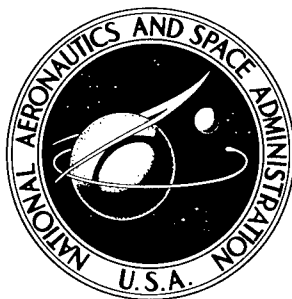


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(FATIGUE OF FOUR STAINLESS STEELS  
AND THREE TITANIUM ALLOYS  
BEFORE AND AFTER EXPOSURE TO  
550° F (561° K) UP TO 8800 HOURS)

*by Walter Illg and Claude B. Castle*  
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*Langley Station, Hampton, Va.*

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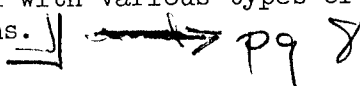
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SUMMARY

Fatigue and tensile sheet specimens of four steels and three titanium alloys were tested before and after exposure to 550° F (561° K) for periods up to 1 year. None of the seven materials exhibited a serious degradation in fatigue life in any of the four specimen configurations used. However, in two cases (Ti-4Al-3Mo-1V spot-welded, Ti-8Al-1Mo-1V edge-notched), a slight but steady life-reduction trend was observed. The static joint efficiencies, prior to exposure, of both spot-welded and fusion-welded specimens were higher for titanium alloys than for steels.

INTRODUCTION

Structural materials located near leading edges of a supersonic transport may reach temperatures as high as 550° F (561° K) due to aerodynamic heating during flight at Mach 3. Since this condition will exist during most of the flying hours throughout the life of the aircraft, the heat environment may affect the long-time load-carrying capacity of the materials of construction. Therefore, <sup>THIS</sup> an investigation <sup>WAS CONDUCTED</sup> ~~is~~ underway to determine effects of exposure to a 550° F (561° K) environment on fatigue strengths of a number of stainless steel and titanium alloys in sheet form. Exposure periods will run up to 30,000 hours. This report presents the results of static and fatigue tests before and after soaking periods up to 1 year (8800 hours). Aircraft construction methods were simulated with various types of specimens including notched and welded configurations. 

SYMBOLS

The units used for the physical quantities defined in this paper are given both in the U.S. Customary Units and in the International System of Units, (SI). Factors relating the two systems are given in reference 1.

e	permanent tensile elongation in given gage length, percent
$K_T$	theoretical stress concentration factor
N	life of fatigue specimen after exposure to 550° F (561° K), cycles
$N_i$	life of fatigue specimen before exposure, cycles
$S_f$	fatigue limit, stress value below which fatigue failure will not occur in $10^7$ cycles, ksi (MN/m <sup>2</sup> )
$S_{max}$	maximum nominal stress during a fatigue load cycle, ksi (MN/m <sup>2</sup> )
$S_{mean}$	mean stress during a fatigue load cycle, ksi (MN/m <sup>2</sup> )
$S_u$	static tensile ultimate strength, ksi (MN/m <sup>2</sup> )
$S_y$	static tensile yield strength, 0.2-percent offset, ksi (MN/m <sup>2</sup> )
$\rho$	density, lb/in. <sup>3</sup> (kg/m <sup>3</sup> )

#### SPECIMENS

Four stainless steels and three titanium alloys were included in this investigation. The steels used were PH 15-7 Mo in the TH 1050 condition, AM 350 in both the double-aged condition (designated AM 350 DA) and the 20-percent cold reduced plus tempered condition (designated AM 350 CRT), and AISI 301 in the full-hard condition (50-percent cold reduction) (designated AISI 301 CR). The titanium alloys used were Ti-4Al-3Mo-1V solution treated and aged, Ti-6Al-4V annealed, and Ti-8Al-1Mo-1V single-annealed. Chemical composition and heat-treating details are given in the appendix.

Three types of fatigue specimens were used to represent widely differing types of stress raisers found in aircraft construction and these types are shown in figure 1. Unnotched specimen tests were also conducted to reveal changes in fatigue strength of the basic material. The edge-notched specimens had a stress concentration factor of 4. This configuration of specimens has been used in a variety of studies of fatigue behavior in aluminum alloys because it has been suggested (ref. 2) that its fatigue behavior is similar to that of contemporary fabricated structures. The relative fatigue behavior among structures made of stainless steels, titanium alloys, and aluminum alloys may be ascertained by comparing the results of the present investigation with data for aluminum alloys. Welded joints were investigated in the spot-weld and fusion-weld form. Symmetrical butt joints were chosen to minimize bending stresses under axial

load. A single row of spot-welds was used for simplicity. The number of spot-welds was designed to obtain maximum strength without short-circuiting the current through adjacent welds. The result was seven spot-welds for the steel specimens and five for the titanium alloy specimens. No filler rod was used for the fusion-welded specimens. Details of fabrication and handling procedures may be found in the appendix.

