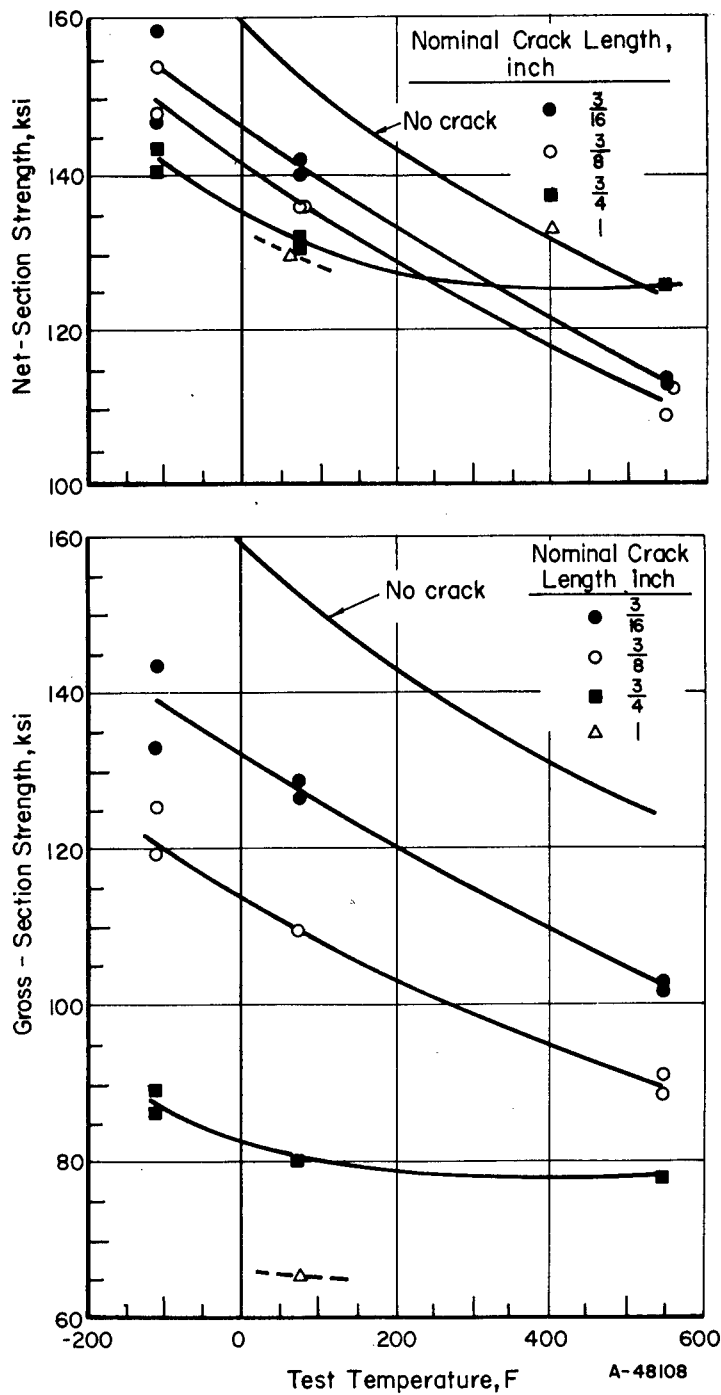


FIGURE 13. EFFECT OF TEST TEMPERATURE AT SEVERAL CRACK LENGTHS ON NET-SECTION STRENGTH AND GROSS-SECTION STRENGTH OF CENTER-CRACKED Ti-8Al-1Mo-1V SHEET SPECIMENS

2-inch-wide longitudinal specimens.

Effect of Orientation With Respect to the Rolling Direction

Specimens containing nominal 3/16-, 3/8-, 3/4-, and 1-inch cracks were tested at room temperature, both parallel and perpendicular to the rolling direction, to determine the effect of specimen orientation on residual strength. The results are shown in Figure 14 and Table 9. At all crack lengths investigated, transverse specimens (i. e., those with the specimen axis perpendicular to the rolling direction) exhibited a lower residual strength than did longitudinal specimens. The difference in the strength levels between the two specimen orientations is about the same to crack lengths up to $l/\omega = 0.500$.

Effect of Fatigue Conditions Used to Introduce Cracks

To determine whether or not the residual strength of fatigue-cracked Ti-8Al-1Mo-1V is influenced by the manner in which the crack is introduced, experiments were performed in which the fatigue-stress amplitude, fatigue temperature, and cycling speed were varied.

Effect of Fatigue-Stress Amplitude. Four different stress amplitudes were employed to introduce fatigue cracks in Ti-8Al-1Mo-1V. These were 9.5-, 18.5-, 34.5- and 43.5-ksi (θ values of 0.38, 0.74, 1.38, and 1.74, respectively), all superposed upon a mean stress of 25 ksi. In Section C of Table 10, the net-section and gross-section strengths are given for several values of stress amplitudes (and θ) at several crack lengths and for both longitudinal and transverse specimen orientations. It is apparent that fatigue-stress amplitude, in the range studied, has virtually no effect on residual strength.

Effect of Fatigue-Cracking Temperature. Fatigue cracks 3/4-inch long were introduced at temperatures of -110, 75, and 550 F, prior to determination of residual strength at room temperature. An examination of Section A of Table 10 shows that there is no appreciable effect of fatigue-cracking temperature on the residual strength of the 8Al-1Mo-1V titanium alloy.

Effect of Cyclic Frequency. Two different cyclic frequencies, 1725 and 34 cycles per minute, were used to introduce 3/4-inch fatigue cracks in Ti-8Al-1Mo-1V sheet specimens. As shown in Section B of Table 10, no effect of cyclic speed upon residual strength was observed.

Effect of Exposure to 1-g Stress at 550 F

Center-notched Ti-8Al-1Mo-1V sheet specimens were exposed in air to a 1-g (25.0 ksi) net-section stress at 550 F for 8000 hours prior to introducing fatigue cracks. Center-cracked specimens then were tested at -110, 75, and 550 F, with the results shown in Table 11 and Figure 15. The results indicate that an 8000-hour exposure weakens the titanium alloy slightly if long cracks are present (3/4 inch in a 2-inch-wide specimen). The data are somewhat inconsistent in this regard, with reference to

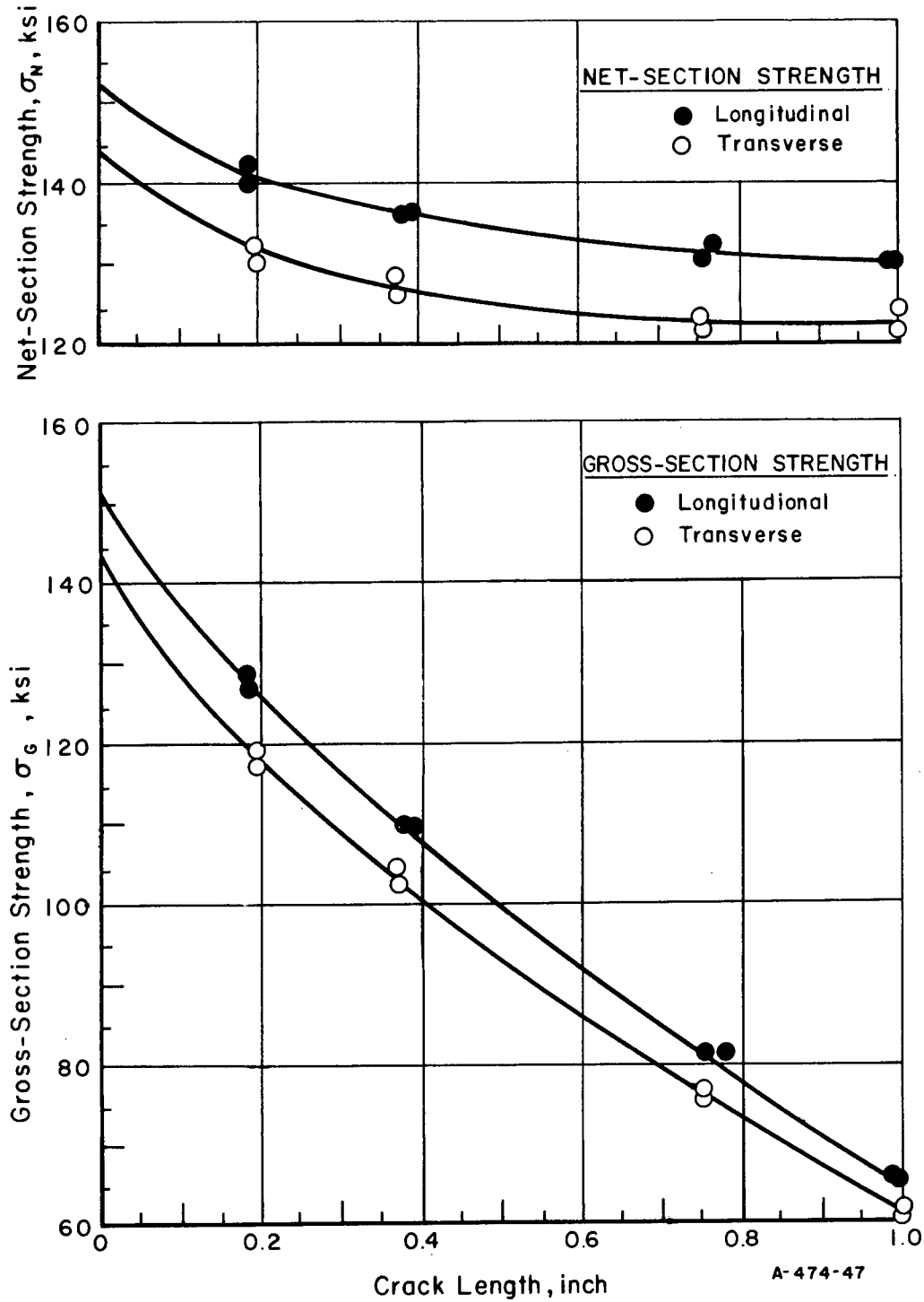


FIGURE 14. EFFECT OF SPECIMEN ORIENTATION ON NET-SECTION STRENGTH AND GROSS-SECTION STRENGTH OF 2-INCH-WIDE, CENTER-CRACKED Ti-8Al-1Mo-1V SHEET SPECIMENS AT ROOM TEMPERATURE

TABLE 10. RESULTS OF ROOM-TEMPERATURE TENSILE TESTS ON 2-INCH WIDE, CENTER-CRACKED, Ti-8Al-1Mo-1V SHEET SPECIMENS, FATIGUE-CRACKED AT VARIOUS TEMPERATURES, CYCLIC FREQUENCIES, AND ALTERNATING STRESS AMPLITUDES

| Specimen | Orientation | Crack Length, inches | Thickness, inch | Fatigue-Cracking Conditions | | | | | $\sigma_N^{(a)}$, ksi | $\sigma_G^{(b)}$, ksi |
|--|-------------|----------------------|-----------------|-----------------------------|----------------|-----------------------|----------------------|----------|------------------------|------------------------|
| | | | | Temperature, F | Frequency, cpm | σ_{mean} , ksi | σ_{alt} , ksi | θ | | |
| <u>Section A. Effect of Fatigue Temperature</u> | | | | | | | | | | |
| 8162 | L | 0.766 | 0.041 | -110 | 1725 | 25 | 18.5 | 0.74 | 131.3 | 81.0 |
| 8174 | L | 0.768 | 0.0405 | -110 | 1725 | 25 | 18.5 | 0.74 | 134.0 | 82.6 |
| 6354 | L | 0.752 | 0.046 | -110 | 1725 | 25 | 18.5 | 0.74 | 130.3 | 81.2 |
| 7338 | L | 0.754 | 0.0445 | 75 | 1725 | 25 | 18.5 | 0.74 | 130.4 | 81.2 |
| 8175 | L | 0.767 | 0.0405 | 75 | 1725 | 25 | 18.5 | 0.74 | 132.2 | 81.5 |
| 7336 | L | 0.748 | 0.044 | 550 | 1725 | 25 | 18.5 | 0.74 | 131.9 | 82.4 |
| 6344 | L | 0.749 | 0.047 | 550 | 1725 | 25 | 18.5 | 0.74 | 131.2 | 82.2 |
| <u>Section B. Effect of Cyclic Frequency</u> | | | | | | | | | | |
| 7343 | L | 0.750 | 0.0445 | 75 | 34 | 25 | 18.5 | 0.74 | 130.6 | 81.5 |
| 8163 | L | 0.752 | 0.0415 | 75 | 34 | 25 | 18.5 | 0.74 | 130.6 | 81.4 |
| 7338 | L | 0.754 | 0.0445 | 75 | 1725 | 25 | 18.5 | 0.74 | 130.4 | 81.2 |
| 8175 | L | 0.767 | 0.0405 | 75 | 1725 | 25 | 18.5 | 0.74 | 132.2 | 81.5 |
| <u>Section C. Effect of Alternating Stress Amplitude</u> | | | | | | | | | | |
| 7343 | L | 0.750 | 0.0445 | 75 | 34 | 25 | 18.5 | 0.74 | 130.6 | 81.5 |
| 8163 | L | 0.752 | 0.0415 | 75 | 34 | 25 | 18.5 | 0.74 | 130.6 | 81.4 |
| 8168 | L | 0.779 | 0.042 | 75 | 34 | 25 | 34.5 | 1.38 | 132.9 | 81.0 |
| 7347 | L | 0.755 | 0.044 | 75 | 34 | 25 | 34.5 | 1.38 | 130.7 | 81.3 |
| 6353 | L | 1.000 | 0.046 | 75 | 1725 | 25 | 9.5 | 0.38 | 127.1 | 63.5 |
| 8332 | L | 1.000 | 0.042 | 75 | 1725 | 25 | 9.5 | 0.38 | 129.8 | 64.9 |
| 8328 | L | 0.989 | 0.0433 | 75 | 1725 | 25 | 18.5 | 0.74 | 130.1 | 65.7 |
| 7337 | L | 0.997 | 0.044 | 75 | 1725 | 25 | 18.5 | 0.74 | 130.0 | 65.3 |
| 7332 | L | 1.004 | 0.044 | 75 | 1200 | 25 | 43.5 | 1.74 | 127.8 | 63.7 |
| 8330 | L | 0.999 | 0.042 | 75 | 1200 | 25 | 43.5 | 1.74 | 128.9 | 64.6 |
| 7225 | T | 0.999 | 0.0435 | 75 | 1725 | 25 | 9.5 | 0.38 | 122.4 | 61.2 |
| 8230 | T | 0.998 | 0.042 | 75 | 1725 | 25 | 9.5 | 0.38 | 122.2 | 61.2 |
| 8225 | T | 1.000 | 0.042 | 75 | 1725 | 25 | 18.5 | 0.74 | 121.5 | 60.7 |
| 7227 | T | 1.001 | 0.043 | 75 | 1725 | 25 | 18.5 | 0.74 | 123.8 | 61.9 |
| 6207 | T | 1.008 | 0.048 | 75 | 1725 | 25 | 34.5 | 1.38 | 119.0 | 59.0 |
| 7353 | T | 0.997 | 0.044 | 75 | 1725 | 25 | 34.5 | 1.38 | 124.0 | 62.3 |

(a) Net-section strength; $\sigma_N = \frac{\text{maximum load}}{\text{thickness} \times (\text{width} - \text{crack length})}$

(b) Gross-section strength; $\sigma_G = \frac{\text{maximum load}}{\text{thickness} \times \text{width}}$

very small cracks (3/16 inch). Even with the slight weakening observed in the presence of long cracks, however, the material behaves in a ductile fashion at all three test temperatures studied. The ratio of net-section strength to the 1-g stress remains well in excess of 4.0 for all crack lengths and test temperatures.

TABLE 11. EFFECT OF EXPOSURE TO 1-g STRESS (25-KSI) AT 550 F ON RESIDUAL STATIC STRENGTH OF 2-INCH-WIDE CENTER-CRACKED LONGITUDINAL Ti-8Al-1Mo-1V SHEET SPECIMENS

| Specimen | Exposure Time, hours | Test Temperature, F | Initial Crack Length, inch | σ_N , ksi | σ_G , ksi |
|----------|----------------------|---------------------|----------------------------|------------------|------------------|
| 7329 | -- | -110 | 0.186 | 158.6 | 143.8 |
| 7326 | -- | -110 | 0.186 | 147.1 | 133.3 |
| 7430 | 8000 | -110 | 0.185 | 156.3 | 141.9 |
| 6335 | -- | -110 | 0.763 | 140.5 | 86.9 |
| 8167 | -- | -110 | 0.752 | 143.6 | 89.6 |
| 7403 | 8000 | -110 | 0.740 | 136.7 | 86.1 |
| 8325 | -- | 75 | 0.188 | 139.9 | 126.9 |
| 6345 | -- | 75 | 0.186 | 142.2 | 129.0 |
| 7434 | 8000 | 75 | 0.188 | 139.8 | 126.5 |
| 7419 | 8000 | 75 | 0.189 | 134.2 | 121.8 |
| 7338 | -- | 75 | 0.754 | 130.4 | 81.2 |
| 8175 | -- | 75 | 0.767 | 132.2 | 81.5 |
| 7427 | 8000 | 75 | 0.752 | 127.1 | 79.3 |
| 7404 | 8000 | 75 | 0.750 | 128.0 | 80.0 |
| 6351 | -- | 550 | 0.191 | 113.0 | 102.3 |
| 8170 | -- | 550 | 0.188 | 113.6 | 102.9 |
| 7422 | 8000 | 550 | 0.183 | 116.3 | 105.7 |
| 7426 | 8000 | 550 | 0.183 | 118.8 | 107.9 |
| 7333 | -- | 550 | 0.752 | 125.8 | 78.5 |
| 6337 | -- | 550 | 0.752 | 125.9 | 78.5 |
| 7417 | 8000 | 550 | 0.741 | 120.9 | 76.3 |
| 7402 | 8000 | 550 | 0.752 | 109.2 | 67.6 |

As mentioned previously, the residual strength of fatigue-cracked AM-350 was the subject of an earlier investigation. However, tests were conducted in the present study to evaluate the effect of long-time (10,000 hours) exposure to stress at 550 F. → pg 38

Center-notched AM-350 sheet specimens were exposed in air at a net-section stress of 40 ksi at 550 F prior to introducing fatigue cracks. Center-cracked specimens then were tested at -110, 75, and 550 F, with the results shown in Table 12 and

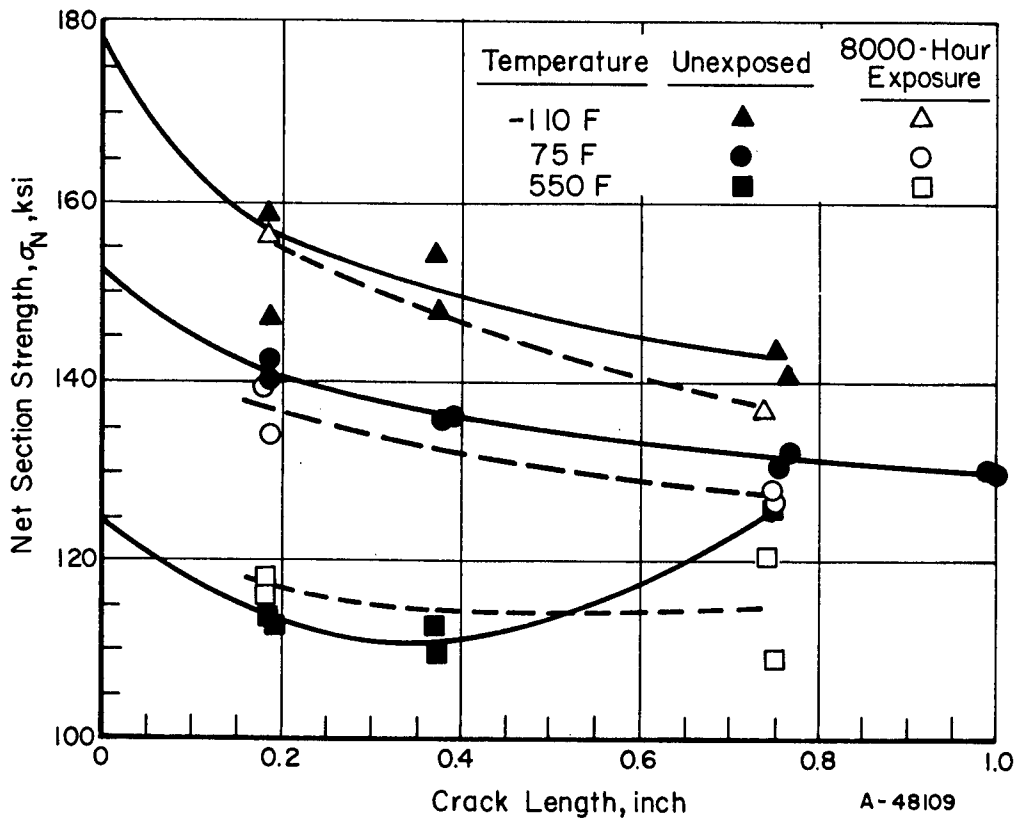


FIGURE 15. EFFECT OF 8000-HOUR EXPOSURE TO 1-G STRESS OF 25-KSI AT 550 F ON NET-SECTION STRENGTH OF 2-INCH-WIDE CENTER-CRACKED LONGITUDINAL Ti-8Al-1Mo-1V SHEET SPECIMENS