The static tensile specimens are shown in figure 2. The welded tensile specimen configurations include both transverse and longitudinal welds as recommended in reference 3. The transverse type is useful for determining the strength of welded joints and the longitudinal type is sensitive to a loss in ductility due to welding.

### PROCEDURE

Approximately 100 fatigue specimens were fabricated from each material and of each configuration. A number of specimens were tested to establish a pre-exposure S-N curve at room temperature using mean stresses of 40 ksi (276 MN/m<sup>2</sup>) and 25 ksi (173 MN/m<sup>2</sup>) for steels and titanium alloys, respectively. These mean stresses were considered to be reasonably representative of operating lg stresses in a supersonic transport. The ratios of mean stress to ultimate strength are between 1/5 and 1/6, or roughly equivalent to the ratios used in contemporary aluminum aircraft.

Sixty fatigue specimens of each type and material were hung on racks in a resistance-heated electric furnace having forced-air circulation. A single standard tensile specimen was included with every 10 fatigue specimens to provide a check on possible deterioration of static strength. The temperature of the furnace was maintained at 550° F (561° K) ± 10° F (5.5° K) and was monitored by a thermocouple welded to a sample specimen.

Specimens were removed from the oven after periods of 2200 hours, 4400 hours, and 8800 hours. Six fusion-weld specimens and five of each of the other configurations were removed each time along with one tensile specimen with each group. Five fatigue specimens were then tested at room temperature at a particular stress level chosen from the preexposure S-N curves. The sixth fusion-weld specimen was tested statically to detect possible changes in tensile strength of the welded specimen due to exposure.

Constant-amplitude fatigue tests were conducted in subresonant-type axial-load fatigue machines which are fully described in reference 4 and are shown in figures 3 and 4. Load was sensed by a weigh-bar in series with the specimen and grips. A wire strain-gage bridge cemented to the weigh-bar supplied a load signal to an oscilloscope which was used to monitor the cyclic loading. Operating frequency was 1800 cycles per minute (30 Hz). The machines were calibrated periodically and a loading accuracy of ±10 pounds (±44 N) was maintained.

## RESULTS AND DISCUSSION

### Preexposure Static Tests

The tensile properties of standard tensile specimens are given in table I and are within ranges normally expected for these materials. The effects of fusion welding on these properties are presented in table II. For comparison purposes, table II includes the preexposure tensile strength and elongations from table I.

All the steels suffered large losses in tensile ultimate and yield strengths in the as-welded condition. However, when PH 15-7 Mo and AM 350 DA were heat treated after welding instead of before, the strength losses were considerably less. All three titanium alloys were little affected strengthwise by fusion welding. The elongation values of the longitudinally welded specimens, measured after fracture, were smaller than those of virgin specimens for all three titanium alloys and for AM 350 20 percent CRT.

The static strengths of the fatigue specimens are given in table III. These data are compared with those found for standard tensile specimens from table I. The strengths of the unnotched specimens were within 5 percent of the value from standard tensile specimens except for the AM 350 DA which showed an increase of 8 percent. A notch-strengthening effect was found for the  $K_T = 4$  specimens except for the AISI 301 where there was a weakening effect and for Ti-4Al-3Mo-1V and AM 350 CRT where no significant effect was noted.

The results of the static tests of spot-welded joints showed that the titanium alloys had higher joint efficiencies than the steels. The joint efficiencies (joint strength divided by material strength) of the titanium alloys with five spot-welds per joint varied from 96 to 99 percent. Those for steels with seven spot-welds per joint varied from 86 to 92 percent. Almost all spot-welded specimens failed through the material immediately adjacent to the heat-affected zones. The exceptions were three Ti-6Al-4V tests and one of two Ti-4Al-3Mo-1V tests wherein failure took place away from the welds.

The joint efficiencies of titanium alloys were also impressive in the fusion-welded configuration. Joint efficiency varied from 101 to 107 percent, whereas for most steels it ranged between 60 and 69 percent. In the case of the two heat-treated steels, their joint efficiencies were nearly 100 percent when the specimens were heat treated after fusion welding instead of before.

Desirable welding characteristics of material for aircraft use would include little or no postweld treatment and little change in strength and elongation values due to welding. Of the materials tested in this program, only the three titanium alloys approached these requirements. Of these three, the welding characteristics of Ti-8Al-1Mo-1V were superior because the Ti-6Al-4V required a postweld moderate temperature stress relief to forestall weld cracking and the Ti-4Al-3Mo-1V exhibited larger reduction in ductility than did Ti-8Al-1Mo-1V.

## Preexposure Fatigue Tests

The results of the preexposure fatigue tests are listed in table IV and are presented in figure 5 as S-N curves. The maximum stress in a cycle is plotted against the number of cycles to failure. In all cases except one, the curves displayed a real fatigue limit (a definite tendency to become horizontal before reaching  $10^7$  cycles). The exception was Ti-6Al-4V in the unnotched configuration (fig. 5(e)) in which case the S-N curve had a negative slope up to  $10^7$  cycles.

An unusually high degree of scatter was observed in the results for AISI 301 unnotched specimens (fig. 5(d)). Photomicrographs (fig. 6) were taken of this material in a search for possible causes for the scatter. It can be seen that stringer-like inclusions are present and occasionally very large ones are evident up to 0.006 inch (0.015 cm) in size. It is possible that these inclusions may be responsible for early fatigue failures. Such extreme scatter did not occur for the edge-notched and spot-welded specimens probably because the effects of the high stress concentration factor at the notch or weld masked the effects of inclusions.

The fatigue-limit—density ratios of the various materials and types of specimens are compared in figure 7. Densities are given in the appendix. This normalization puts the stainless steels and titanium alloys on a comparable footing since the mean stresses are, fortuitously, in approximately the same ratio as the densities. The results of the tests of unnotched and edge-notched specimens show that the ratios for the stainless steels and titanium alloys are generally equivalent in those configurations. However, in the case of welded joints, both spot-welded and fusion-welded, the titanium alloys had higher ratios. The ratios for currently used aluminum alloys (2024-T3 and 7075-T6) in the edge-notched configuration (ref. 5) are roughly equivalent to those found in this investigation. Figure 7 also shows the ratios for the spot-welded joint to be roughly equivalent to those for the edge-notched specimens.

A measure of the effect of fusion welding on the fatigue limit can be obtained by determining the percent of the fatigue limit for unnotched specimens that was retained by the welded specimens. (See fig. 7.) The percentages for the titanium alloys are higher (83 to 97 percent) than those for the steels (70 to 82 percent). The fatigue limit for Ti-6Al-4V appears to be almost insensitive to fusion welding.

If the materials are serially ranked for each kind of specimen on the basis of fatigue-limit—density ratio  $S_f/\rho$  and the rank numbers then added, the results would be a rough overall ranking as has been done in the following table:

Material	Specimen type				Total	Overall rank
	K <sub>T</sub> = 1	K <sub>T</sub> = 4	Spot-weld	Fusion-weld		
PH 15-7 Mo	6	2	5	6	19	5
AM 350 CRT	4	5	6	5	20	6
AM 350 DA	2	1	4	4	11	2
AISI 301	7	7	7	7	28	7
Ti-6Al-4V	3	4	3	1	11	2
Ti-4Al-3Mo-1V	5	6	1	3	15	4
Ti-8Al-1Mo-1V	1	3	2	2	8	1

In the ranking of the fusion-welded specimens, those steel specimens which were welded before heat treating were omitted. This ranking should be regarded cautiously since it was drawn from very limited data and from only one type of test.

#### Postexposure Static Tests

The effect of exposure on the static tensile strength was examined in a cursory manner by use of one standard tensile specimen for each exposure time. A more complete investigation of these effects is reported in reference 6. Table I and figure 8 present the results from the present investigation. No important changes in strength are evident although it may be pointed out that PH 15-7 Mo and AISI 301 showed a consistent rise in tensile ultimate and yield strengths up to 8800 hours.

The results of the static tests of fusion-welded fatigue specimens are given in table V. The only significant change occurred in AM 350 CRT where the strength decreased from 139 ksi to 103 ksi (958 to 710 MN/m<sup>2</sup>) in 4400 hours.

#### Postexposure Fatigue Tests

The results of the fatigue tests of exposed specimens are given in table VI and are plotted in figure 8. The effect of exposure on fatigue life is expressed as a ratio of the as-exposed life to the preexposure life at one particular maximum stress level. The test stress levels were chosen from the faired S-N curves in figure 5 so that preexposure life was between 50,000 and 500,000 cycles. The logarithmic average of the exposure test results was used to compare with the preexposure lives as obtained from the faired S-N curves.