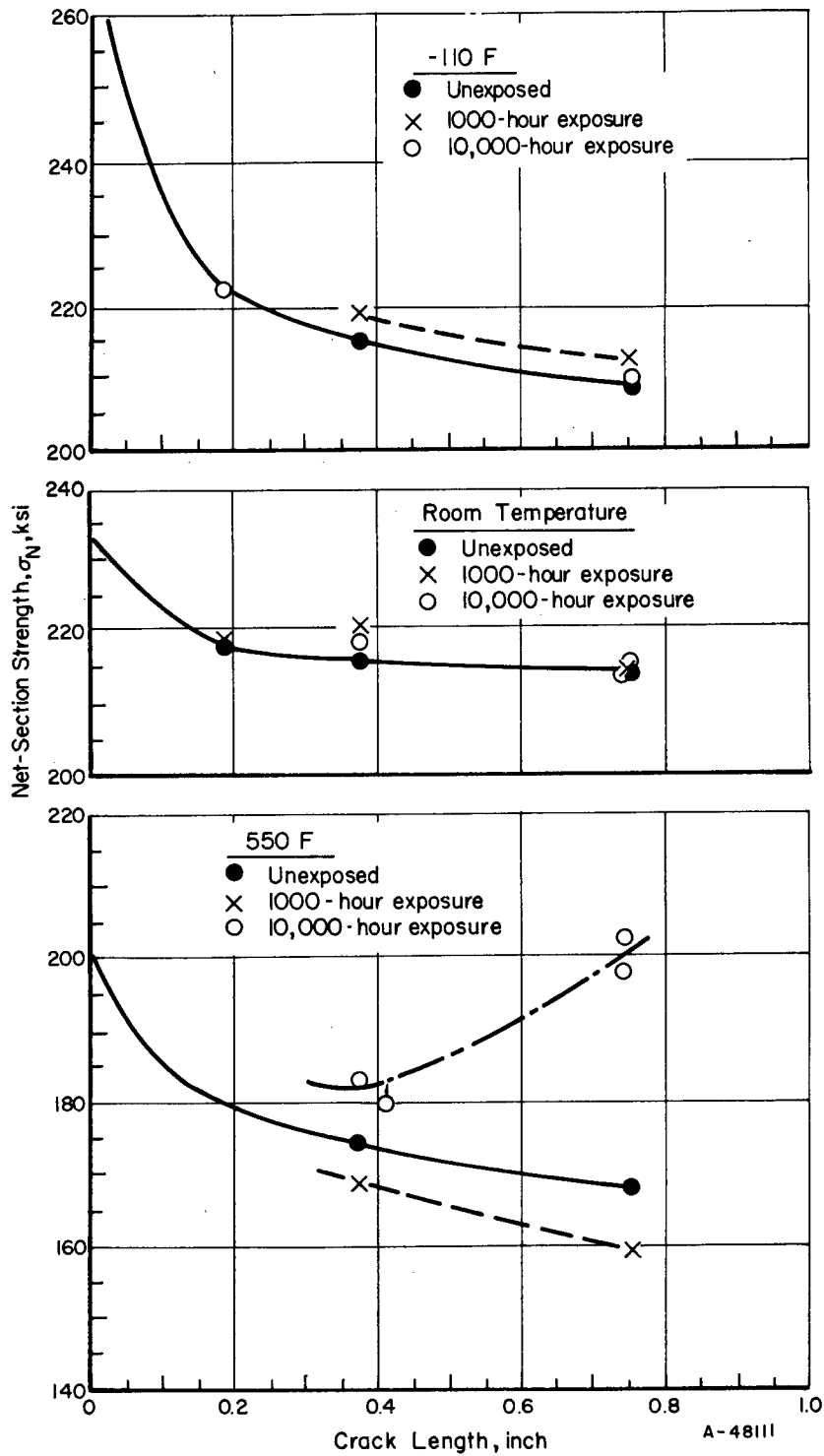


FIGURE 16. EFFECT OF 10,000-HOUR EXPOSURE TO 1-G STRESS OF 40-KSI AT 550 F ON NET-SECTION STRENGTH OF 2-INCH-WIDE CENTER-CRACKED LONGITUDINAL AM-350 SHEET SPECIMENS

TABLE 12. EFFECT OF EXPOSURE TO 1-G STRESS OF 40-KSI AT 550 F ON RESIDUAL STATIC-STRENGTH OF 2-INCH-WIDE, CENTER-CRACKED, LONGITUDINAL AM-350 SHEET SPECIMENS

| Specimen | Exposure Time, hours | Test Temperature, F | Initial Crack Length, inches | σ_N , ksi | σ_G , ksi |
|----------|----------------------|---------------------|------------------------------|------------------|------------------|
| 634 | -- | -110 | 0.183 | (a) | (a) |
| 832 | 1,000 | -110 | 0.190 | (a) | (a) |
| 6320 | 10,000 | -110 | 0.182 | 222.3 | 202.0 |
| 6311 | -- | -110 | 0.375 | 215.4 | 175.0 |
| 7317 | 1,000 | -110 | 0.374 | 218.9 | 177.9 |
| 6316 | -- | -110 | 0.752 | 209.0 | 130.4 |
| 8317 | 1,000 | -110 | 0.749 | 212.8 | 133.1 |
| 838 | 10,000 | -110 | 0.753 | 209.5 | 131.0 |
| 6310 | -- | 75 | 0.188 | 217.5 | 197.1 |
| 834 | 1,000 | 75 | 0.188 | (a) | (a) |
| 831 | 1,000 | 75 | 0.186 | 218.4 | 198.0 |
| 7314 | 10,000 | 75 | 0.178 | (a) | (a) |
| 631 | 10,000 | 75 | 0.191 | (a) | (a) |
| 6313 | -- | 75 | 0.375 | 216.0 | 175.5 |
| 8320 | 1,000 | 75 | 0.375 | 220.8 | 179.4 |
| 8318 | 10,000 | 75 | 0.376 | 218.5 | 177.5 |
| 6317 | -- | 75 | 0.751 | 214.1 | 133.7 |
| 8311 | 1,000 | 75 | 0.747 | 214.4 | 134.3 |
| 6314 | 10,000 | 75 | 0.739 | 213.7 | 134.8 |
| 731 | 10,000 | 75 | 0.750 | 215.5 | 134.8 |
| 638 | -- | 550 | 0.181 | (a) | (a) |
| 8316 | 1,000 | 550 | 0.189 | (a) | (a) |
| 6318 | 10,000 | 550 | 0.201 | (a) | (a) |
| 635 | 10,000 | 550 | 0.180 | (a) | (a) |
| 6312 | -- | 550 | 0.373 | 174.7 | 142.2 |
| 835 | 1,000 | 550 | 0.375 | 168.9 | 137.3 |
| 8315 | 10,000 | 550 | 0.376 | 183.4 | 149.0 |
| 7312 | 10,000 | 550 | 0.412 | >179.8(a) | >142.7(a) |
| 8319 | -- | 550 | 0.753 | 168.2 | 104.9 |
| 8313 | 1,000 | 550 | 0.758 | 159.5 | 99.0 |
| 6319 | 10,000 | 550 | 0.746 | 203.0 | 127.4 |
| 739 | 10,000 | 550 | 0.744 | 198.3 | 124.4 |

(a) Specimen failed in grips.

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Figure 16. There appears to be little effect of exposure at test temperatures of -110 and 75 F, but a significant effect is apparent when testing at 550 F. A 1000-hour exposure leads to a loss in net-section strength at 550 F, whereas a 10,000-hour exposure raises the net-section strength to a level substantially greater than that observed for unexposed specimens. The reason for this marked improvement in net-section strength at 550 F after 10,000 hours exposure to stress at 550 F is not apparent. No difference in Rockwell hardness was discernible at room temperature when comparing exposed with unexposed specimens.

These results, combined with those of the previous investigation, indicate that AM-350 behaves in a ductile fashion at all temperatures and crack lengths studied, and is not adversely affected by long-time exposure to a 1-g stress at 550 F. As was the case for Ti-8Al-1Mo-1V, the AM-350 exhibits ratios of net-section strength to 1-g stress in excess of 4.0.

FATIGUE BEHAVIOR

The stress-lifetime behavior of unnotched and notched ($K_t = 4.0$) AM-350 stainless steel specimens and Ti-8Al-1Mo-1V alloy specimens were evaluated. The behavior of the two materials at -110 F, room temperature, and 550 F and at their respective 1-g mean stresses of 40 ksi and 25 ksi is summarized in Reference (1). The current program has been concerned with the base fatigue strength of the steel alloy at room temperature and 550 F and at mean stresses of zero, 20, and 100 ksi and for the titanium alloy at the same temperatures and mean stresses of zero and 60 ksi. These data have permitted stress-range diagrams for room temperature and 550 F to be constructed. In addition, the effect of notched-specimen orientation at room temperature has been explored. The effects of prior stressed exposure on notched specimens were investigated for exposure times of 10,500 hours at 40 ksi and 550 F for AM-350 and 10,000 hours at 25 ksi and 550 F for Ti-8Al-1Mo-1V. The tabular stress-lifetime data are given in Appendix C.

^{SS, Ti}
S-N curves that illustrate the base fatigue behavior of the two alloys at room temperature and at 550 F are shown in Figures 17 through 25. With these figures and appropriate ones from Reference (1), the stress-range diagrams of Figures 26 through 29 have been constructed. These figures show that the unnotched fatigue behavior of the two materials generally decreased with an increase in temperature. The notched behavior of both materials as shown in the next section seems consistent with experience on high-strength aluminum alloys used extensively in aircraft in the past 30 years. The AM-350 steel with higher static strength also shows higher fatigue strengths.

Figures 30 and 31 illustrate the results of the limited study of notched-specimen orientation. The evaluation was made at room temperature and for each material at the appropriate 1-g mean stress. From the figures it is seen that orientation of the specimen does not influence the behavior in fatigue of the two materials.

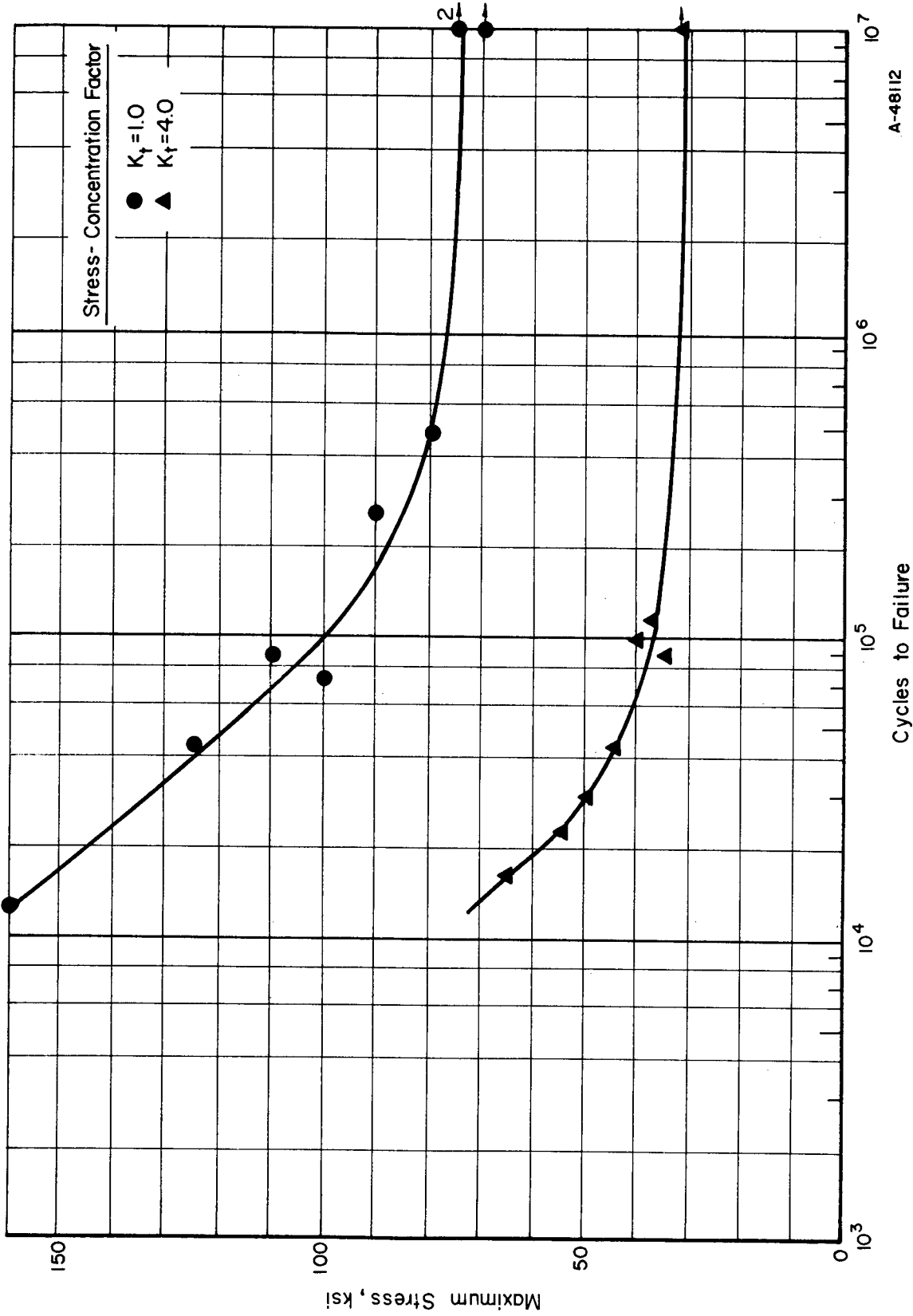


FIGURE 17. FATIGUE BEHAVIOR OF UNEXPOSED LONGITUDINAL AM-350 STAINLESS STEEL SPECIMENS AT ROOM TEMPERATURE AND ZERO MEAN STRESS

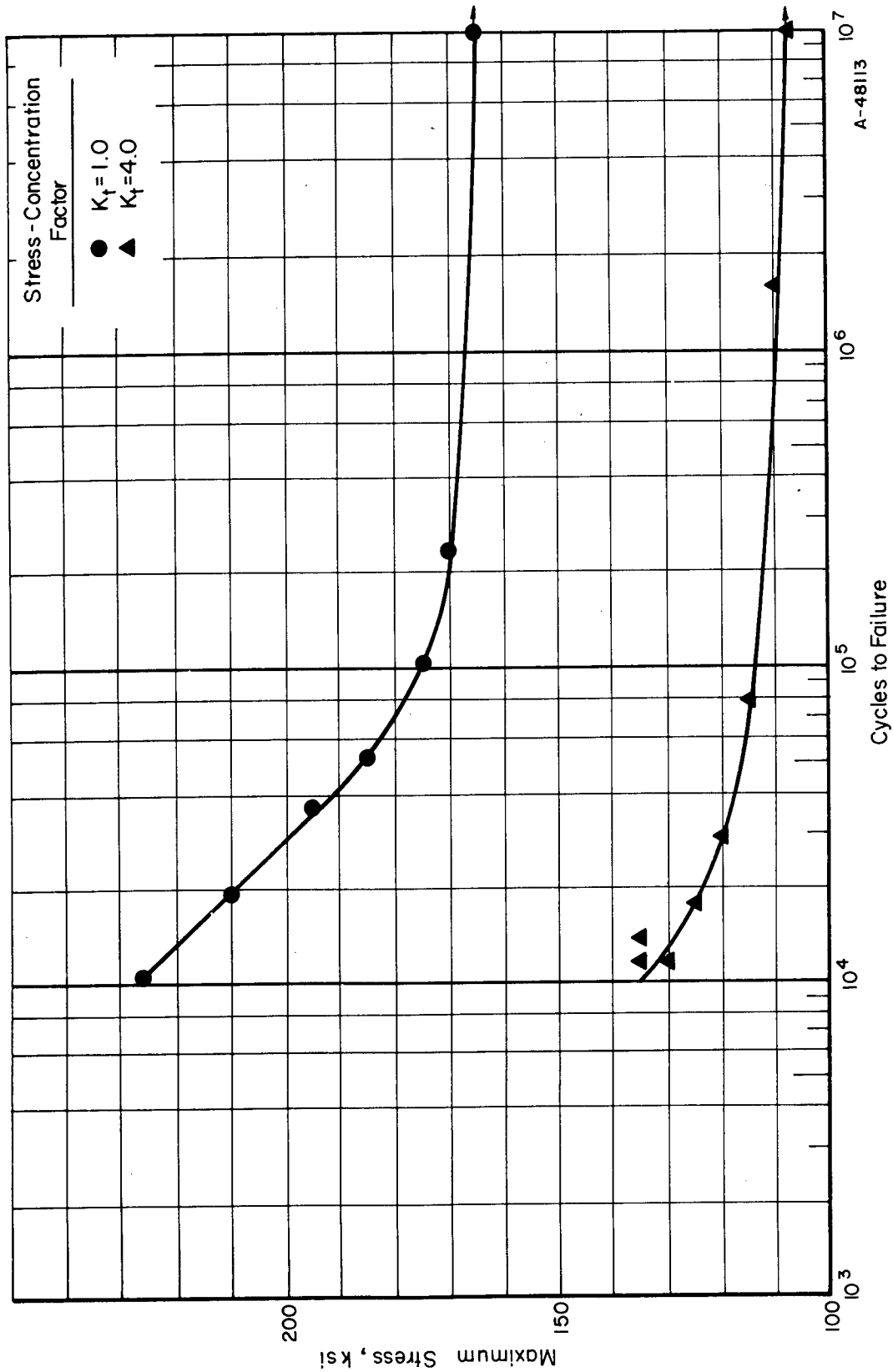


FIGURE 18. FATIGUE BEHAVIOR OF UNEXPOSED LONGITUDINAL AM-350 STAINLESS STEEL SPECIMENS AT ROOM TEMPERATURE AND 100-KSI MEAN STRESS

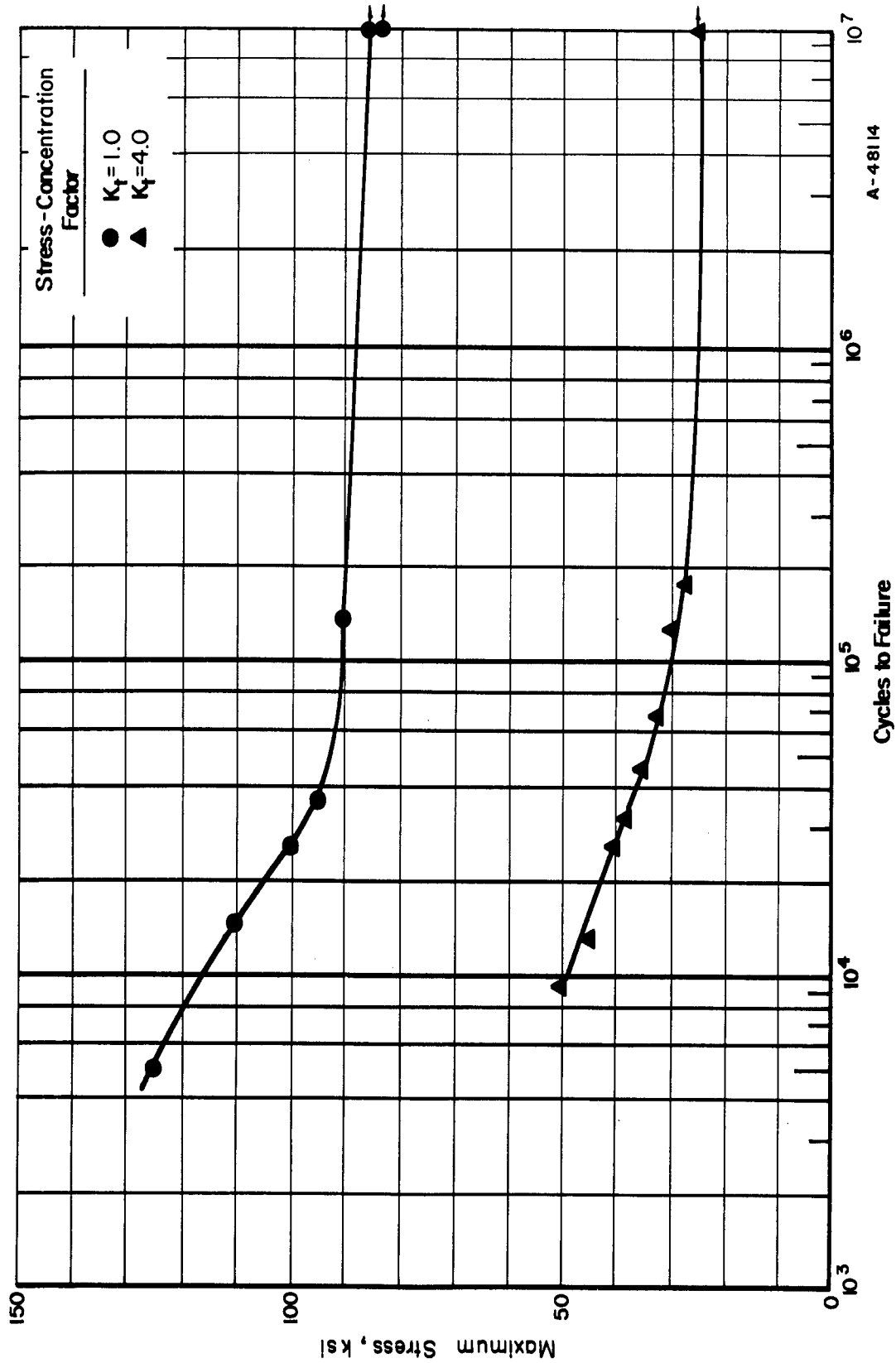


FIGURE 19. FATIGUE BEHAVIOR OF UNEXPOSED LONGITUDINAL AM-350 STAINLESS STEEL SPECIMENS AT 550 F AND ZERO MEAN STRESS

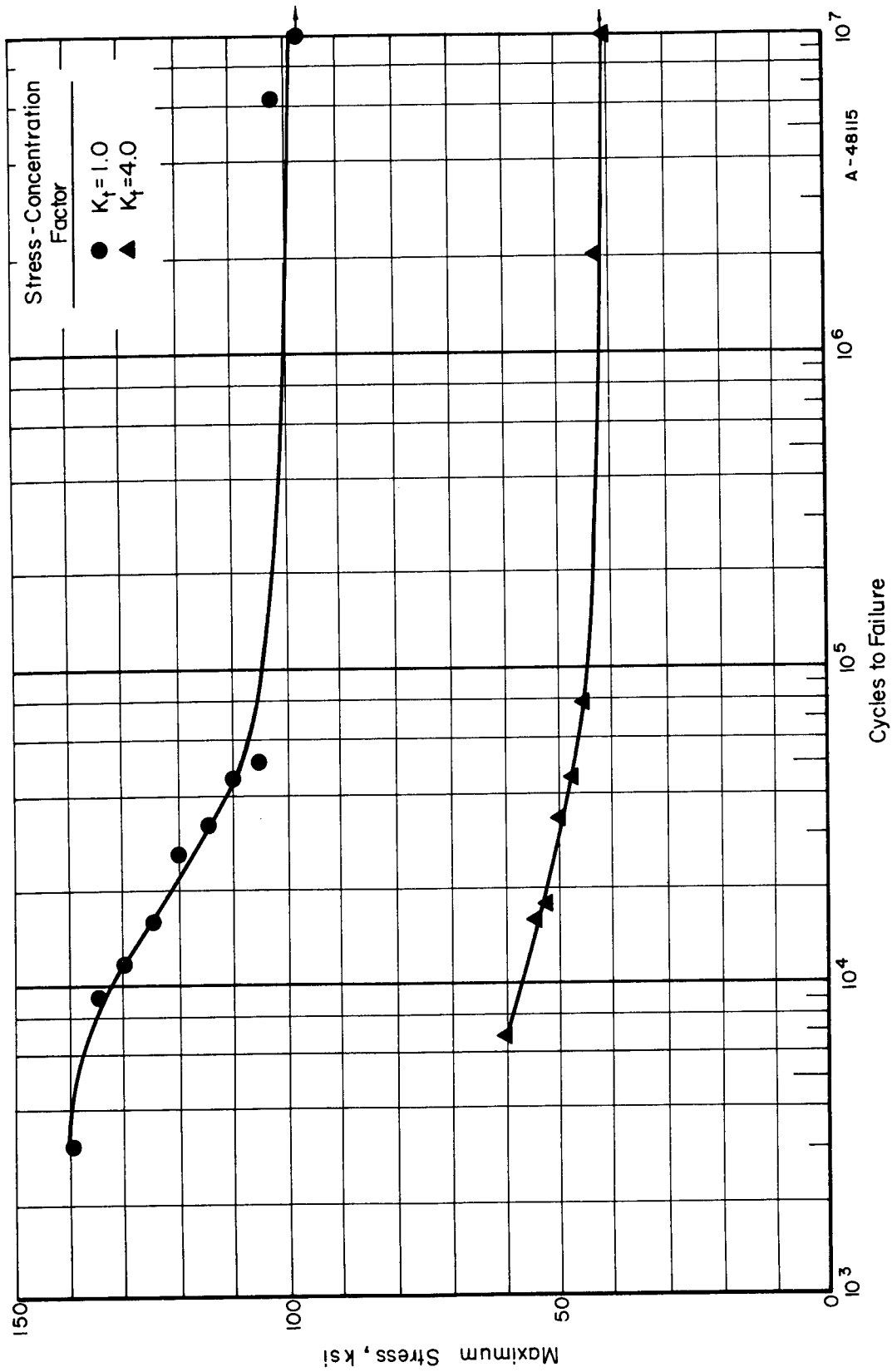


FIGURE 20. FATIGUE BEHAVIOR OF UNEXPOSED LONGITUDINAL AM-350 STAINLESS STEEL SPECIMENS AT 550 F AND 20-KSI MEAN STRESS

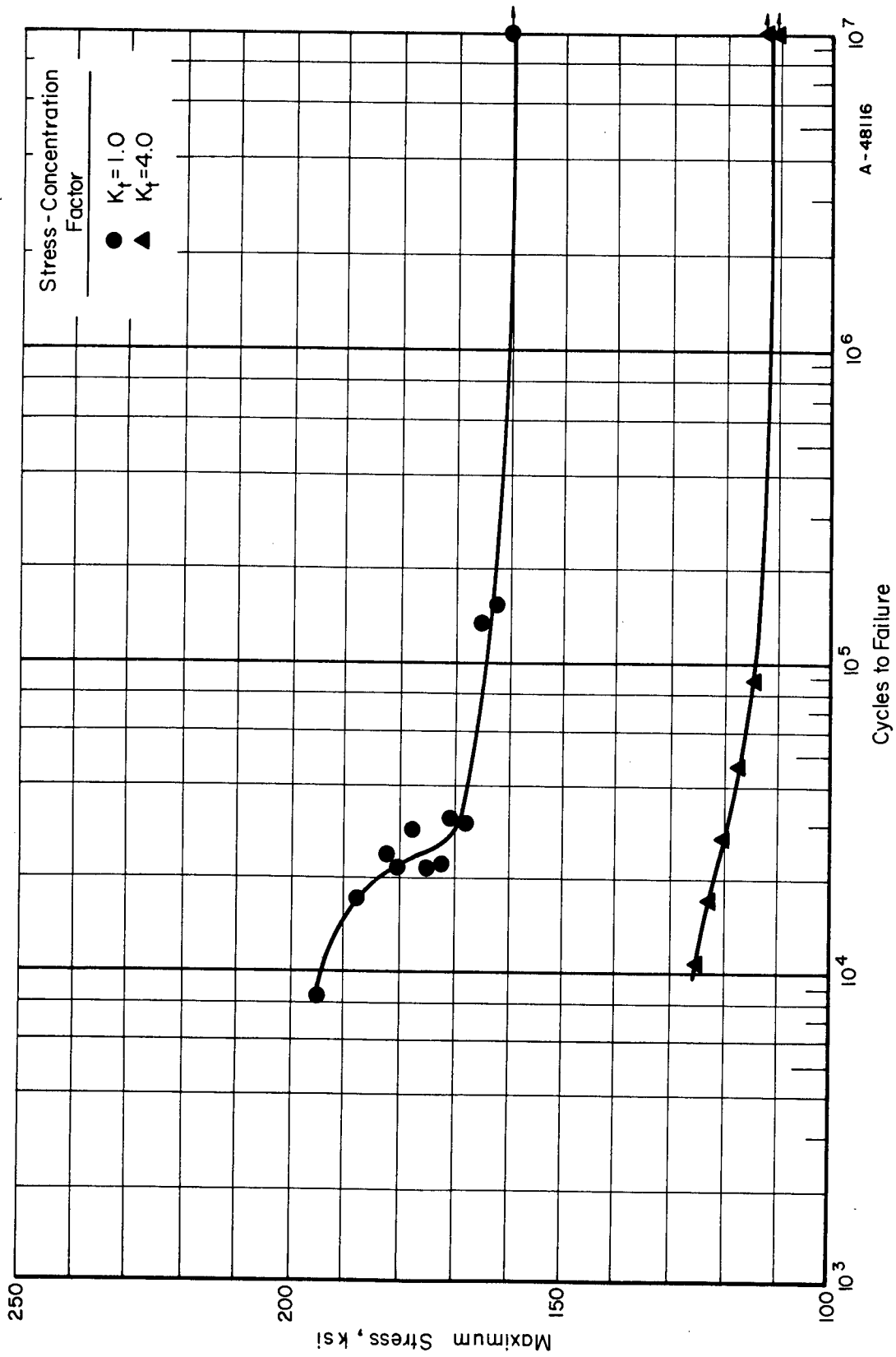


FIGURE 21. FATIGUE BEHAVIOR OF UNEXPOSED LONGITUDINAL AM-350 STAINLESS STEEL SPECIMENS AT 550 F AND 100-KSI MEAN STRESS

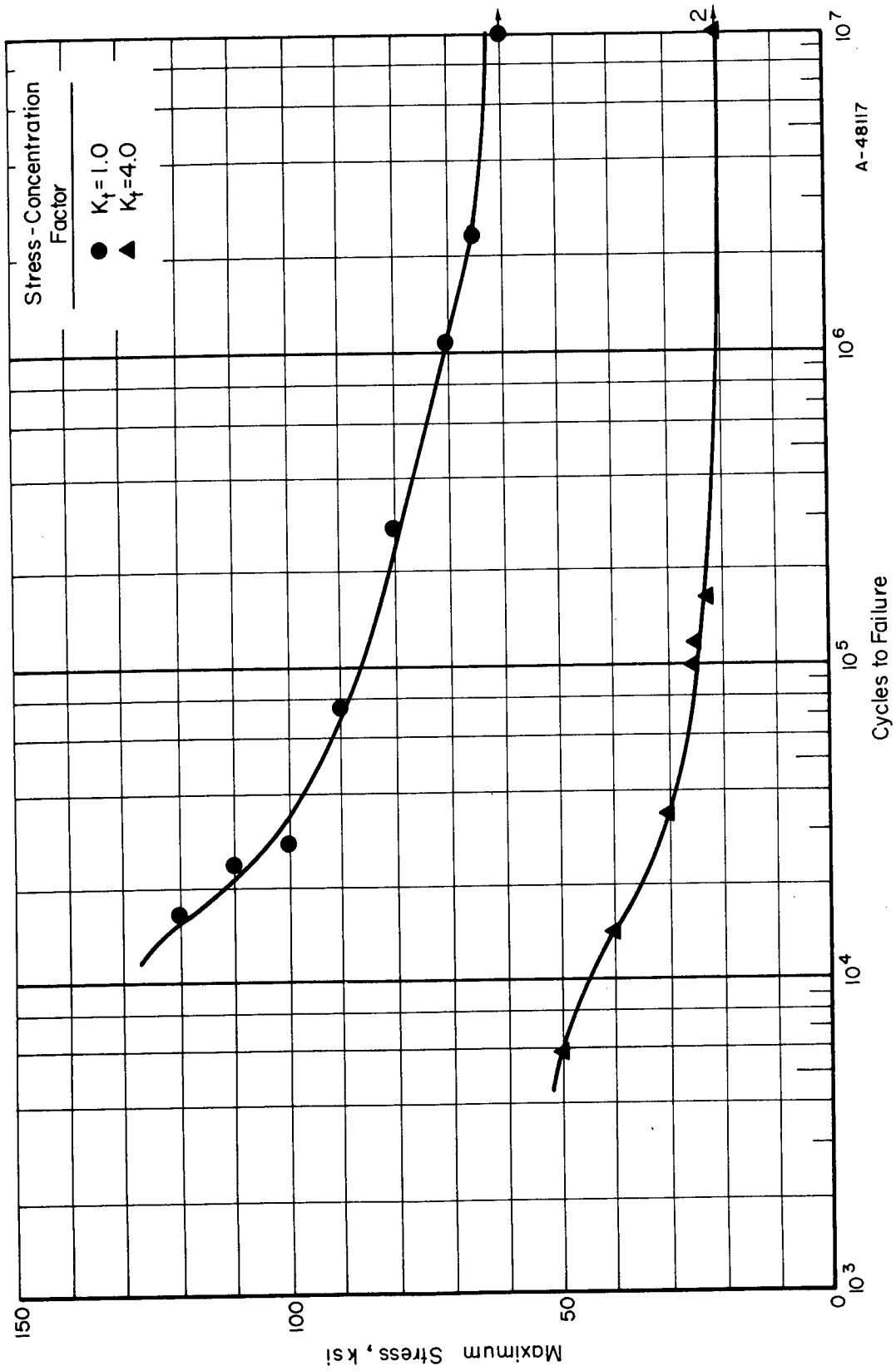


FIGURE 22. FATIGUE BEHAVIOR OF UNEXPOSED LONGITUDINAL Ti-8Al-1Mo-IV ALLOY SPECIMENS AT ROOM TEMPERATURE AND ZERO MEAN STRESS

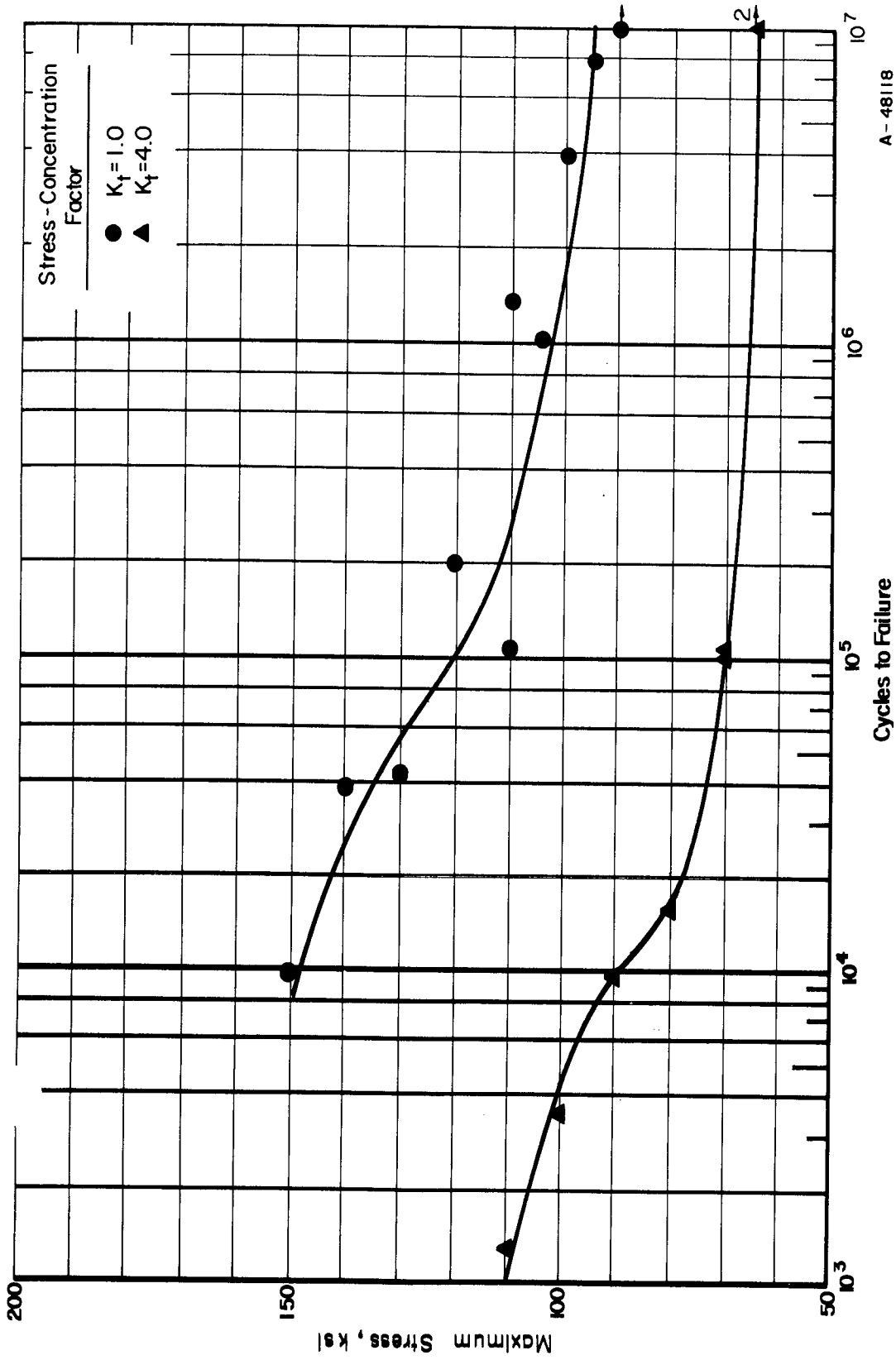
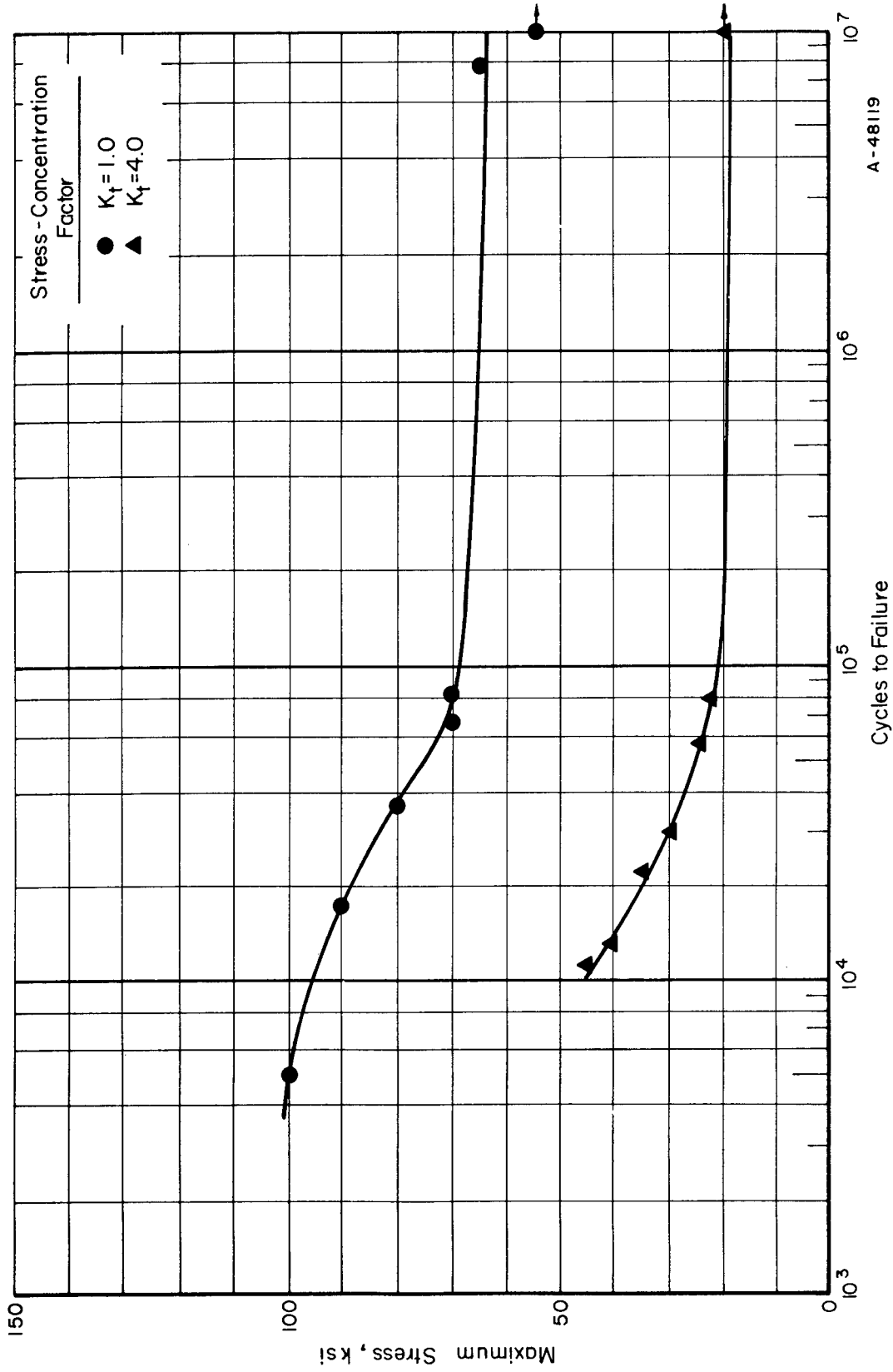