Although the data are somewhat erratic, one important conclusion may be drawn; that is, no catastrophic degradation of fatigue life has been found after exposure to 550° F (561° K). It must be noted, however, that these specimens were not under stress while exposed to elevated temperature. It is known that the addition of stress to a heated material can accelerate metallurgical changes and thereby affect mechanical properties (ref. 7).

The most extreme improvement occurred for the unnotched specimens of Ti-8Al-1Mo-1V. (See fig. 8.) The fatigue-life ratio increased from 1 to 13 in the interval between 4400 hours and 8800 hours. Since half of those specimens tested at 8800 hours failed at normal lifetimes, the sudden rise should probably be ascribed to scatter in the test results, especially since the results for edge-notched specimens did not indicate a similar trend.

A number of points fell at life ratios below 1. However, in most cases, the next exposure interval indicated an increase; thus, the fluctuations could be ascribed to test scatter. But in some cases, such as Ti-4Al-3Mo-1V spot-welded and Ti-8Al-1Mo-1V edge-notched, the life ratio declined steadily up to 8800 hours. Subsequent tests after longer periods of exposure should contribute additional evidence.

CONCLUDING REMARKS

Fatigue and <sup>A//</sup> tensile specimens of four stainless steels and three titanium alloys have been exposed to 550° F (561° K) for periods up to 8800 hours. At intervals, the specimens were tested under axial load at room temperature and their fatigue lives and static strengths before and after exposure were determined.

It was found that the <sup>A//</sup> preexposure fatigue limits of spot-welded specimens were approximately equal to those of edge-notched specimens with a stress concentration factor of 4. The fatigue limits of fusion-welded specimens were slightly lower than those of unnotched specimens. On the basis of fatigue-limit-density ratios, the stainless steels and titanium alloys were generally equivalent. The titanium alloys, however, had somewhat higher ratios for spot-welded and fusion-welded joints than did the stainless steels.

The efficiencies of spot-welded joints (ratio of strength of joint to that of the virgin sheet material) was substantially higher for titanium alloys than for stainless steels.

The exposure to 550° F (561° K) did not seriously degrade the fatigue life for any of the materials tested during the indicated exposure periods. A slight but steady life-reduction trend was found for Ti-4Al-3Mo-1V spot-welded specimens and Ti-8Al-1Mo-1V edge-notched specimens. The static strengths showed no significant changes due to exposure.

end

Langley Research Center,  
National Aeronautics and Space Administration,  
Langley Station, Hampton, Va., March 4, 1965.

APPENDIX

FABRICATION AND TREATMENT OF SPECIMENS

Four stainless steel and three titanium alloys were included in this investigation. The chemical composition and densities of these sheet materials obtained from the producers are given in the following tables:

(a) Titanium alloys

Alloy	Chemical composition, percent (on weight basis) (*)									All Density, lb/in. <sup>3</sup> (g/m <sup>3</sup> )
	C	Fe	N <sub>2</sub>	H <sub>2</sub>	Al	V	Cr	Mo	Ti	
Ti-8Al-1Mo-1V	0.034	0.09	0.013	0.005	7.8	1.1		1.1	Balance	0.156 (4.32)
Ti-6Al-4V	.026	.15	.013	.011	6.1	4.0			Balance	.161 (4.46)
Ti-4Al-3Mo-1V	.015	.16	.011	.010	4.4	1.1		3.0	Balance	.163 (4.51)

\*Average for different heats.

(b) Stainless steels

Alloy	Chemical composition, percent (on weight basis)											Density, lb/in. <sup>3</sup> (g/m <sup>3</sup> )
	C	Mn	P	S	Si	Cr	Ni	Co	Mo	Al	Fe	
AM 350	0.080	0.76	0.019	0.012	0.30	16.80	4.15		2.80		Balance	0.286 (7.92)
PH 15-7 Mo	.063	.55	.020	.011	.44	14.96	7.23		2.15	1.14	Balance	.277 (7.67)
AISI 301	.089	.15	.023	.017	.47	17.30	7.70	0.05	.16		Balance	.287 (7.95)

Specimen Fabrication

Unnotched specimens.- The  $7\frac{1}{2}$ -inch (19-cm) radius of the unnotched specimens (fig. 1) was cut in a lathe by mounting the blanks on the headstock in stacks of 6 to 12 at one time. Machining speed was 14 revolutions per minute or 11 inches (28 cm) per second. Each of the final two passes removed 0.001 inch (25  $\mu$ m) of material producing a finish of 64  $\mu$ in. (1.6  $\mu$ m) root mean square. Although machining techniques were chosen to minimize burrs, they could not be eliminated entirely. Therefore, the corners in the fatigue critical areas were chamfered to remove the burred material. The beveling tool was a block of wood having about a  $7\frac{1}{2}$ -inch (19-cm) radius with number 600 emery paper fixed to the circumference. The bevel was produced by hand with light longitudinal strokes. The resulting bevel face was approximately 0.004 inch (0.10 mm) wide at a 45° angle to the surface of the specimen.

## APPENDIX

Notched specimens.- The notch radii of the notched specimens (fig. 1) were formed by drilling successively larger holes. The final three drill sizes were 0.110 inch, 0.113 inch, and 0.116 inch (2.80, 2.87, and 2.94 mm) diameter. The first two drills were guided by a bushing, but the last drill was free. The blanks were drilled in stacks of 10 against a thick plate of cold-rolled steel. Only new drills were used and each was discarded after drilling the stack once. Drilling speed was 925 revolutions per minute and 11/64 inch per minute (73  $\mu$ m/s) feed with the drills lubricated continuously. The notches were completed by slotting from the edge with a 3/32-inch (2.38 mm) wide milling tool. Burrs produced by the drilling operation were removed by chamfering the edges of the hole at a 45° angle. The beveling tool was a cone-shaped piece of rubber-abrasive composite chucked in a drill press which ran at 3000 revolutions per minute. The procedure required the specimens to be lightly touched against the cone to produce a chamfer 0.004 inch (0.10 mm) wide.

Spot-welded specimens.- The four components of the spot-welded specimens (fig. 1) were machined to size prior to welding. Edge finish was 64  $\mu$ in. (1.6  $\mu$ m) root mean square and the corners were broken with a fine file. Welding parameters and tests were applied to check the weld quality.

Fusion-welded specimens.- The two components of the fusion-welded specimens (fig. 1) were premachined to a rectangular shape. They were then clamped in position in a tungsten inert gas automatic welding machine and welded without filler rod. The radius was machined in the same manner as for the unnotched specimen except that spacers were placed between the fusion-welded specimens away from the weld to compensate for weld bulge while stacked for machining. The weld bulge was left as welded.

### Handling and Treatment of Specimens

General requirements.- Sheets were covered with protective paper prior to shearing. Specimens were not scribed, scratched, or marred in anyway. Specimens were separated by paper or racked in designated shipping containers. Handling of specimens was at all times conducive to the retention of a scratch-free and chemically clean surface. The special treatment given each material is outlined in the following table:

Material	Cleaning method	Grit-blast oxidation removal	Heat treatment
PH 15-7 Mo	A	Yes	I
AISI 301	B	No	None
AM 350 CRT	B	No	None
AM 350 DA	B	Yes	II
Ti-6Al-4V	C	No	III
Ti-4Al-3Mo-1V	C	Yes	IV
Ti-8Al-1Mo-1V	C	No	None

## APPENDIX

Cleaning methods.- The specimens were cleaned both before heat treatment and immediately before insertion into oven at 550° F (561° K). The three different cleaning processes used are as follows:

- Method A: (1) Remove markings such as manufacturer's stamp, crayon, etc., using acetone or alcohol and cloth.
- (2) Vapor degrease using trichlorethylene vapor.
  - (3) Hand scrub using fiber brush and a detergent.
  - (4) Hand scrub and rinse in hot running water.
  - (5) Rinse in cold running water.
  - (6) Check for uniform wetting of specimen surface.
  - (7) Wipe dry using clean cloth or paper towels.
- Method B: (1) Remove markings such as manufacturer's stamps, crayon, etc., using acetone or alcohol and cloth.
- (2) Vapor degrease using trichlorethylene vapor.
  - (3) Rinse in hot water.
  - (4) Immerse in nitric acid, 20 percent by volume, for approximately 5 minutes.
  - (5) Wash in hot water.
  - (6) Rinse in cold water.
  - (7) Check for uniform wetting of specimen surface.
  - (8) Wipe dry using clean cloth or paper towels.
- Method C: (1) Immerse in alkaline cleaner for 10 minutes. Use at 180° F (355° K) to 200° F (366° K).
- (2) Rinse in hot water 2 to 3 minutes.
  - (3) Immerse in nitric acid, 20 percent by volume, for 30 seconds.
  - (4) Rinse in hot water, agitated.
  - (5) Rinse in cold water, agitated, continuous supply.
  - (6) Check for uniform wetting of specimen surface.
  - (7) Wipe dry using clean cloth or paper towels.