FIGURE 23. FATIGUE BEHAVIOR OF UNEXPOSED LONGITUDINAL, Ti-8Al-1Mo-1V ALLOY SPECIMENS AT ROOM TEMPERATURE AND 60-KSI MEAN STRESS



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FIGURE 24. FATIGUE BEHAVIOR OF UNEXPOSED LONGITUDINAL Ti-8Al-1Mo-IV ALLOY SPECIMENS AT 550 F AND ZERO MEAN STRESS

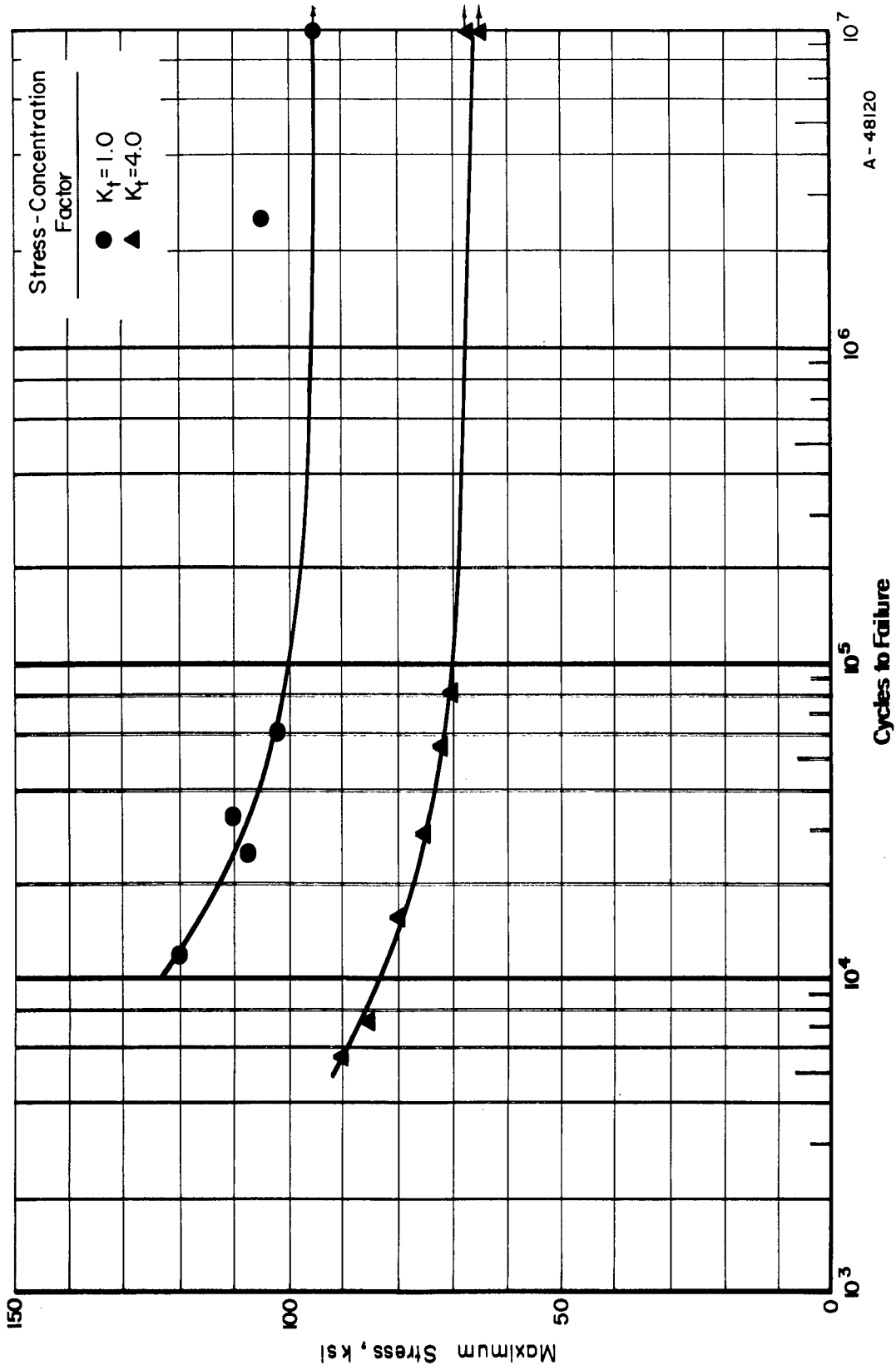


FIGURE 25. FATIGUE BEHAVIOR OF UNEXPOSED LONGITUDINAL Ti-8Al-1Mo-1V ALLOY SPECIMENS AT 550 F AND 60-KSI MEAN STRESS

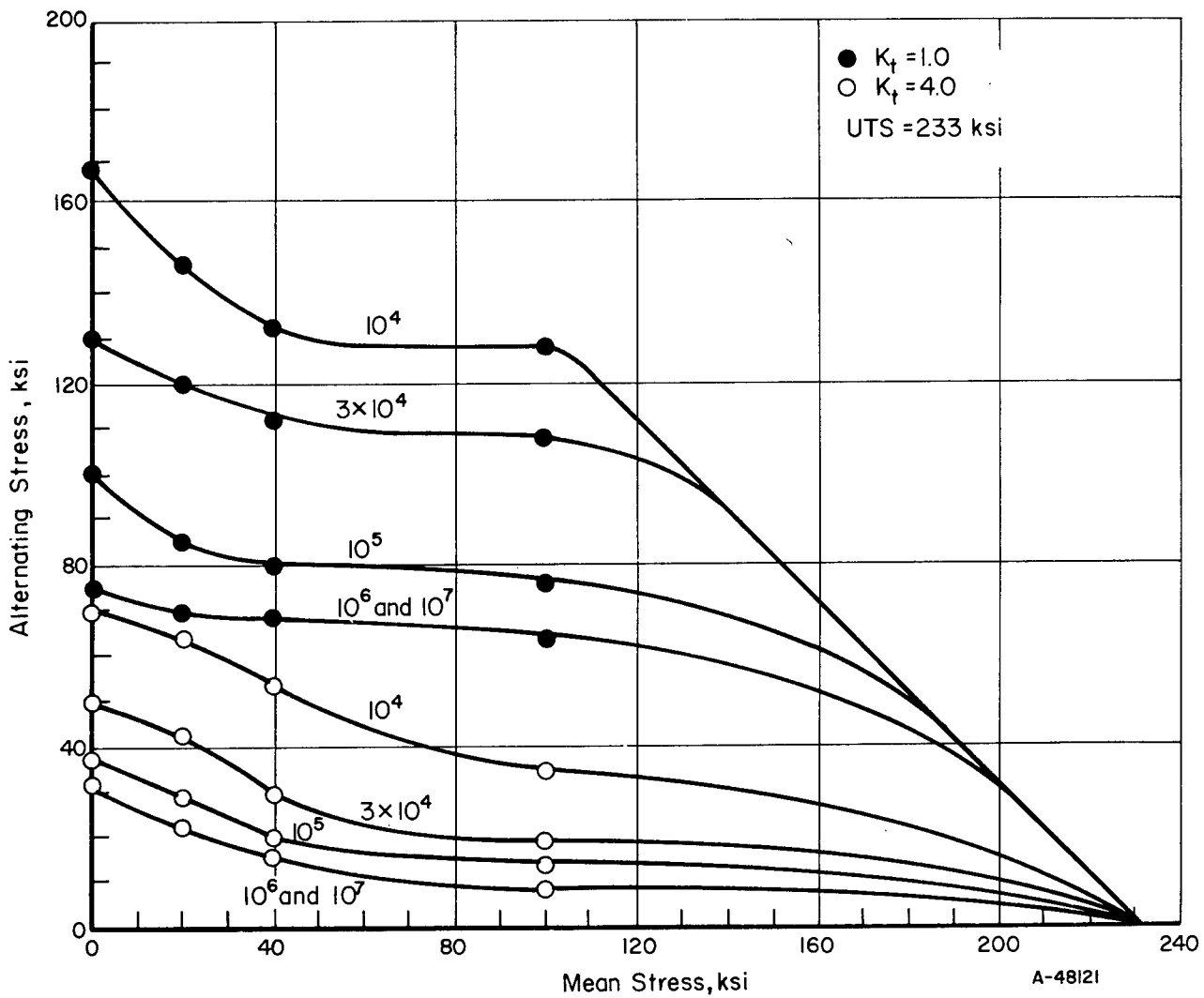


FIGURE 26. STRESS-RANGE DIAGRAM FOR AM-350 STAINLESS STEEL AT ROOM TEMPERATURE



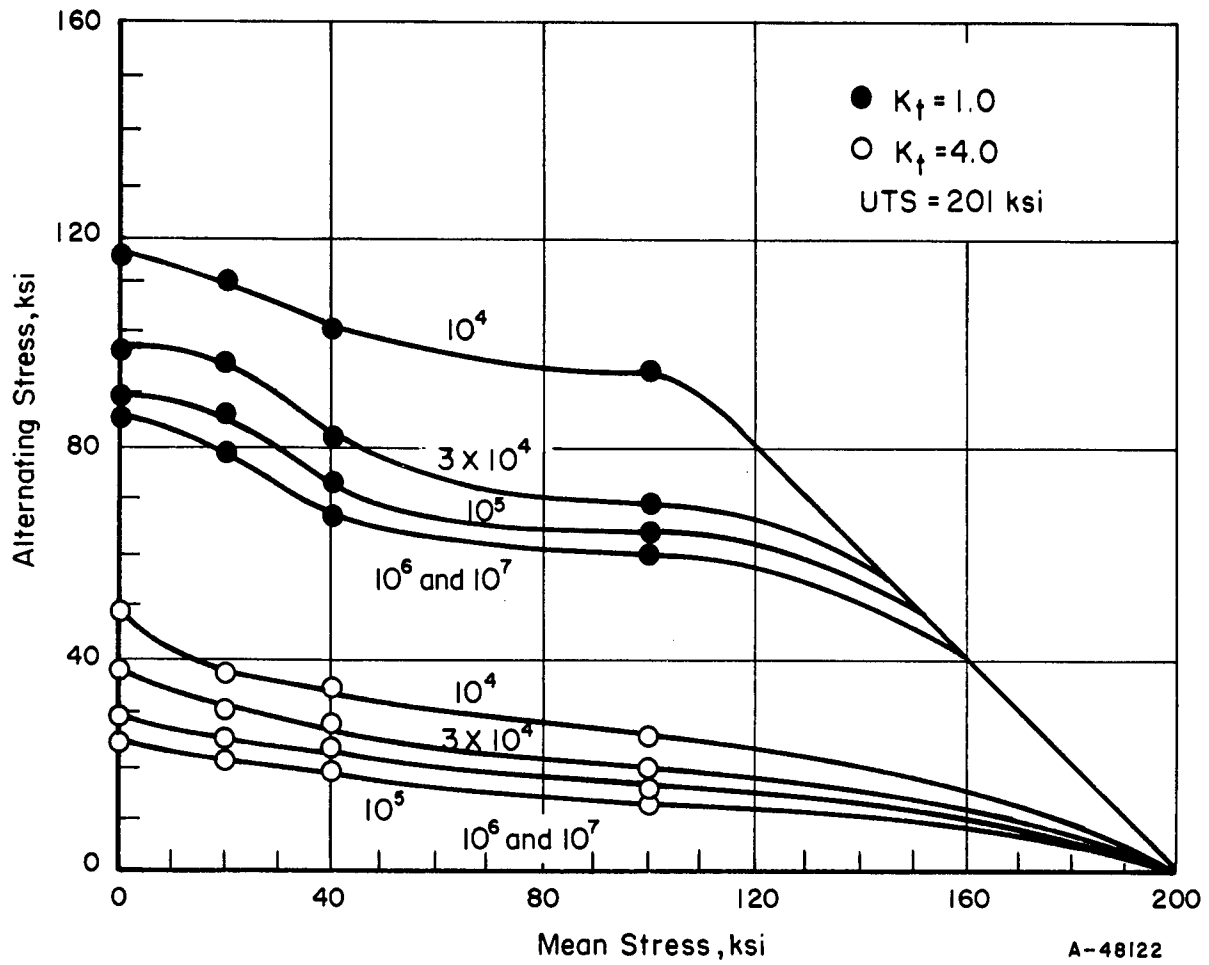


FIGURE 27. STRESS-RANGE DIAGRAM FOR AM-350 STAINLESS STEEL AT 550 F

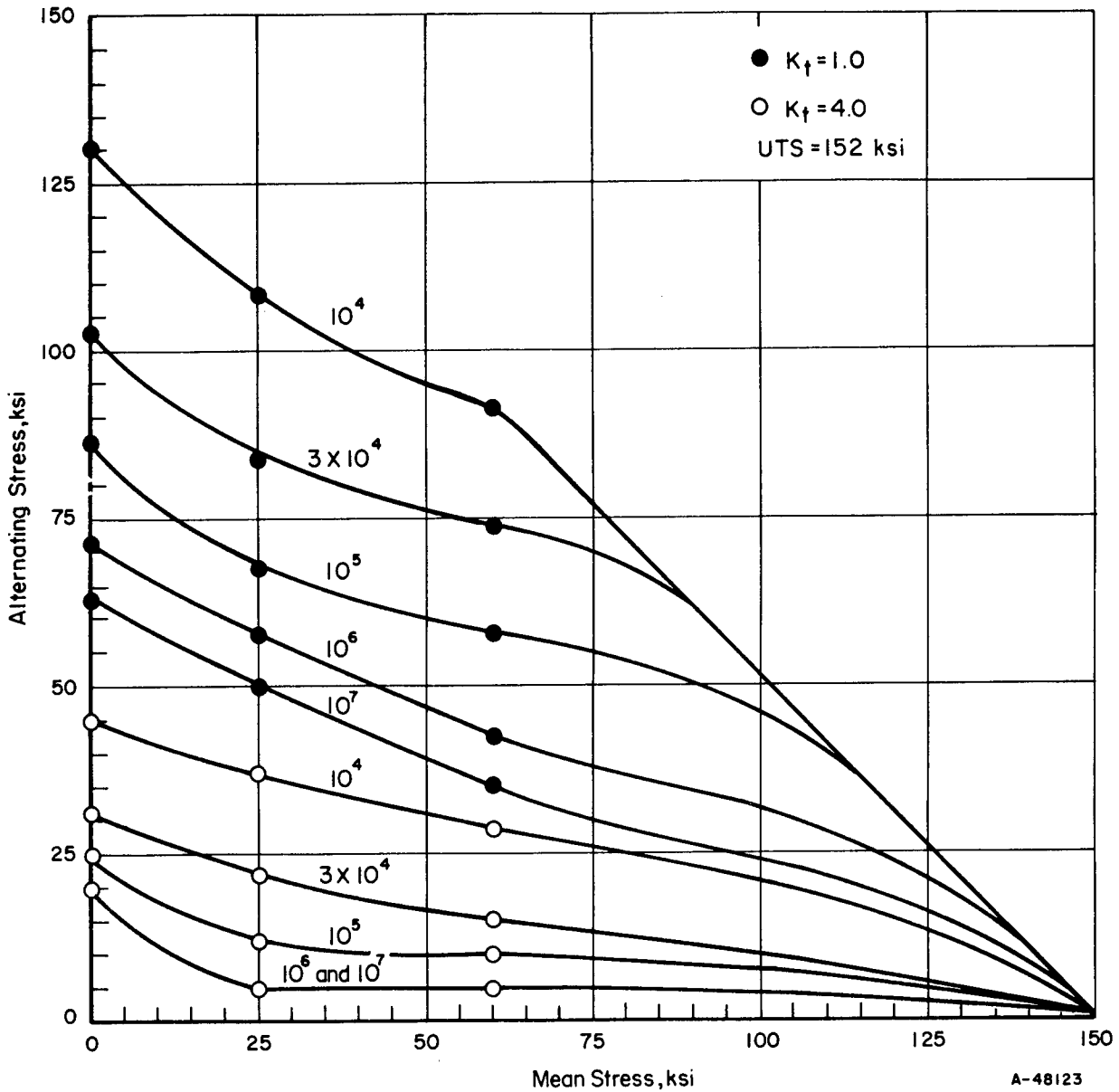


FIGURE 28. STRESS-RANGE DIAGRAM FOR Ti-8Al-1Mo-1V ALLOY AT ROOM TEMPERATURE

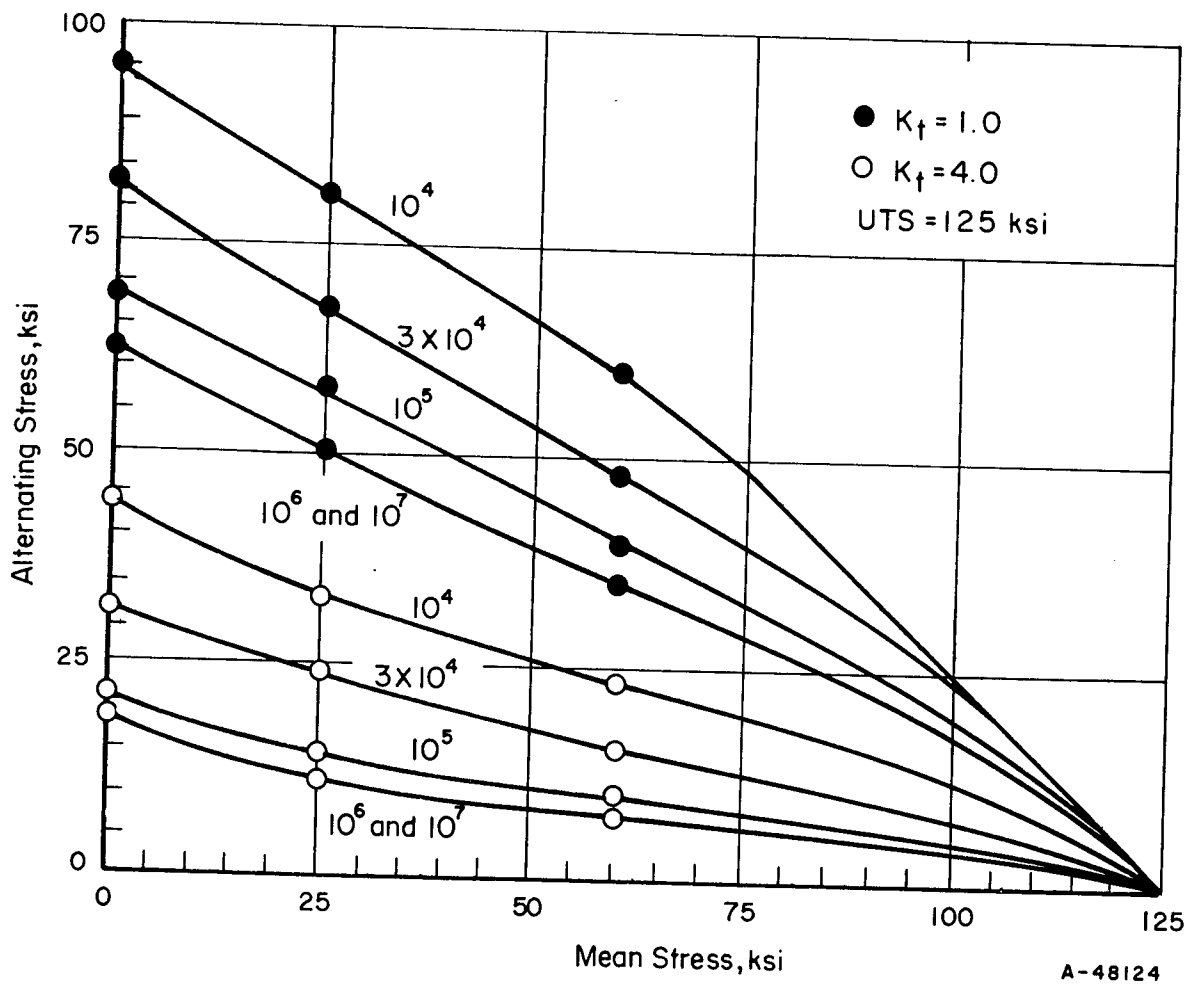


FIGURE 29. STRESS-RANGE DIAGRAM FOR Ti-8Al-1Mo-1V ALLOY AT 550 F