## APPENDIX

Heat treatments.- The procedures used for the heat treatments of the various materials are as follows:

PH 15-7 Mo: Heat treat the material PH 15-7 Mo to the TH 1050 condition as follows:

- (1) Heat to  $1400^{\circ}\text{F} \pm 25^{\circ}\text{F}$  ( $1033^{\circ}\text{K} \pm 14^{\circ}\text{K}$ ) in argon atmosphere. Hold for 90 minutes.
- (2) Cool to  $60^{\circ}\text{F} + 0^{\circ}$ ,  $-10^{\circ}\text{F}$  ( $289^{\circ}\text{K} + 0^{\circ}$ ,  $-5^{\circ}\text{K}$ ) within 1 hour. Hold for 30 minutes.
- (3) Heat to  $1050^{\circ}\text{F} \pm 10^{\circ}\text{F}$  ( $837^{\circ}\text{K} \pm 5^{\circ}\text{K}$ ) in argon atmosphere. Hold for 90 minutes. Air cool to room temperature.

AM 350: Heat treat the material AM 350 to the double-aged condition as follows:

- (1) Heat to  $1375^{\circ}\text{F} \pm 25^{\circ}\text{F}$  ( $1022^{\circ}\text{K} \pm 14^{\circ}\text{K}$ ) in argon atmosphere. Hold for 3 hours.
- (2) Air cool to  $80^{\circ}\text{F} + 0^{\circ}$ ,  $-10^{\circ}\text{F}$  ( $300^{\circ}\text{K} + 0^{\circ}$ ,  $-5^{\circ}\text{K}$ ).
- (3) Heat to  $850^{\circ}\text{F} \pm 25^{\circ}\text{F}$  ( $727^{\circ}\text{K} \pm 14^{\circ}\text{K}$ ) in argon atmosphere. Hold for 3 hours. Air cool to room temperature.

Ti-6Al-4V: Fusion-welded specimens of the material Ti-6Al-4V were stress-relieved within 72 hours after welding as follows:

- (1) Heat to  $1150^{\circ}\text{F} \pm 25^{\circ}\text{F}$  ( $894^{\circ}\text{K} \pm 14^{\circ}\text{K}$ ) in argon atmosphere for 1 hour.
- (2) Air cool to room temperature.

Ti-4Al-3Mo-1V: Heat treat the material Ti-4Al-3Mo-1V as follows:

- (1) Heat to  $1050^{\circ}\text{F}$  ( $837^{\circ}\text{K}$ ) in an argon atmosphere. Hold for 4 hours.
- (2) Air cool to room temperature.

Welding procedures.- Prior to welding the spot-weld and fusion-weld components, oxidation was removed by a grit-blast process from the PH 15-7 Mo, AM 350 AM 350 DA, and Ti-4Al-3Mo-1V materials. Prior to welding fatigue specimens, one sample specimen was welded, sectioned, and etched to check penetration and nugget size. Spot-weld shear test qualifying specimens were made according to military specifications MIL-W-6858-B (ref. 8) at the beginning and end of a material run and also after 20 fatigue specimens. A 50 kVA  $3\phi$  combination seam and spot-welder was used for all spot-welds. It has an electrode face diameter of 5/16 inch (0.67 cm) and a tip radius of 3 inches (7.62 cm). The spot-weld parameters for the various materials are given in the following table:

APPENDIX

Material	Welds per row	Penetration, percent	Nugget diameter, in. (mm)
PH 15-7 Mo	7	70	0.13 (3.3)
AM 350 CRT	7	80	.20 (5.1)
AM 350 DA	7	80	.18 (4.6)
AISI 301	7	75	.16 (4.1)
Ti-6Al-4V	5	80	.24 (6.1)
Ti-4Al-3Mo-1V	5	80	.23 (5.8)
Ti-8Al-1Mo-1V	5	80	.19 (4.8)

The fusion-welds were made without a filler rod. A 200-ampere welding machine was used; its electrode was made of tungsten, 2-percent thoria and had a diameter of 0.040 inch (1.0 mm). The fusion-weld parameters for the various materials are given in the following table:

Material	Shield inert gas flow rate, cu ft/hr			Current, A
	Top (*)	Bottom	Trailing (**)	
PH 15-7 Mo	30	*20	0	19
AM 350 CRT	50	***15	0	24
AM 350 DA	50	***15	0	24
AISI 301	50	***15	0	24
Ti-6Al-4V	30	**5	20	44
Ti-4Al-3Mo-1V	30	**5	30	46
Ti-8Al-1Mo-1V	30	**30	30	42

\*75-percent helium, 25-percent argon.

\*\*Argon.

\*\*\*Helium.