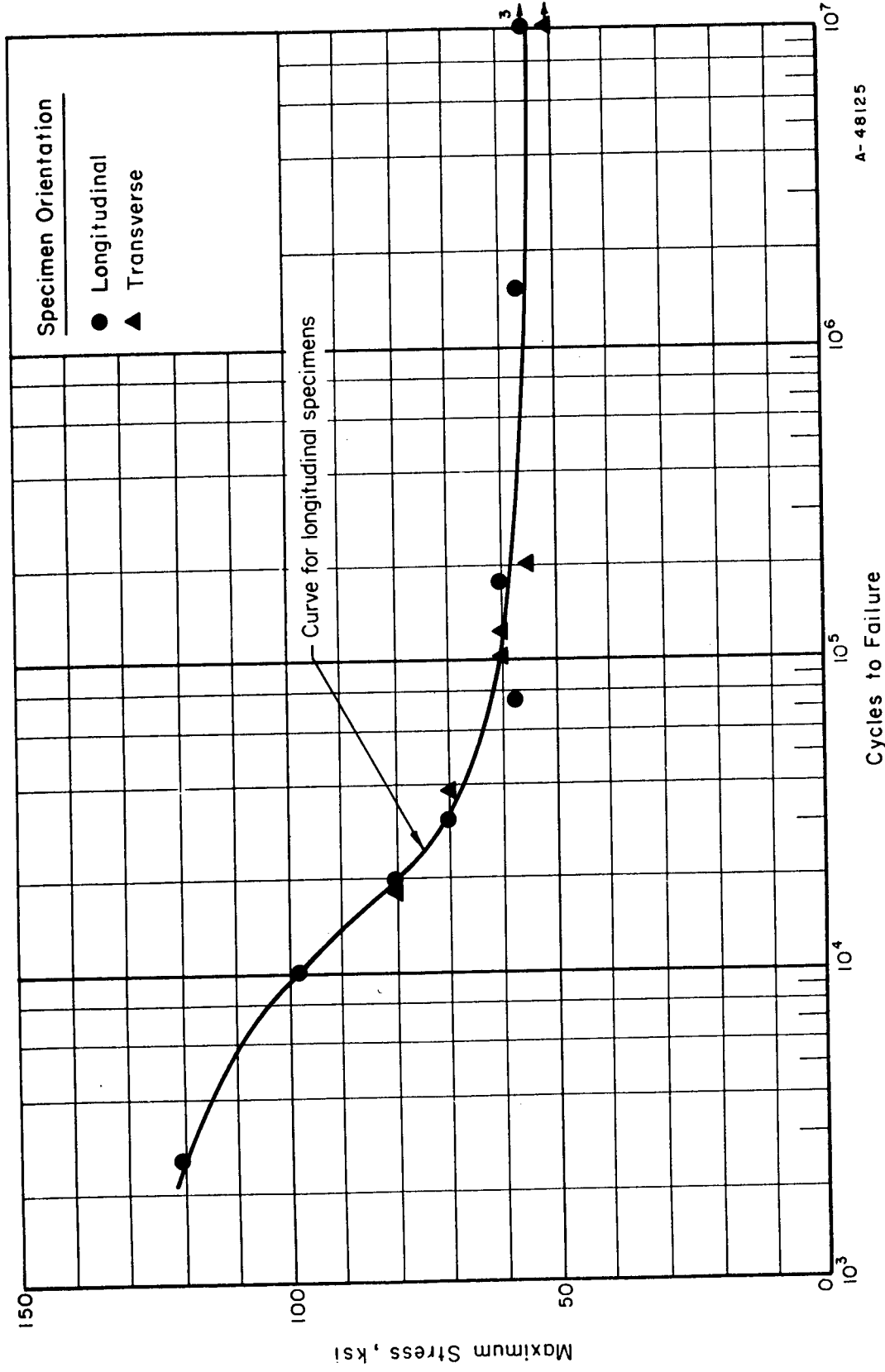
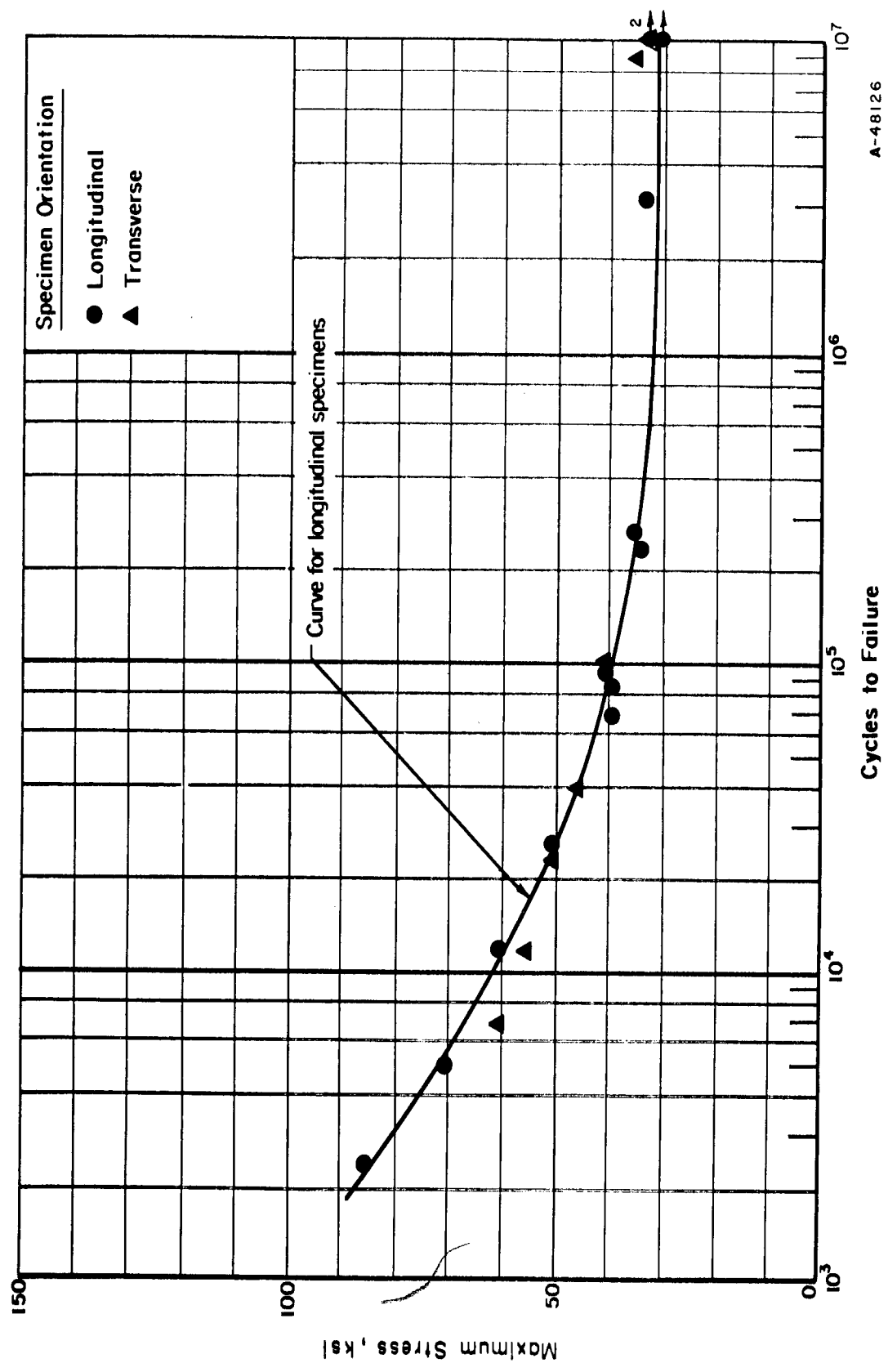


FIGURE 30. EFFECT OF SPECIMEN ORIENTATION ON FATIGUE BEHAVIOR OF UNEXPLODED NOTCHED ($K_t = 4.0$) AM-350 STAINLESS STEEL AT ROOM TEMPERATURE AND 40-KSI MEAN STRESS



A-48126

FIGURE 31. EFFECT OF SPECIMEN ORIENTATION ON FATIGUE BEHAVIOR OF UNEXPOSED NOTCHED ($K_t = 4.0$) Ti-8Al-1Mo-1V ALLOY AT ROOM TEMPERATURE AND 25-KSI MEAN STRESS

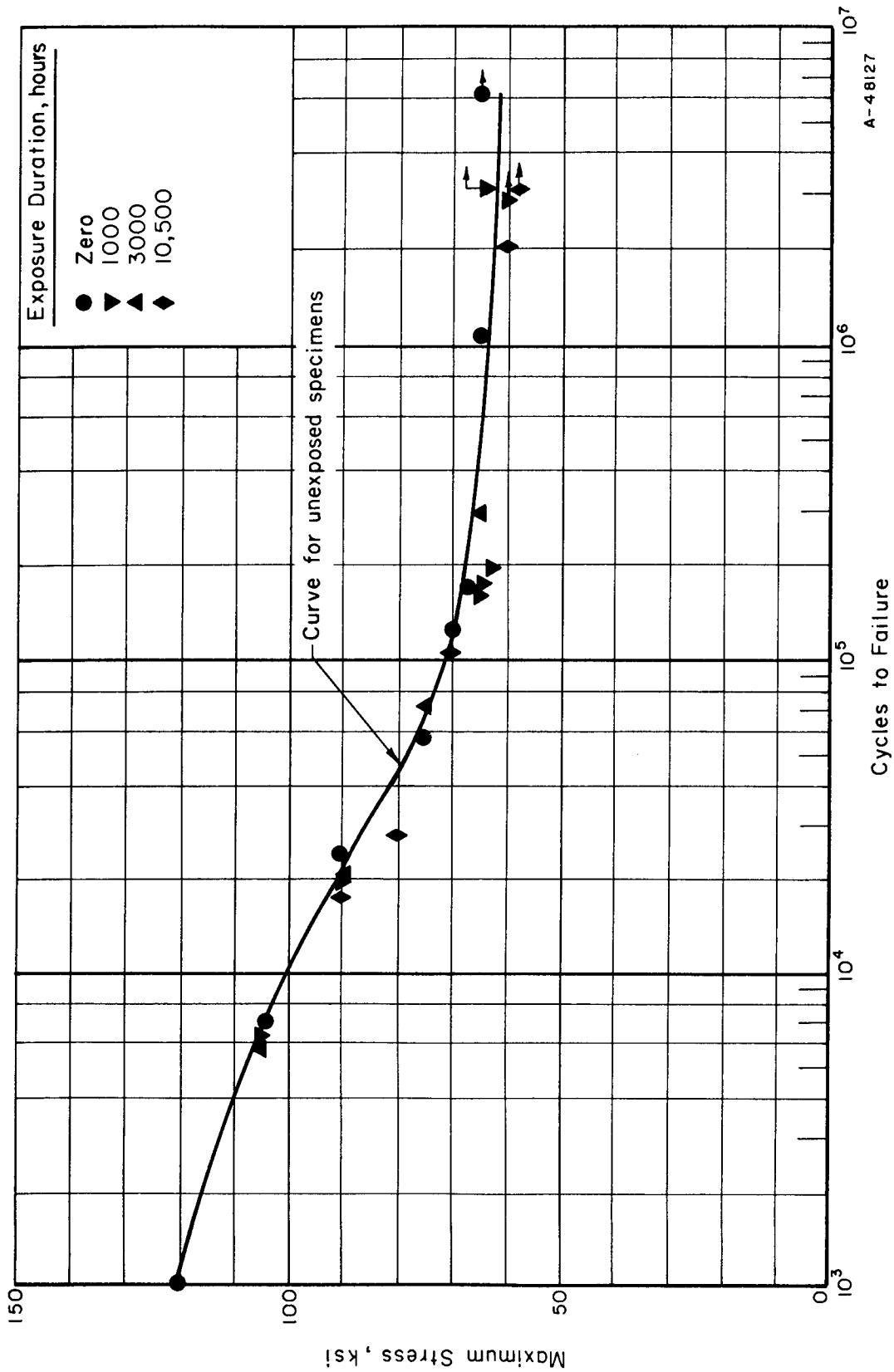


FIGURE 32. EFFECT OF STRESSED EXPOSURE ON FATIGUE BEHAVIOR OF NOTCHED (K_t = 4.0) AM-350 STAINLESS STEEL AT -110 F AND 40-KSI MEAN STRESS

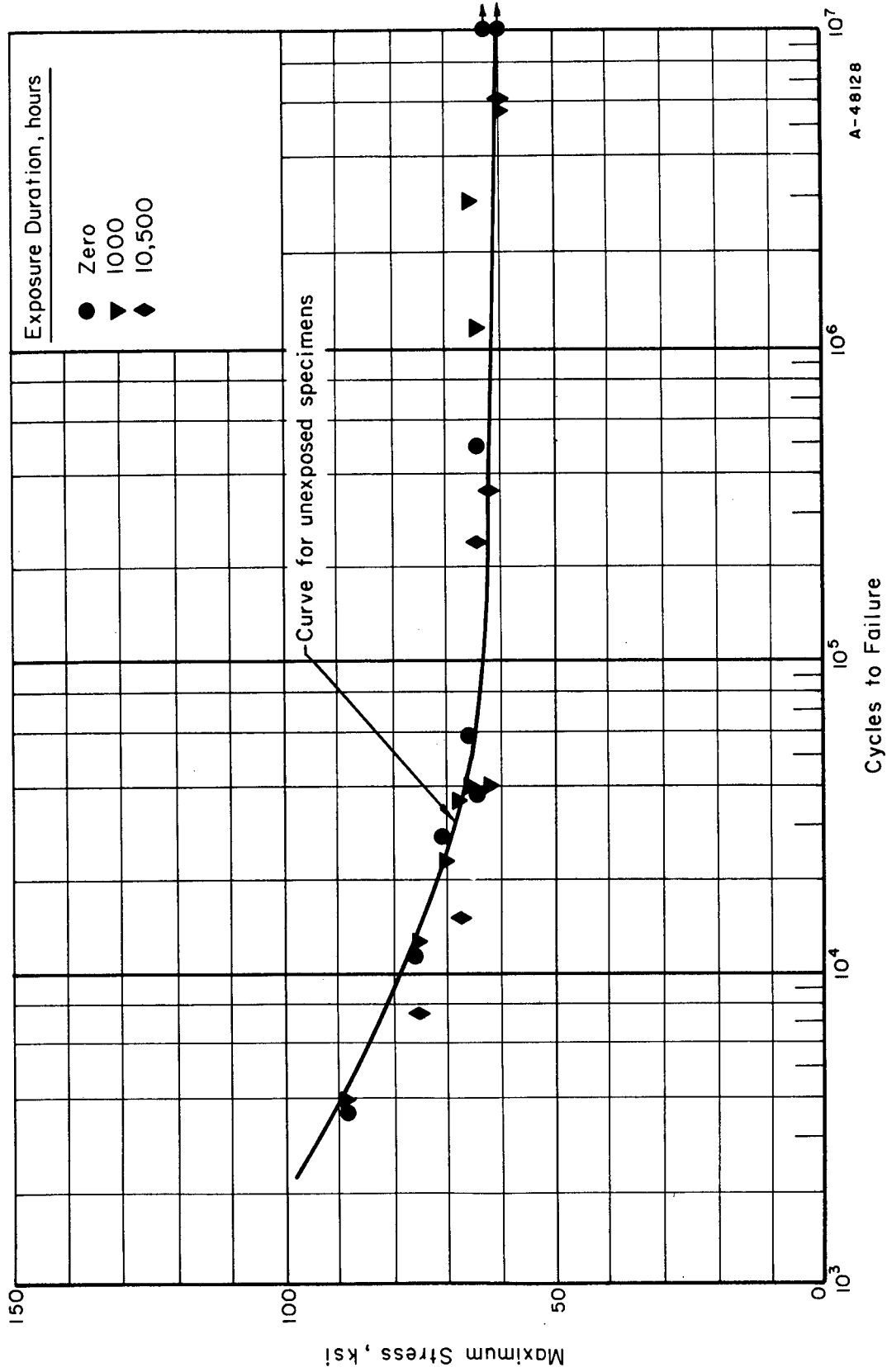


FIGURE 33. EFFECT OF STRESSED EXPOSURE ON FATIGUE BEHAVIOR OF NOTCHED (K_t = 4.0) AM-350 STAINLESS STEEL AT 550 F AND 40-KSI MEAN STRESS

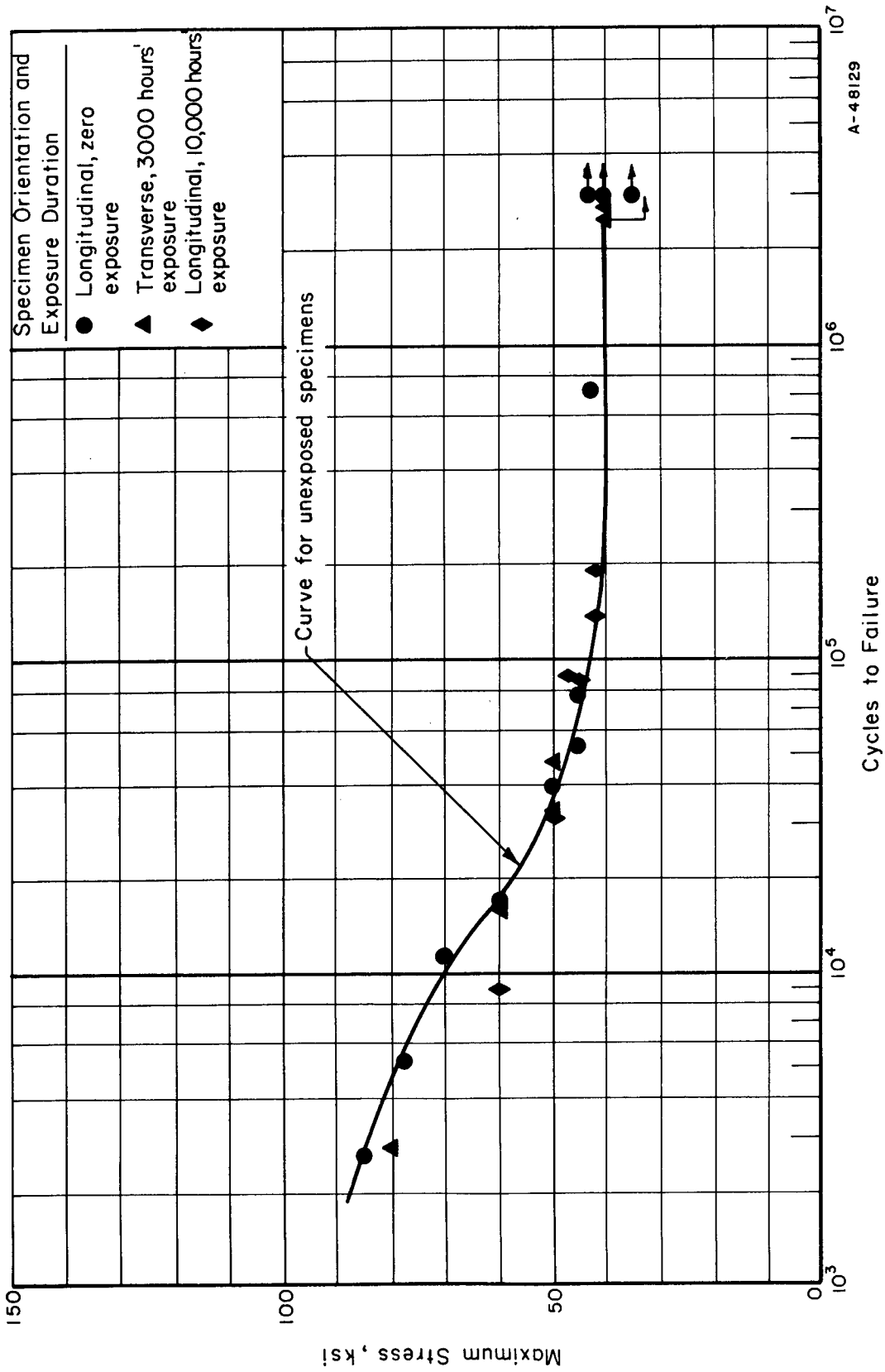
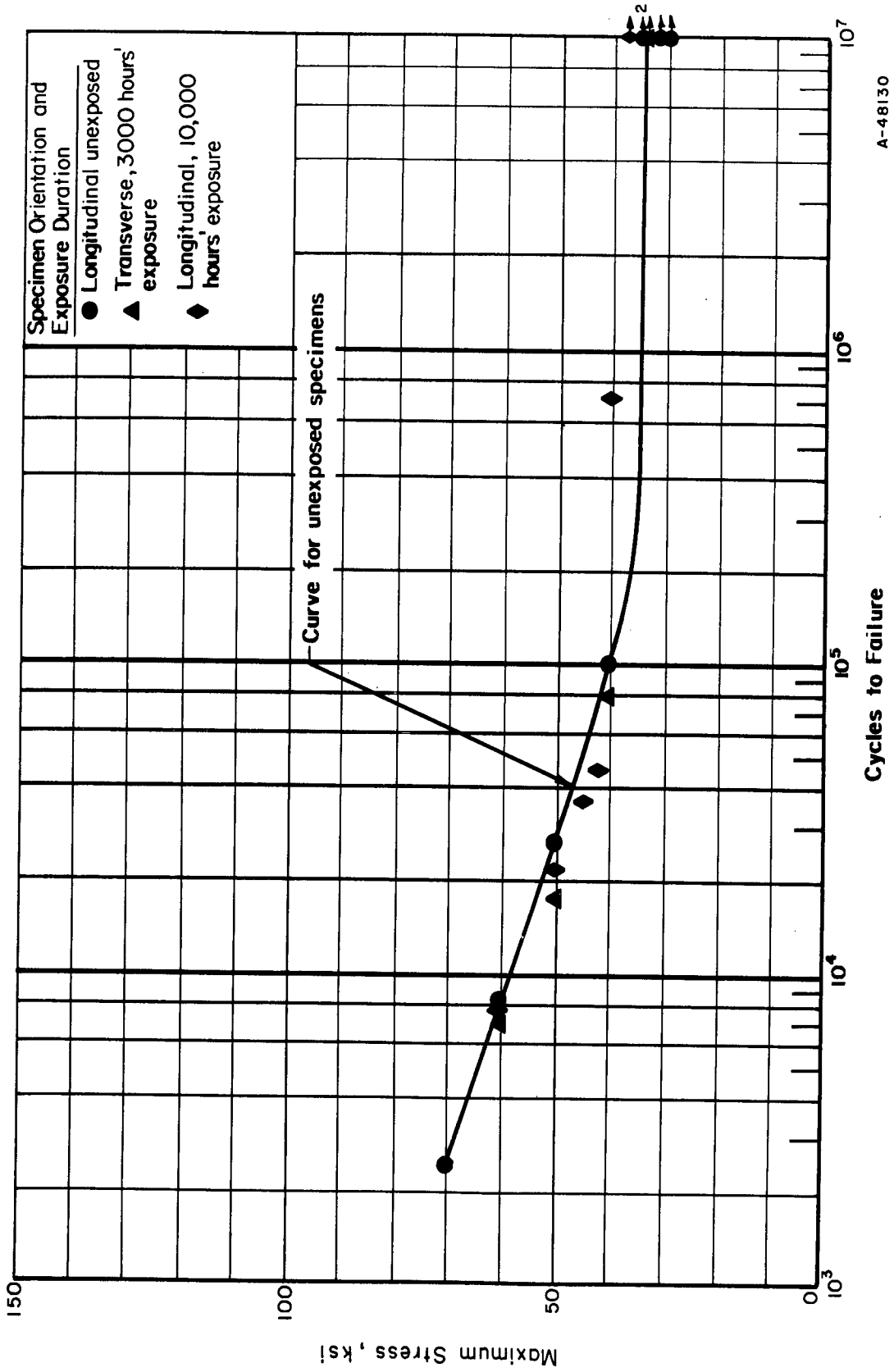


FIGURE 34. EFFECT OF STRESSED EXPOSURE ON FATIGUE BEHAVIOR OF NOTCHED ($K_t = 4.0$) Ti-8Al-1Mo-1V ALLOY AT -110 F AND 25-KSI MEAN STRESS



A-48130

FIGURE 35. EFFECT OF STRESSED EXPOSURE ON FATIGUE BEHAVIOR OF NOTCHED ($K_t = 4.0$) Ti-8Al-1Mo-1V ALLOY AT 550 F AND 25-KSI MEAN STRESS

The manner in which prior stressed exposure affected the fatigue strength of the two alloys in question is shown by the data plotted on Figures 32 through 35. Figures 32 and 33 illustrate all of the data obtained on AM-350 CRT alloy. Involved are exposure times of 0 hours, 1000 and 3000 hours from Reference (1), and 10,500 hours. From the two figures it is seen that there is no influence of prior stressed exposure, to lifetimes of 10,500 hours, on fatigue strength.

Figures 34 and 35 show for the titanium alloy that prior stressed exposure also does not influence fatigue strength for lifetimes up to 10,000 hours.

Since the exposure temperature is higher than the expected service temperatures for skin surfaces other than leading edges, it would appear that metallurgical instability is not a problem for the two alloys, at least up to about 10,000 hours.

DISCUSSION AND CONCLUDING REMARKS

This program has been concerned with a study of the fatigue behavior of two materials under consideration as skin materials for the supersonic transport: AM-350 CRT and triplex-annealed Ti-8Al-1Mo-1V alloy. The intended operating environment of this aircraft raises questions, concerned with structural material behavior, not encountered in the past in relation to subsonic flight. One of these is concerned with the problem of moderate-temperature exposure. The problem is that of metallurgical instability of the two materials for the operating life of 30,000 to 40,000 hours. Another is also stimulated by temperature. This relates to the fact that operating conditions include subzero temperatures in addition to the moderate-temperature regime.

It is for this reason that this program (consisting of 2 year's research) has included examination of the effect of temperature on fatigue behavior over the range from -110 F to 550 F. This range is somewhat broader than the expected service temperature range.

A number of aspects are of interest in relation to fatigue of the skin and structural materials. In this program three were considered: (1) crack propagation, (2) remaining static strength, and (3) the base fatigue behavior. All of the testing was carried out on small laboratory specimens, so that the data in certain cases are indicative of what may be expected of the materials; however, judgment has to be exercised in translating the information to large scale structure.

In this concluding section, information obtained during the past 2 years is reviewed briefly and discussed in terms of prior experience. Conclusions are drawn when warranted in each subsection.

Crack Propagation

The factors that were considered important to examine in regard to its effect on crack propagation were as follows:



- (1) Alternating stress amplitude
- (2) Crack length
- (3) Specimen orientation
- (4) Stress-cycle rate
- (5) Temperature
- (6) Prior stressed exposure.

Mean stress also is a variable that is known to affect crack propagation. In this program, however, one mean stress was used for each material.

From the experimental program, the following conclusions appear warranted in regard to crack propagation:

- (1) The alternating stress component and the crack length strongly influenced the rate of crack propagation. Where direct comparison was possible, the rate of crack propagation of the stainless steel frequently was slightly higher than that of the titanium alloy at the same relative alternating stress level (θ) and crack length.
- (2) Specimen orientation with rolling direction was a slight influence on crack propagation. For the titanium alloy, longitudinal specimens had higher propagation rates than did transverse specimens.
- (3) Cyclic rate had an effect on the crack-propagation behavior of the titanium alloy. Crack-propagation rate increased with decreasing cyclic rate. This effect was more noticeable at high alternating stress and with long cracks. It was not clear whether there was a frequency effect for the stainless steel.
- (4) Temperature at which the fatigue crack is propagated was found to be important. For the titanium alloy, crack-growth rates increased with decreasing temperature. However, for the steel alloy, crack-growth rates decreased with decreasing temperature.
- (5) Exposure to steady stress and to a temperature of 550 F for 10,000 hours prior to crack propagation did not influence the rate of crack propagation of AM-350 alloy. Exposure time of 8,000 hours for the titanium alloy resulted in a slight increase in crack propagation rate.

Residual Static Strength

Once again there were many factors considered important that might influence the residual strength of these materials. Included in this program were the following:

- (1) Crack length
- (2) Specimen orientation with rolling direction

(3) Temperature

(4) Prior exposure

(5) Fatigue conditions to introduce the crack.

Since most of the data for AM-350 alloy were presented in Reference (1), Figures 36 and 37 contain a summary of all pertinent data. Note that in these figures residual static strength is expressed as a ratio of the gross-area stress to the ultimate strength of the material.

A number of conclusions can be stated based upon the program results:

- (1) For both materials, the residual static strength was strongly affected by crack length at all temperatures. The fact that all specimens failed at net stress values at or above the yield strength indicates that both materials were relatively tough. AM-350 steel was slightly stronger than the titanium alloy at room temperature.
- (2) Specimen orientation with rolling direction had an influence on residual static strength. Transverse specimens of AM-350 alloy had much lower strength than did longitudinal specimens. Ti-8Al-1Mo-1V alloy exhibited essentially no effect of orientation on residual strength based upon σ_G/σ_u as shown in Figure 37. However, since σ_u in the transverse direction was less than that in the longitudinal direction, there was actually a small reduction in static strength of transverse specimens compared with longitudinal specimens.
- (3) Temperature of test also had an important influence on remaining strength. For AM-350 either the high or the low temperature reduced strength, whereas, with the titanium alloy only the low temperature reduced strength.
- (4) Prior exposure at 550 F to a static stress of 40 ksi for 10,000 hours for the steel and of 25 ksi for 8,000 hours for the titanium alloy did not produce a large change in residual strength, in general, for either material. The results for AM-350 alloy were not consistent, suggesting no certain effect of exposure. Those for titanium showed a slight reduction in residual strength after exposure.

Among the factors that were examined concerned with fatigue conditions used in growing cracks prior to residual strength testing were stress amplitude, fatigue cracking temperature, and cyclic frequency. The results indicate the following conclusions:

- (5) Stress amplitude, fatigue cracking temperature, and cyclic frequency - all related to fatigue conditions to form the crack - did not influence the residual strength of either material.

Fatigue Behavior

The fatigue strength of the two materials has been evaluated primarily at room temperature and at 550 F. Some study was made at -110 F. Notched and unnotched

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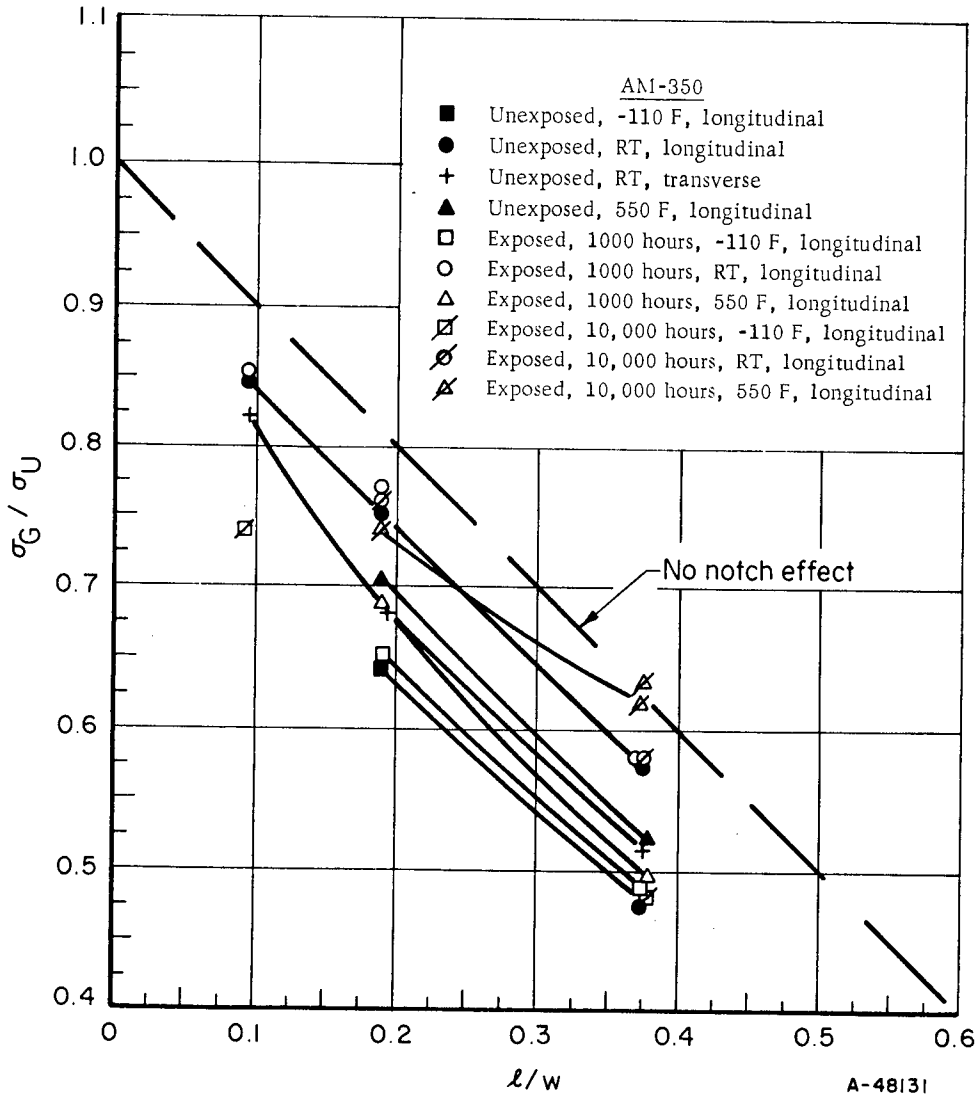


FIGURE 36. EFFECTS OF CRACK LENGTH ON THE RATIO OF RESIDUAL STRENGTH TO ULTIMATE STRENGTH FOR 2-INCH-WIDE AM-350 STAINLESS STEEL SHEET SPECIMENS

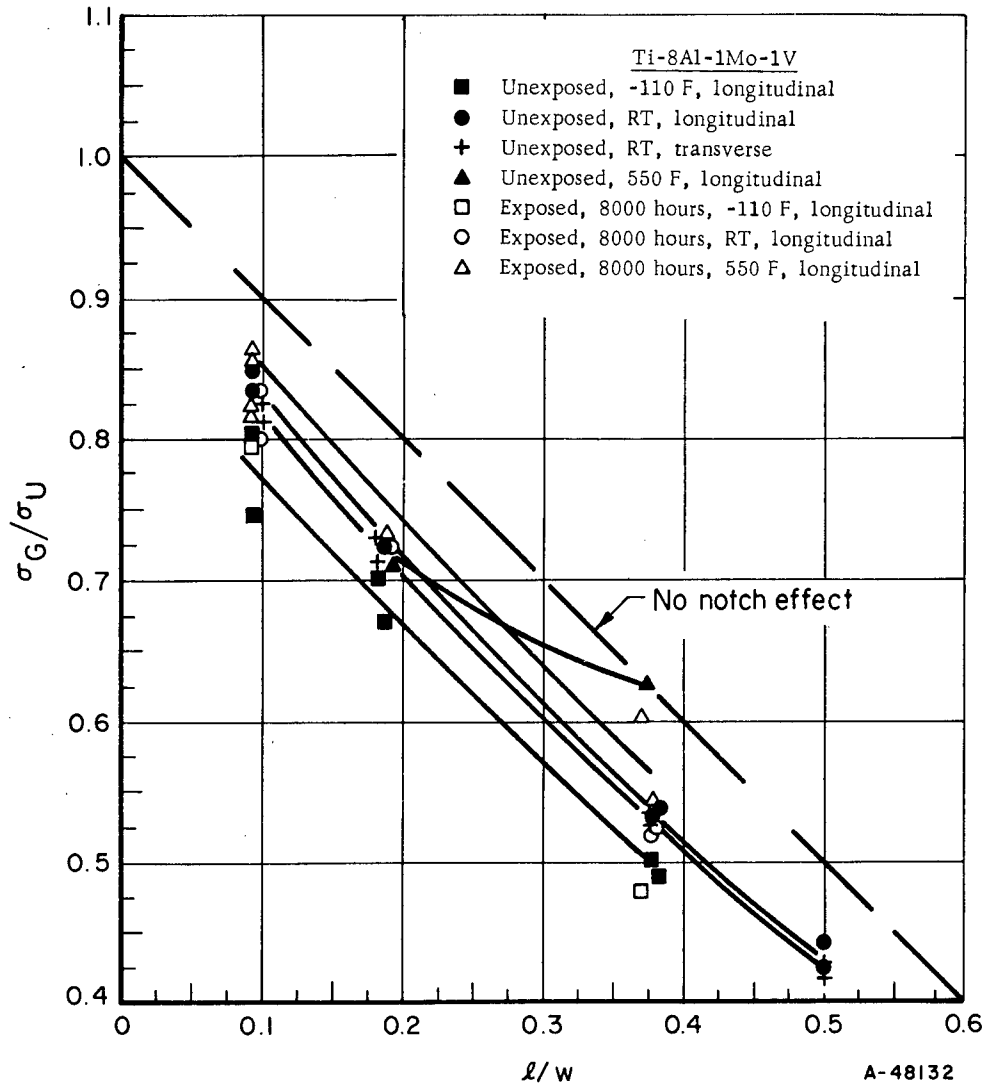



FIGURE 37. EFFECTS OF CRACK LENGTH ON THE RATIO OF RESIDUAL STRENGTH TO ULTIMATE STRENGTH FOR 2-INCH-WIDE Ti-8Al-1Mo-1V ALLOY SHEET SPECIMENS


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specimen behavior was evaluated. A number of comments can be made regarding the data.

- (1) From the stress-range diagrams of Figures 26 to 29, it is seen that both materials behaved in fatigue much like other structural materials.
- (2) AM-350 had higher values of fatigue strength than did the titanium alloy.
- (3) There was no evidence that prior stressed exposure of about 10,000 hours at 550 F influenced fatigue strength of the notched specimens.

A final point concerns notch sensitivity of the two materials. Table 13 has been prepared from the stress-lifetime diagrams for room-temperature conditions. In this table, K_f values are listed for several lifetimes and for two mean-stress conditions. These values were computed on the basis of the ratio of unnotched maximum stress to the notched maximum stress at the same mean stress and lifetime. These values can be compared with similar information listed in Table 13 obtained on two aluminum alloys extensively used in aircraft construction^(2, 17). In this table the mean stress for each aluminum alloy represents approximately the same ratio of mean stress to ultimate strength as existed for the two test materials. It appears from the tabulation that the fatigue strength reduction factors, K_f , for the two materials were comparable to K_f values for 2024-T3 and 7075-T6 aluminum alloys.

On the basis of the investigation it appears that the fatigue behavior of both sheet materials, AM-350 and Ti-8Al-1Mo-1V, are not too different from that of materials currently used in subsonic aircraft. Neither material exhibited a significant tendency toward metallurgical instability as a consequence of about 10,000 hours' exposure at a temperature of 550 F.


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TABLE 13. FATIGUE NOTCH FACTORS AT ROOM TEMPERATURE FOR EDGE-NOTCHED SPECIMENS OF AM-350 AND Ti-8Al-1Mo-1V WITH $K_t = 4.0$

| Lifetime, cycles | K_f | |
|---------------------|---------------------------|---------------------------|
| | AM-350 | Ti-8Al-1Mo-1V |
| | <u>Zero Mean Stress</u> | <u>Zero Mean Stress</u> |
| 4×10^4 | 2.7 | 3.5 |
| 1×10^5 | 2.6 | 3.0 |
| 1×10^7 | 2.3 | 3.4 |
| | <u>40 Ksi Mean Stress</u> | <u>25-Ksi Mean Stress</u> |
| 4×10^4 | 2.1 | 2.2 |
| 1×10^5 | 2.0 | 2.2 |
| 1×10^7 | 2.1 | 2.2 |

TABLE 14. FATIGUE NOTCH FACTORS AT ROOM TEMPERATURE FOR TWO AIRCRAFT STRUCTURAL ALUMINUM ALLOYS WITH $K_t = 4.0$

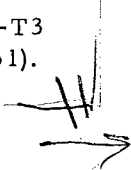

| Lifetime, cycles | K_f | |
|---------------------|---------------------------|---------------------------|
| | 2024-T3 | 7075-T6 |
| | <u>Zero Mean Stress</u> | <u>Zero Mean Stress</u> |
| 4×10^4 | 3.0 | 2.6 |
| 1×10^5 | 3.4 | 3.1 |
| 1×10^7 | 3.6 | 3.6 |
| | <u>12 Ksi Mean Stress</u> | <u>14-Ksi Mean Stress</u> |
| 4×10^4 | 2.4 | 2.8 |
| 1×10^5 | 2.6 | 2.7 |
| 1×10^7 | 1.9 | 2.7 |



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Include Appendix
A - B & C.