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TABLE I.- ROOM-TEMPERATURE TENSILE PROPERTIES FOR TENSILE  
SPECIMENS, LONGITUDINAL GRAIN DIRECTION

[Each value for 0 exposure time represents four tests. For  
all other exposure times only one test is represented.]

Material	Exposure time, hr	$S_u$ ,		$S_y$ , (* )		e, percent in 2 in. (5.08 cm)
		ksi	MN/m <sup>2</sup>	ksi	MN/m <sup>2</sup>	
PH 15-7 Mo TH 1050	0	201	1390	196	1350	7
	2200	205	1420	200	1380	7
	4400	208	1440	202	1390	7
	8800	210	1450	205	1420	7
AM 350 20 percent CRT	0	201	1390	185	1280	19
	2200	192	1330	187	1290	20
	4400	194	1340	189	1310	20
	8800					
AM 350 double aged	0	190	1310	158	1090	13
	2200	192	1330	158	1090	13
	4400	191	1320	157	1080	13
	8800					
AISI 301 50 percent CR	0	216	1500	203	1400	4
	2200	231	1600	199	1380	3
	4400	230	1590	201	1390	3
	8800					
Ti-6Al-4V annealed	0	149	1030	142	983	12
	2200	158	1090	149	1030	11
	4400	159	1100	148	1020	10
	8800					
Ti-4Al-3Mo-1V aged	0	142	983	122	846	10
	2200	142	983	122	846	10
	4400	142	983	122	846	9
	8800	142	983	121	838	10
Ti-8Al-1Mo-1V single annealed	0	157	1080	145	1010	16
	2200	157	1080	144	1000	16
	4400	156	1080	146	1010	17
	8800	157	1080	146	1010	15

\*0.2-percent offset.

TABLE II.- ROOM-TEMPERATURE TENSILE PROPERTIES OF FUSION-WELDED SPECIMENS,  
GRAIN PARALLEL TO ROLLING DIRECTION

[Four tests per value]

Material	Direction of weld	$S_u$ , ksi ( $MN/m^2$ )		$S_y$ , ksi ( $MN/m^2$ ) (***)		e, percent in 2 in. (5.08 cm)	
		Welded	Virgin	Welded	Virgin	Welded	Virgin
PH 15-7 Mo* TH 1050	Transverse	120 (828)	201 (1390)	105 (724)	196 (1350)	3	7
	Longitudinal	175 (1210)		144 (993)		12	
PH 15-7 Mo** TH 1050	Transverse	197 (1370)	201 (1390)	185 (1280)	196 (1350)	2	7
	Longitudinal	203 (1400)		194 (1340)		10	
AM 350 20 percent CRT	Transverse	132 (910)	201 (1390)	100 (690)	185 (1280)	4	19
	Longitudinal	163 (1120)		106 (731)		9	
AM 350* double aged	Transverse	133 (917)	190 (1310)	103 (710)	158 (1090)	4	13
	Longitudinal	170 (1170)		113 (780)		19	
AM 350** double aged	Transverse	180 (1240)	190 (1310)	150 (1030)	158 (1090)		13
	Longitudinal	178 (1230)		144 (993)			
AISI 301 50 percent CR	Transverse	133 (917)	216 (1500)	70 (483)	203 (1400)	7	4
	Longitudinal	170 (1170)		120 (828)		10	
Ti-6Al-4V annealed	Transverse	150 (1030)	149 (1030)	144 (993)	142 (983)	12	12
	Longitudinal	162 (1120)		157 (1080)		7	
Ti-4Al-3Mo-1V aged	Transverse	143 (986)	142 (983)	125 (862)	122 (846)	8	10
	Longitudinal	156 (1080)		129 (890)		5	
Ti-8Al-1Mo-1V single annealed	Transverse	147 (1010)	157 (1080)	135 (930)	145 (1010)	14	16
	Longitudinal	156 (1080)		106 (731)		10	

\*Welded after heat treatment.

\*\*Welded before heat treatment.

\*\*\*0.2-percent offset.