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APPENDIX A

TENSILE DATA

APPENDIX A

TENSILE DATA ON AM-350 AND
Ti-8Al-Mo-1V SHEETS

TABLE A-1. MANUFACTURER'S DATA ON AM-350 CRT STAINLESS STEEL

Material: AM-350 stainless steel, CRT condition
 Number of Sheets: Three, designated XA5, XA7, XA8
 Size of Sheet: 36 x 96 x 0.050 in.
 Heat: 55431

| Chemical Analysis | | Mechanical Properties |
|-------------------|------------------|--|
| Element | Weight, per cent | |
| C | 0.096 | Yield Strength, 183,970 psi Tensile Strength, 233,460 psi Elongation, 13.0 per cent Hardness, 48 RC |
| Mn | 0.75 | |
| P | 0.015 | |
| S | 0.010 | |
| Si | 0.27 | |
| Cr | 16.64 | |
| Ni | 4.30 | |
| Mo | 2.79 | |
| N ₂ | 0.096 | |

TABLE A-2. MANUFACTURER'S DATA ON Ti-8Al-1Mo-1V ALLOY

Material: 8Al-1Mo-1V titanium alloy
 Condition: Triplex annealed
 8 hours, 1450 F, furnace cool
 +5 minutes, 1850 F, air cool
 +15 minutes, 1375 F, air cool
 Number of Sheets: Three, designated TA6, TA7, TA8
 Size of Sheets: 36 x 96 x (0.038 to 0.049) inch

| Element | Chemical Analysis | | Mechanical Properties | | |
|----------------|-------------------|--|-----------------------|-----------------------|----------------------|
| | Weight, per cent | | Yield Strength, psi | Tensile Strength, psi | Elongation, per cent |
| C | 0.023 | | 130,300 min | 142,300 min | 11 min |
| Fe | 0.09 | | 141,100 max | 152,600 max | 16 max |
| N ₂ | 0.013 | | 133,000 avg | 147,000 avg | 13 avg |
| Al | 7.6 | | | | |
| Va | 1.0 | | | | |
| Mo | 1.1 | | | | |
| H ₂ | 0.010-0.014 | | | | |

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APPENDIX B

CRACK-PROPAGATION DATA

F

 $\theta = 0.74$, Room Temperature, 34 cpm, Longitudinal, Unexposed

| | | | | | | | | | | | | | | |
|------|----|----|----|----|----|-----|------|------|------|------|------|------|------|------|
| 6339 | 24 | 28 | 35 | 39 | 39 | 6.0 | 11.7 | 15.7 | 20.3 | 23.7 | 26.9 | 32.0 | 32.9 | 39.4 |
| 7334 | 19 | 29 | 34 | 38 | 38 | 5.5 | 11.9 | 16.2 | 21.3 | 24.8 | 28.2 | 33.4 | 34.7 | 42.6 |
| 7343 | 24 | 28 | 34 | 40 | 40 | 7.8 | 12.9 | 17.1 | 21.9 | 25.4 | 28.5 | -- | -- | -- |
| 8163 | 23 | 26 | 33 | 36 | 36 | 6.5 | 12.4 | 16.7 | 21.8 | 25.4 | 28.9 | -- | -- | -- |

G

 $\theta = 0.74$, Room Temperature, 1725 cpm, Longitudinal, Unexposed

| | | | | | | | | | | | | | | |
|------|----|----|----|----|----|-----|------|------|------|------|------|------|------|------|
| 6331 | 18 | 24 | 29 | 31 | 31 | 7.2 | 14.1 | 19.3 | 25.4 | 29.6 | 31.8 | 40.2 | 41.5 | 50.0 |
| 6335 | 19 | 23 | 28 | 31 | 31 | 7.5 | 14.3 | 19.4 | 25.3 | 29.7 | 33.7 | -- | -- | -- |
| 6337 | 19 | 23 | 28 | 30 | 30 | 6.9 | 13.9 | 18.8 | 24.7 | 28.8 | 32.9 | -- | -- | -- |
| 7328 | 22 | 25 | 30 | 33 | 33 | 6.8 | 11.7 | 16.3 | 22.2 | 26.3 | 30.2 | 36.2 | 37.7 | 45.1 |
| 7333 | 21 | 24 | 30 | 30 | 30 | 7.5 | 13.8 | 18.9 | 24.5 | 28.7 | 32.9 | -- | -- | -- |
| 7337 | 21 | 25 | 31 | 31 | 36 | 6.9 | 13.4 | 17.9 | 23.5 | 27.4 | 31.0 | 36.8 | 38.1 | -- |
| 7338 | 21 | 24 | 29 | 31 | 31 | 7.5 | 13.7 | 18.5 | 24.3 | 28.5 | 32.6 | -- | -- | -- |
| 8167 | 19 | 23 | 29 | 30 | 30 | 7.2 | 13.5 | 18.5 | 24.4 | 28.7 | 32.9 | -- | -- | -- |
| 8175 | 19 | 23 | 30 | 32 | 32 | 6.7 | 12.8 | 17.6 | 23.5 | 27.6 | 31.5 | -- | -- | -- |
| 8328 | 17 | 22 | 27 | 31 | 31 | 6.7 | 14.0 | 19.2 | 25.2 | 29.5 | 33.7 | 40.2 | 41.9 | -- |

H

 $\theta = 0.74$, Room Temperature, 1725 cpm, Longitudinal, 8000 Hours' Exposure

| | | | | | | | | | | | | | | |
|------|----|----|----|----|----|-----|------|------|------|------|------|------|------|------|
| 7402 | 24 | 31 | 37 | 45 | 45 | 6.6 | 11.2 | 15.0 | 19.3 | 22.2 | 25.0 | -- | -- | -- |
| 7403 | 23 | 28 | 35 | 37 | 37 | 7.7 | 13.1 | 17.1 | 22.0 | 25.4 | 28.8 | -- | -- | -- |
| 7404 | 21 | 33 | 33 | 39 | 39 | 6.0 | 11.4 | 15.5 | 20.0 | 23.5 | 26.7 | -- | -- | -- |
| 7414 | 24 | 23 | 34 | 38 | 38 | 6.7 | 11.9 | 15.9 | 20.7 | 24.0 | 27.3 | -- | -- | -- |
| 7420 | 23 | 26 | 32 | 34 | 38 | 6.5 | 12.7 | 17.1 | 22.1 | 25.9 | 29.3 | 34.6 | 36.0 | 43.0 |
| 7421 | 23 | 27 | 35 | 39 | 39 | 6.6 | 12.0 | 16.2 | 21.0 | 24.3 | 27.5 | 32.7 | 34.0 | 41.5 |
| 7427 | 23 | 28 | 35 | 37 | 37 | 5.3 | 10.9 | 15.0 | 19.8 | 23.3 | 26.7 | -- | -- | -- |

I

 $\theta = 0.74$, Room Temperature, 1725 cpm, Transverse, Unexposed

| | | | | | | | | | | | | | | |
|------|----|----|----|----|----|-----|------|------|------|------|------|------|------|------|
| 6209 | 16 | 21 | 25 | 29 | 29 | 8.7 | 15.6 | 21.6 | 28.0 | 32.6 | 36.9 | -- | -- | -- |
| 6211 | 18 | 22 | 27 | 30 | 31 | 8.8 | 15.7 | 21.0 | 27.0 | 31.2 | 35.3 | 41.7 | 43.1 | 51.8 |
| 7227 | 19 | 21 | 28 | 31 | 31 | 7.5 | 14.7 | 19.8 | 25.8 | 29.9 | 33.9 | 40.0 | 41.6 | -- |
| 7350 | 20 | 21 | 28 | 31 | 31 | 8.5 | 14.5 | 19.2 | 25.4 | 29.9 | 34.0 | 40.5 | 42.1 | 51.1 |
| 8225 | 18 | 23 | 27 | 31 | 31 | 7.3 | 14.1 | 19.4 | 25.5 | 29.9 | 34.3 | 40.9 | 42.6 | -- |
| 8227 | 17 | 22 | 26 | 26 | 26 | 8.3 | 16.2 | 21.8 | 28.5 | 33.3 | 38.1 | -- | -- | -- |

Table B-1. (Continued)

| Condition | Specimen | Crack Propagation Rate, μ in./cycle, at | | | | | | | | | | Total Thousands of Cycles to Indicated Crack Length ^(a) , inch | | | | | | | | | | | |
|---|----------|--|-------|-------|-------|-------|-------|-------|-------|-------|-------|---|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|------------------------|
| | | Indicated Crack Length ^(a) , inch | | | | | 0.150 | | | | | 0.150 | | | | | 1,000 | | | | | | |
| | | 0.250 | 0.350 | 0.500 | 0.625 | 0.750 | 0.950 | 0.950 | 0.250 | 0.350 | 0.500 | 0.625 | 0.750 | 0.950 | 1,000 | 0.250 | 0.350 | 0.500 | 0.625 | 0.750 | 0.950 | 1,000 | Failure ^(b) |
| $\theta = 0.74$, 550 F, 1725 cpm, Longitudinal, Unexposed | | | | | | | | | | | | | | | | | | | | | | | |
| J | 6344 | 12 | 14 | 17 | 17 | 17 | -- | 6.9 | 17.5 | 25.2 | 34.8 | 42.0 | 49.2 | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| | 7336 | 14 | 15 | 18 | 18 | 18 | -- | 8.7 | 16.7 | 23.7 | 32.9 | 39.7 | 46.5 | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| | 7339 | 13 | 15 | 17 | 18 | 18 | 18 | 8.3 | 18.0 | 25.5 | 35.0 | 42.1 | 48.9 | 59.9 | 62.2 | 78.7 | | | | | | | |
| | 8171 | 13 | 17 | 19 | 20 | 20 | 20 | 6.5 | 15.6 | 23.0 | 31.9 | 38.6 | 44.9 | 54.9 | 57.4 | 74.3 | | | | | | | |
| $\theta = 1.04$, Room Temperature, 1725 cpm, Longitudinal, Unexposed | | | | | | | | | | | | | | | | | | | | | | | |
| K | 6329 | 36 | 43 | 52 | 52 | 52 | 52 | 4.4 | 7.9 | 10.6 | 14.1 | 16.6 | 18.8 | 22.5 | 23.4 | 30.2 | | | | | | | |
| | 7324 | 36 | 36 | 43 | 50 | 50 | 50 | 3.4 | 7.0 | 9.8 | 13.2 | 15.8 | 18.3 | 22.4 | 23.4 | 30.5 | | | | | | | |
| | 8326 | 35 | 43 | 47 | 47 | 47 | 47 | 3.4 | 6.8 | 9.5 | 13.7 | 16.5 | 19.1 | 23.3 | 24.3 | -- | | | | | | | |
| $\theta = 1.38$, -110 F, 1725 cpm, Longitudinal, Unexposed | | | | | | | | | | | | | | | | | | | | | | | |
| L | 6350 | 57 | 71 | 83 | 89 | 89 | 89 | 1.8 | 4.2 | 5.7 | 7.6 | 9.0 | 10.4 | 12.6 | 13.1 | 15.8 | | | | | | | |
| | 6357 | 58 | 63 | 82 | 82 | 82 | 82 | 1.9 | 4.2 | 5.8 | 7.9 | 9.4 | 10.9 | 13.4 | 14.0 | 17.0 | | | | | | | |
| $\theta = 1.38$, Room Temperature, 34 cpm, Longitudinal, Unexposed | | | | | | | | | | | | | | | | | | | | | | | |
| M | 7342 | 58 | 63 | 78 | 78 | 78 | 8 | 1.5 | 3.7 | 5.4 | 7.5 | 9.1 | 10.7 | 13.3 | 13.8 | 16.5 | | | | | | | |
| | 7347 | 56 | 63 | 79 | 79 | 79 | -- | 1.2 | 3.8 | 5.5 | 7.5 | 9.1 | 10.7 | -- | -- | -- | | | | | | | |
| | 8161 | 53 | 58 | 71 | 71 | 76 | 76 | 1.2 | 3.8 | 5.7 | 7.9 | 9.7 | 11.4 | 14.0 | 14.6 | 17.5 | | | | | | | |
| | 8168 | 49 | 63 | 78 | 78 | 78 | -- | 1.8 | 4.3 | 6.2 | 8.5 | 10.1 | 11.7 | -- | -- | -- | | | | | | | |
| $\theta = 1.38$, Room Temperature, 1725 cpm, Longitudinal, Unexposed | | | | | | | | | | | | | | | | | | | | | | | |
| N | 6342 | 44 | 50 | 62 | 62 | 62 | 56 | 2.3 | 5.3 | 7.4 | 10.1 | 12.2 | 14.2 | 17.8 | 18.8 | 23.7 | | | | | | | |
| | 7325 | 50 | 56 | 64 | 64 | 64 | 64 | 1.8 | 4.3 | 6.2 | 8.8 | 10.7 | 12.6 | 15.7 | 16.5 | -- | | | | | | | |
| | 8324 | 45 | 53 | 59 | 59 | 59 | 59 | 2.4 | 4.9 | 7.2 | 9.7 | 11.8 | 13.9 | 17.3 | 18.1 | 21.0 | | | | | | | |
| $\theta = 1.38$, Room Temperature, 1725 cpm, Transverse, Unexposed | | | | | | | | | | | | | | | | | | | | | | | |
| O | 6207 | 43 | 48 | 61 | 61 | 61 | 61 | 2.2 | 5.2 | 7.4 | 10.1 | 12.2 | 14.2 | 17.5 | 18.3 | -- | | | | | | | |
| | 6210 | 38 | 46 | 52 | 52 | 52 | 52 | 2.4 | 5.6 | 8.2 | 11.3 | 13.7 | 16.1 | 20.0 | 21.0 | 25.1 | | | | | | | |
| | 7353 | 44 | 46 | 60 | 60 | 60 | 50 | 2.5 | 5.2 | 7.5 | 10.4 | 12.5 | 14.5 | 18.0 | 19.1 | -- | | | | | | | |
| | 8177 | 42 | 46 | 58 | 58 | 58 | 58 | 1.3 | 4.7 | 7.0 | 9.9 | 12.0 | 14.2 | 17.6 | 18.5 | 22.2 | | | | | | | |

| P | $\theta = 1.38, 550 \text{ F}, 1725 \text{ cpm}, \text{ Longitudinal, Unexposed}$ | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|------|----|----|----|----|----|----|----|----|----|----|-----|-----|-----|-----|------|------|------|------|------|------|------|------|------|------|------|------|------|
| | 8165 | 8172 | 31 | 30 | 39 | 42 | 45 | 44 | 53 | 44 | 45 | 44 | 5.3 | 5.5 | 8.4 | 8.6 | 11.9 | 12.1 | 14.7 | 14.9 | 17.2 | 17.7 | 21.6 | 22.2 | 22.7 | 23.3 | 26.0 | 28.2 | |
| Q | 6347 | 7332 | 57 | 58 | 70 | 71 | 83 | 83 | 83 | 83 | 83 | 83 | 3.6 | 3.2 | 5.3 | 4.7 | 7.3 | 6.7 | 8.8 | 8.2 | 10.3 | 9.7 | 12.9 | 11.9 | 13.6 | 12.6 | 16.6 | 15.1 | 16.6 |
| | 8330 | | 50 | 61 | 71 | 75 | 75 | 63 | 75 | 63 | 75 | 63 | 4.0 | 4.0 | 5.7 | 5.7 | 8.1 | 8.1 | 9.8 | 9.8 | 11.5 | 11.5 | 14.5 | 14.5 | 15.3 | 15.3 | -- | -- | -- |

$\theta = 1.74, \text{ Room Temperature, } 1200 \text{ cpm, Longitudinal, Unexposed}$

- (a) Tip-to-tip crack length.
 (b) Specimens cycled to failure from a 1-inch nominal crack length without further adjustment of net-section stress.
 (c) θ = Net-section alternating stress amplitude/net-section mean stress.
 (d) Blank indicates specimen test stopped; specimen employed in residual-static-strength studies.

TABLE B-2. CRACK-PROPAGATION DATA FOR 4-INCH WIDE Ti-8Al-1Mo-
Center-notched, longitudinal, unexposed triplex-annealed specimens at a

| θ (b) | Specimen | Crack Propagation Rate, μ in./cycle, at Indicated Crack Length ^(a) , inch | | | | | | | | | | | 0.150 (Initiation) | |
|--------------|----------|--|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-----------------------|-------|
| | | 0.250 | 0.350 | 0.500 | 0.625 | 0.700 | 0.750 | 0.950 | 1.000 | 1.250 | 1.500 | 1.750 | | 1.900 |
| 0.38 | 8-C | 6.2 | 9.1 | 14 | 17 | 17 | 17 | 21 | 21 | 22 | 23 | 23 | 23 | 30.7 |
| | 8-D | 5.6 | 8.5 | 12 | 14 | 17 | 17 | 21 | 21 | 23 | 23 | 23 | 23 | 47.0 |
| 0.74 | 8-A | 24 | 34 | 38 | 44 | 50 | 52 | 60 | 60 | 65 | 69 | 69 | 69 | 7.3 |
| | 8-B | 24 | 29 | 40 | 45 | 47 | 50 | 59 | 59 | 67 | 67 | 67 | 67 | 7.3 |

(a) Tip-to-tip crack length.

(b) θ = Net-section alternating stress amplitude/net-section mean stress.

(c) Specimens cycled to failure from 2-inch nominal crack length without further adjustment of net-section stress.

TABLE B-3. CRACK-PROPAGATION DATA FOR 2-INCH WIDE Ti-8Al-1Mo-
Center notched ($K_t \approx 7.9$) longitudinal, unexposed, triplex-annealed specimens at an

| θ (b) | Specimen | Crack Propagation Rate, μ in./cycle, at Indicated Crack Length ^(a) , in. | | | | | |
|--------------|----------|---|-------|-------|-------|-------|-------|
| | | 0.250 | 0.350 | 0.500 | 0.625 | 0.750 | 0.950 |
| 0.26 | 7348 | 2.0 | 3.2 | 5.2 | 7.9 | 11 | 19 |
| 0.38 | 7345 | 5.6 | 8.8 | 14 | 19 | 25 | 35 |
| 0.74 | 7344 | 22 | 28 | 46 | 55 | 75 | 117 |
| 1.04 | 6341 | 34 | 50 | 75 | 100 | 142 | 208 |
| 1.38 | 8166 | 46 | 59 | 81 | 107 | 143 | 285 |
| 1.74 | 8164 | 70 | 115 | 131 | 225 | 375 | 575 |

(a) Tip-to-tip crack length.

(b) θ = original net-section alternating stress amplitude original net-section mean stress.

TABLE B-4. CRACK-PROPAGATION DATA FOR 2-INCH WIDE AM-350 STAINLESS STEEL SHEET
Center-notched ($K_t \approx 7.9$), longitudinal specimens at a constant net-

| Specimen | Crack Propagation Rate, μ in./cycle, at Indicated Crack Length ^(b) , in. | | | | | | 0.130 (Initiation) |
|----------|---|-------|-------|-------|-------|-------|-----------------------|
| | 0.250 | 0.350 | 0.500 | 0.625 | 0.750 | 0.950 | |
| 630 | 19 | 23 | 29 | 33 | 34 | 38 | 3.0 |
| 6314 | 20 | 25 | 32 | 34 | 36 | (d) | 2.6 |
| 6319 | 20 | 25 | 34 | 34 | 34 | -- | 2.4 |
| 731 | 20 | 27 | 34 | 36 | 43 | -- | 3.5 |
| 739 | 20 | 24 | 33 | 38 | 38 | -- | 3.1 |
| 8314 | 20 | 23 | 28 | 29 | 34 | 35 | 3.9 |
| 838 | 20 | 24 | 30 | 31 | 33 | -- | 2.6 |

(a) θ = net-section alternating stress amplitude/net-section mean stress.

(b) Tip-to-tip crack length.

1V ALLOY SHEET SPECIMENS WITH CONSTANT NET-SECTION STRESS

constant net-section mean stress of 25 ksi, room temperature, and 1200 cpm.

| Total Thousands of Cycles to Indicated Crack Length ^(a) , inch | | | | | | | | | | | | | |
|---|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|------------------------|
| 0.250 | 0.350 | 0.500 | 0.625 | 0.700 | 0.750 | 0.950 | 1.000 | 1.250 | 1.500 | 1.750 | 1.900 | 2.000 | Failure ^(c) |
| 52.8 | 68.0 | 80.0 | 88.4 | 92.8 | 95.7 | 107 | 109 | 121 | 132 | 143 | 150 | 154 | 183 |
| 84.2 | 98.5 | 113 | 123 | 128 | 131 | 142 | 145 | 156 | 167 | 178 | 185 | 190 | 222 |
| 13.7 | 17.3 | 21.4 | 24.8 | 26.4 | 27.4 | 31.1 | 31.9 | 35.9 | 39.6 | 43.2 | 45.4 | 46.9 | 54.0 |
| 12.3 | 16.1 | 20.7 | 23.6 | 25.2 | 26.4 | 30.0 | 30.9 | 34.9 | 38.6 | 42.4 | 44.7 | 46.2 | 53.5 |

1V ALLOY SHEET SPECIMENS WITH CONSTANT GROSS-SECTION STRESS

original net-section mean stress of 25 ksi, room temperature, and 1200-1275 cpm.

| Total Thousands of Cycles to Indicated Crack Length ^(a) , in. | | | | | | | | |
|--|-------|-------|-------|-------|-------|-------|-------|---------|
| 0.150 (Initiation) | 0.250 | 0.350 | 0.500 | 0.625 | 0.750 | 0.950 | 1.000 | Failure |
| 943 | 1083 | 1122 | 1158 | 1177 | 1190 | 1205 | 1208 | 1226 |
| 89.5 | 115 | 129 | 142 | 150 | 156 | 163 | 164 | 172 |
| 6.8 | 12.6 | 16.7 | 20.9 | 23.4 | 25.3 | 27.5 | 27.8 | 29.6 |
| 3.4 | 7.3 | 9.8 | 12.2 | 13.6 | 14.6 | 15.6 | 15.9 | 16.6 |
| 1.8 | 4.6 | 6.6 | 8.8 | 10.1 | 11.2 | 12.2 | 12.4 | 12.8 |
| 1.1 | 2.9 | 4.1 | 5.3 | 6.0 | 6.4 | 6.8 | 6.9 | 7.2 |

SPECIMENS AFTER 10,000 HOURS' STRESSED EXPOSURE WITH CONSTANT NET-SECTION STRESS

section mean stress of 40 ksi, room temperature, 1200 cpm, and $\theta^{(a)} = 0.75$.

| Total Thousands of Cycles to Indicated Crack Length ^(b) , in. | | | | | | | | |
|--|-------|-------|-------|-------|-------|-------|-------|------------------------|
| 0.150 (Initiation) | 0.250 | 0.350 | 0.500 | 0.625 | 0.750 | 0.950 | 1.000 | Failure ^(c) |
| 4.8 | 11.3 | 16.1 | 22.1 | 26.1 | 29.9 | 35.4 | 36.7 | 45.5 |
| 4.1 | 10.0 | 14.5 | 19.9 | 23.8 | 27.4 | -- | -- | -- |
| 3.9 | 9.8 | 14.3 | 19.3 | 23.0 | 26.6 | -- | -- | -- |
| 5.3 | 12.3 | 16.7 | 21.8 | 25.2 | 28.3 | -- | -- | -- |
| 4.7 | 10.3 | 14.9 | 20.3 | 23.9 | 27.2 | -- | -- | -- |
| 5.5 | 11.5 | 16.4 | 22.1 | 26.6 | 30.6 | 36.4 | 37.9 | 47.0 |
| 4.5 | 10.8 | 15.4 | 21.0 | 25.0 | 28.9 | -- | -- | -- |

(c) Specimens cycled to failure from 1-inch nominal crack length without further adjustment of net-section stress.

(d) Blank indicates specimen testing stopped; specimen employed in residual-static-strength studies.

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APPENDIX C

STRESS-LIFETIME DATA

TABLE C-1. STRESS-LIFETIME DATA FOR AM-350
STAINLESS STEEL AT -110 F

| Specimen | Maximum Stress, ksi | Cycles to Failure |
|---|------------------------|-----------------------|
| <u>Unexposed, Notched ($K_t = 4.0$), Longitudinal, 40-Ksi Mean Stress</u> | | |
| 7135 | 120.0 | 1,000 |
| 7163 | 105.0 | 7,000 |
| 7164 | 90.0 | 25,000 |
| 7132 | 75.0 | 58,000 |
| 6139 | 70.0 | 120,000 |
| 7158 | 67.5 | 177,000 |
| 6148 | 65.0 | 5,959,000, D.N.F. (a) |
| <u>10,500 Hours' Exposure, Notched ($K_t = 4.0$), Longitudinal, 40-Ksi Mean Stress</u> | | |
| 8145 | 90.0 | 17,800 |
| 8128 | 80.0 | 27,000 |
| 7150 | 70.0 | 104,000 |
| 8146 | 65.0 | 171,800 |
| 7138 | 60.0 | 1,973,500 |
| 8135 | 57.5 | 3,067,000, D.N.F. |

(a) D.N.F. - did not fail.

TABLE C-2. STRESS-LIFETIME DATA FOR AM-350
STAINLESS STEEL AT ROOM
TEMPERATURE

| Specimen | Maximum Stress, ksi | Cycles to Failure |
|--|------------------------|--------------------------|
| <u>Unexposed, Unnotched, Longitudinal Zero Mean Stress</u> | | |
| 8166 | 160.0 | 12,300 |
| 8167 | 125.0 | 43,300 |
| 8171 | 110.0 | 87,500 |
| 8163 | 100.0 | 71,500 |
| 8165 | 90.0 | 256,200 |
| 8169 | 80.0 | 471,700 |
| 8150 | 75.0 | 10,107,500, D. N. F. (a) |
| 8148 | 75.0 | 16,256,900, D. N. F. |
| 8168 | 70.0 | 10,041,600, D. N. F. |
| <u>Unexposed, Notched ($K_t = 4.0$), Longitudinal, Zero Mean Stress</u> | | |
| 6319 | 65.0 | 16,100 |
| 7318 | 55.0 | 22,700 |
| 6316 | 50.0 | 30,000 |
| 7324 | 45.0 | 43,400 |
| 7322 | 40.0 | 99,000 |
| 8317 | 37.5 | 116,000 |
| 6320 | 35.0 | 88,400 |
| 8322 | 32.5 | 10,087,000, D. N. F. |
| <u>Unexposed, Notched ($K_t = 4.0$), Longitudinal, 40-Ksi Mean Stress</u> | | |
| 7131 | 120.0 | 2,500 |
| 6143 | 98.0 | 10,000 |
| 6156 | 80.0 | 19,500 |
| 6158 | 70.0 | 30,000 |
| 7130 | 60.0 | 173,000 |
| 8138 | 57.5 | 72,000 |
| 6144 | 56.6 | 1,484,000 |
| 8133 | 55.0 | 10,248,000, D. N. F. |

TABLE C-2. (Continued)

| Specimen | Maximum Stress, ksi | Cycles to Failure |
|---|------------------------|----------------------|
| <u>Unexposed, Notched ($K_t = 4.0$), Transverse, 40-Ksi Mean Stress</u> | | |
| 6180 | 80.0 | 17,800 |
| 6178 | 70.0 | 37,300 |
| 6174 | 60.0 | 99,400 |
| 6179 | 60.0 | 119,100 |
| 6172 | 55.0 | 195,300 |
| 6177 | 55.0 | 10,115,500, D. N. F. |
| 6173 | 55.0 | 14,450,300, D. N. F. |
| 6169 | 50.0 | 17,026,300, D. N. F. |
| <u>Unexposed, Unnotched, Room Temperature, 100-Ksi Mean Stress</u> | | |
| 8154 | 226.4 | 11,000 |
| 8158 | 210.0 | 19,400 |
| 6308 | 195.0 | 37,600 |
| 8309 | 185.0 | 52,500 |
| 6301 | 175.0 | 104,200 |
| 7302 | 170.0 | 230,000 |
| 6310 | 165.0 | 11,951,800, D. N. F. |
| <u>Unexposed, Notched ($K_t = 4.0$), Room Temperature, 100-Ksi Mean Stress</u> | | |
| 7326 | 135.0 | 11,700 |
| 7311 | 134.8 | 13,700 |
| 8319 | 130.0 | 11,800 |
| 6311 | 125.0 | 18,000 |
| 8318 | 120.0 | 29,700 |
| 7321 | 115.0 | 80,000 |
| 7313 | 110.0 | 1,606,000 |
| 6324 | 107.5 | 10,118,000, D. N. F. |

(a) D. N. F. - did not fail.

TABLE C-3. STRESS-LIFETIME DATA FOR AM-350
STAINLESS STEEL AT 550 F

| Specimen | Maximum Stress, ksi | Cycles to Failure |
|--|------------------------|--------------------------|
| <u>Unexposed, Unnotched, Longitudinal, Zero Mean Stress</u> | | |
| 6353 | 125.0 | 5,000 |
| 6355 | 110.0 | 15,000 |
| 8173 | 100.0 | 26,200 |
| 8174 | 95.0 | 36,300 |
| 7174 | 90.0 | 138,200 |
| 7306 | 85.0 | 11,859,900, D. N. F. (a) |
| 7173 | 82.5 | 10,071,900, D. N. F. |
| <u>Unexposed, Notched ($K_t = 4.0$), Longitudinal, Zero Mean Stress</u> | | |
| 6323 | 50.0 | 9,300 |
| 6312 | 45.0 | 13,200 |
| 7323 | 40.0 | 26,000 |
| 8312 | 37.5 | 31,400 |
| 6313 | 35.0 | 46,600 |
| 6314 | 32.5 | 67,200 |
| 7316 | 30.0 | 128,400 |
| 8313 | 27.5 | 180,900 |
| 7320 | 25.0 | 12,006,000, D. N. F. |
| <u>Unexposed, Unnotched, Longitudinal, 20-Ksi Mean Stress</u> | | |
| 6302 | 140.0 | 3,000 |
| 8306 | 135.0 | 9,100 |
| 7184 | 130.0 | 11,400 |
| 8305 | 125.0 | 15,400 |
| 6303 | 120.0 | 25,500 |
| 7183 | 115.0 | 31,600 |
| 7189 | 110.0 | 45,700 |
| 6301 | 105.0 | 49,600 |
| 7171 | 102.5 | 6,351,900 |
| 7188 | 97.5 | 10,001,000, D. N. F. |

TABLE C-3. (Continued)

| Specimen | Maximum Stress, ksi | Cycles to Failure |
|---|------------------------|----------------------|
| <u>Unexposed, Notched ($K_t = 4.0$), Longitudinal, 20-Ksi Mean Stress</u> | | |
| 6182 | 60.0 | 6,600 |
| 8324 | 55.0 | 15,400 |
| 7325 | 52.5 | 18,000 |
| 7327 | 50.0 | 32,900 |
| 8326 | 47.5 | 45,000 |
| 6317 | 45.0 | 76,100 |
| 7329 | 42.5 | 1,984,600, D. N. F. |
| 7328 | 40.0 | 10,032,000, D. N. F. |
| <u>Unexposed, Notched ($K_t = 4.0$), Longitudinal, 40-Ksi Mean Stress</u> | | |
| 6138 | 100.0 | 2,500 |
| 6135 | 88.0 | 3,500 |
| 6145 | 75.0 | 11,000 |
| 6134 | 70.0 | 27,000 |
| 8142 | 65.0 | 58,000 |
| 8141 | 63.7 | 38,000 |
| 7162 | 62.5 | 12,598,000, D. N. F. |
| 7157 | 60.0 | 10,044,800, D. N. F. |
| <u>10,500 Hours' Exposure, Notched ($K_t = 4.0$), Longitudinal, 40-Ksi Mean Stress</u> | | |
| 8139 | 75.0 | 7,200 |
| 8131 | 67.5 | 14,300 |
| 8147 | 65.0 | 239,800 |
| 7146 | 62.5 | 340,200 |
| 8129 | 60.0 | 6,113,700 |

TABLE C-3. (Continued)

| Specimen | Maximum Stress, ksi | Cycles to Failure |
|---|------------------------|----------------------|
| <u>Unexposed, Unnotched, Longitudinal, 100-Ksi Mean Stress</u> | | |
| 7177 | 195.0 | 8,400 |
| 8303 | 187.5 | 17,200 |
| 7304 | 182.5 | 24,100 |
| 7190 | 180.0 | 21,800 |
| 7303 | 177.5 | 29,000 |
| 6351 | 175.0 | 21,800 |
| 6352 | 172.5 | 22,300 |
| 6354 | 170.0 | 31,100 |
| 8172 | 167.5 | 30,100 |
| 6306 | 165.0 | 135,200 |
| 7305 | 162.5 | 152,500 |
| 7185 | 160.0 | 11,788,900, D. N. F. |
| <u>Unexposed, Notched ($K_t = 4.0$), Longitudinal, 100-Ksi Mean Stress</u> | | |
| 6321 | 125.0 | 10,900 |
| 7319 | 122.5 | 17,000 |
| 8316 | 120.0 | 27,000 |
| 7315 | 117.5 | 46,000 |
| 7317 | 115.0 | 89,000 |
| 6318 | 112.5 | 12,188,000, D. N. F. |
| 8320 | 110.0 | 11,959,400, D. N. F. |

(a) D. N. F. - did not fail.

TABLE C-4. STRESS-LIFETIME DATA FOR Ti-8Al-1Mo-1V
ALLOY AT -110 F

| Specimen | Maximum Stress, ksi | Cycles to Failure |
|---|------------------------|-------------------------|
| <u>Unexposed, Notched ($K_t = 4.0$), Longitudinal, 25-Ksi Mean Stress</u> | | |
| 8132 | 85.0 | 2,600 |
| 7120 | 77.5 | 5,100 |
| 8138 | 70.0 | 11,500 |
| 7114 | 60.0 | 16,700 |
| 8150 | 50.0 | 39,000 |
| 8133 | 45.0 | 54,000 |
| 8114 | 45.0 | 73,000 |
| 8134 | 42.5 | 722,000 |
| 6132 | 42.5 | 2,965,400, D. N. F. (a) |
| 7117 | 40.0 | 2,760,800, D. N. F. |
| 6134 | 35.0 | 2,810,400, D. N. F. |
| <u>3000 Hours' Exposure, Notched ($K_t = 4.0$), Transverse, 25-Ksi Mean Stress</u> | | |
| 7141 | 80.0 | 2,700 |
| 7144 | 60.0 | 16,300 |
| 8143 | 50.0 | 47,500 |
| 6140 | 49.8 | 36,000 |
| 6144 | 40.0 | 2,485,200, D. N. F. |
| <u>10,000 Hours' Exposure, Notched ($K_t = 4.0$), Longitudinal, 25-Ksi Mean Stress</u> | | |
| 6155 | 60.0 | 9,000 |
| 6160 | 50.0 | 32,000 |
| 6152 | 47.5 | 89,000 |
| 6129 | 45.0 | 86,500 |
| 6130 | 42.5 | 139,000 |
| 6138 | 42.5 | 192,000 |
| 6150 | 40.0 | 2,719,400, D. N. F. |

(a) D. N. F. - did not fail.

TABLE C-5. STRESS-LIFETIME DATA FOR Ti-8Al-1Mo-1V
ALLOY AT ROOM TEMPERATURE

| Specimen | Maximum Stress, ksi | Cycles to Failure |
|--|------------------------|--------------------------|
| <u>Unexposed, Unnotched, Longitudinal, Zero Mean Stress</u> | | |
| 7303 | 120.0 | 17,000 |
| 7310 | 110.0 | 23,800 |
| 6311 | 100.0 | 28,200 |
| 8134 | 90.0 | 74,000 |
| 8302 | 80.0 | 286,000 |
| 6309 | 70.0 | 1,089,500 |
| 6308 | 65.0 | 2,280,900 |
| 7309 | 60.0 | 10,011,600, D. N. F. (a) |
| <u>Unexposed, Notched ($K_t = 4.0$), Longitudinal, Zero Mean Stress</u> | | |
| 6177 | 50.0 | 5,900 |
| 6146 | 40.0 | 13,900 |
| 6147 | 30.0 | 33,400 |
| 6176 | 25.0 | 115,600 |
| 6179 | 22.0 | 99,500 |
| 6188 | 22.0 | 156,300 |
| 6189 | 20.0 | 10,015,900, D. N. F. |
| 6148 | 20.0 | 10,217,800, D. N. F. |
| <u>Unexposed, Notched ($K_t = 4.0$), Longitudinal, 25-Ksi Mean Stress</u> | | |
| 6158 | 85.0 | 2,400 |
| 7113 | 70.0 | 5,000 |
| 6128 | 60.0 | 12,000 |
| 8148 | 50.0 | 26,000 |
| 7111 | 40.0 | 94,000 |
| 6180 | 39.0 | 68,000 |
| 6181 | 39.0 | 83,500 |
| 7118 | 35.0 | 267,000 |
| 8111 | 33.7 | 236,000 |
| 7119 | 33.0 | 3,098,000 |
| 6145 | 32.5 | 10,000,000, D. N. F. |
| 8135 | 30.0 | 11,483,600, D. N. F. |



TABLE C-5. (Continued)

| Specimen | Maximum Stress, ksi | Cycles to Failure |
|--|------------------------|----------------------|
| <u>Unexposed, Notched ($K_t = 4.0$), Transverse, 25-Ksi Mean Stress</u> | | |
| 8222 | 60.0 | 6,900 |
| 8223 | 55.0 | 11,600 |
| 8141 | 50.0 | 22,500 |
| 6139 | 45.0 | 40,000 |
| 7223 | 40.0 | 101,300 |
| 7222 | 35.0 | 8,681,200 |
| 7221 | 32.5 | 10,012,900, D. N. F. |
| <u>Unexposed, Unnotched, Longitudinal, 60-Ksi Mean Stress</u> | | |
| 8307 | 150.0 | 9,700 |
| 8301 | 140.0 | 38,200 |
| 6318 | 130.0 | 42,500 |
| 7304 | 120.0 | 196,600 |
| 8305 | 110.0 | 106,900 |
| 7305 | 110.0 | 1,344,300 |
| 7306 | 105.0 | 1,014,100 |
| 6317 | 100.0 | 3,862,500 |
| 6313 | 95.0 | 8,739,000 |
| 8310 | 90.0 | 13,206,700 |
| <u>Unexposed, Notched ($K_t = 4.0$), Longitudinal, 60-Ksi Mean Stress</u> | | |
| 8113 | 110.0 | 1,300 |
| 6320 | 100.0 | 3,500 |
| 8137 | 90.0 | 9,600 |
| 8145 | 80.0 | 15,400 |
| 6203 | 70.0 | 103,400 |
| 8128 | 70.0 | 109,600 |
| 6190 | 65.0 | 10,076,000, D. N. F. |
| 7318 | 65.0 | 10,013,700, D. N. F. |

(a) D. N. F. - did not fail.

TABLE C-6. STRESS-LIFETIME DATA FOR Ti-8Al-1Mo-1V ALLOY AT 550 F

| Specimen | Maximum Stress, ksi | Cycles to Failure |
|---|------------------------|------------------------|
| <u>Unexposed, Unnotched, Longitudinal, Zero Mean Stress</u> | | |
| 8303 | 100.0 | 5,000 |
| 6316 | 90.0 | 17,200 |
| 8309 | 80.0 | 35,800 |
| 7311 | 70.0 | 65,400 |
| 7313 | 70.0 | 83,400 |
| 8311 | 65.0 | 7,815,800 |
| 6310 | 55.0 | 10,936,500, D.N.F. (a) |
| <u>Unexposed, Notched ($K_t = 4.0$), Longitudinal, Zero Mean Stress</u> | | |
| 6325 | 45.0 | 11,300 |
| 8317 | 40.0 | 13,300 |
| 8320 | 35.0 | 22,000 |
| 6323 | 30.0 | 30,000 |
| 6324 | 25.0 | 57,000 |
| 7322 | 22.5 | 79,100 |
| 7317 | 20.0 | 10,093,700 |
| <u>Unexposed, Notched ($K_t = 4.0$), Longitudinal, 25-Ksi Mean Stress</u> | | |
| 8149 | 70.0 | 2,300 |
| 7115 | 60.0 | 7,500 |
| 8147 | 50.0 | 25,800 |
| 7112 | 40.0 | 99,400 |
| 8130 | 35.0 | 10,197,500, D.N.F. |
| 8131 | 35.0 | 14,379,400, D.N.F. |
| 7116 | 32.5 | 12,053,000, D.N.F. |
| 6136 | 30.0 | 11,174,000, D.N.F. |
| <u>3000 Hours' Exposure, Notched ($K_t = 4.0$), Transverse, 25-Ksi Mean Stress</u> | | |
| 7143 | 60.0 | 6,500 |
| 6142 | 50.0 | 17,300 |
| 8139 | 40.0 | 78,100 |
| 7146 | 35.0 | 9,827,400, D.N.F. |

TABLE C-6. (Continued)

| Specimen | Maximum Stress, ksi | Cycles to Failure |
|--|------------------------|----------------------|
| <u>10,000 Hours' Exposure, Notched (K_t = 4.0), Longitudinal, 25-Ksi Mean Stress</u> | | |
| 6149 | 60.0 | 7,500 |
| 6151 | 50.0 | 21,500 |
| 6161 | 45.0 | 35,900 |
| 6159 | 42.5 | 44,600 |
| 6157 | 40.0 | 713,400 |
| 6131 | 37.5 | 11,805,000, D. N. F. |
| 6156 | 35.0 | 10,025,000, D. N. F. |
| <u>Unexposed, Unnotched, Longitudinal, 60-Ksi Mean Stress</u> | | |
| 8312 | 120.0 | 12,200 |
| 7302 | 110.0 | 33,900 |
| 6306 | 107.5 | 25,000 |
| 7303 | 105.0 | 2,554,500 |
| 6307 | 102.5 | 62,700 |
| 7301 | 95.0 | 10,036,000, D. N. F. |
| <u>Unexposed, Notched (K_t = 4.0), Longitudinal, 60-Ksi Mean Stress</u> | | |
| 8319 | 90.0 | 5,700 |
| 8324 | 85.0 | 7,400 |
| 7316 | 80.0 | 15,800 |
| 6322 | 75.0 | 29,300 |
| 6321 | 72.5 | 55,500 |
| 8321 | 70.0 | 82,300 |
| 6327 | 67.5 | 14,273,500, D. N. F. |
| 8322 | 65.0 | 11,202,900, D. N. F. |

(a) D. N. F. - did not fail.

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