TABLE III.- ROOM-TEMPERATURE TENSILE STRENGTH OF UNEXPOSED FATIGUE SPECIMENS

[Two tests per value]

Material	S <sub>u</sub> , ksi	Tensile strength, ksi (MN/m <sup>2</sup> ) for -						Percent of S <sub>u</sub> for -						
		K <sub>T</sub> = 1		K <sub>T</sub> = 4		Spot-weld		Fusion-weld		K <sub>T</sub> = 1	K <sub>T</sub> = 4	Spot-weld	Fusion-weld	
		Before heat treatment	After heat treatment	Before heat treatment	After heat treatment	Before heat treatment	After heat treatment	Before heat treatment	After heat treatment				Before heat treatment	After heat treatment
PH 15-7 Mo	201	206 (1420)	214 (1480)	173 (1190)	139 (960)	208 (1440)	102	106	86	69	104			
AM 350 CRT	201	195 (1350)	201 (1390)	184 (1270)	139 (960)		97	100	92	69				
AM 350 DA	190	207 (1430)	218 (1500)	169 (1170)	125 (862)	187 (1290)	108	114	89	66	98			
AISI 301	216	206 (1420)	198 (1370)	186 (1280)	130 (896)		95	91	86	60				
Ti-6Al-4V	149	152 (1050)	163 (1120)	148 (1020)	160 (1100)		102	109	99	107				
Ti-4Al-3Mo-1V	142	141 (973)	141 (973)	141 (973)	146 (1010)		99	99	99	103				
Ti-8Al-1Mo-1V	157	156 (1080)	167 (1150)	151 (1040)	159 (1100)		99	106	96	101				

<sup>a</sup>Three specimens tested; all three failed away from welds.

<sup>b</sup>One of two specimens tested failed away from welds.

TABLE IV.- RESULTS OF PREEXPOSURE FATIGUE TESTS

(a) PH 15-7 Mo steel; condition TH 1050

Sheet	S <sub>max</sub>		N, kilocycles	Sheet	S <sub>max</sub>		N, kilocycles
	ksi	MN/m <sup>2</sup>			ksi	MN/m <sup>2</sup>	
K <sub>T</sub> = 1; S <sub>mean</sub> = 40 ksi (276 MN/m <sup>2</sup> )				Fusion weld, welded after heat treatment; S <sub>mean</sub> = 40 ksi (276 MN/m <sup>2</sup> ) - Concluded			
8	160	1104	32	14	90	621	120
8	160	1104	41	14	90	621	129
8	160	1104	44	14	90	621	130
8	140	966	75	14	90	621	170
8	140	966	84	14	90	621	171
8	140	966	99	14	90	621	184
8	140	966	119	14	90	621	328
8	120	828	73	14	90	621	355
8	120	828	119	14	87	600	127
8	120	828	178	14	87	600	215
8	113	780	158	14	87	600	369
8	113	780	710	14	85	587	329
8	113	780	2 873	14	85	587	1 065
8	108	745	973	14	82	566	591
8	108	745	3 516	14	79	545	2 233
K <sub>T</sub> = 4; S <sub>mean</sub> = 40 ksi (276 MN/m <sup>2</sup> )				14	79	545	8 140
8	66.5	459	27	14	78	538	>10 000
6	65	449	54	Fusion weld; welded prior to heat treatment; S <sub>mean</sub> = 40 ksi (276 MN/m <sup>2</sup> )			
4	62	428	41	12	115	794	26
4	62	428	45	12	115	794	32
8	62	428	78	12	115	794	70
2	62	428	94	12	110	759	20
8	58	400	124	12	110	759	57
8	58	400	>10 000	12	110	759	89
8	57	393	>10 000	12	110	759	93
Spotweld; S <sub>mean</sub> = 40 ksi (276 MN/m <sup>2</sup> )				12	110	759	97
10	75	518	19	12	105	725	47
10	75	518	20	12	105	725	52
10	75	518	21	12	105	725	61
6	75	518	27	12	105	725	261
10	55	380	242	12	100	690	80
10	55	380	250	12	100	690	85
10	55	380	252	12	100	690	97
10	50	345	810	12	100	690	129
10	50	345	2 586	12	100	690	220
Fusion weld; welded after heat treatment; S <sub>mean</sub> = 40 ksi (276 MN/m <sup>2</sup> )				12	95	656	275
14	105	725	20	12	95	656	337
14	105	725	22	12	95	656	728
14	105	725	33	12	92	635	206
14	102	704	21	12	92	635	257
13	102	704	72	12	92	635	314
14	100	690	36	12	90	621	58
14	100	690	42	12	90	621	108
14	100	690	49	12	90	621	198
14	95	656	44	12	90	621	223
14	95	656	50	12	90	621	574
14	95	656	60	12	90	621	>10 000
14	90	621	24	12	87	600	843
14	90	621	68	12	87	600	1 352
14	90	621	115	12	87	600	>10 000
				12	85	587	6 828
				12	85	587	>10 000
				12	85	587	>10 000

TABLE IV.-- RESULTS OF PREEXPOSURE FATIGUE TESTS - Continued

(b) AM 350 20 percent CRT steel

Sheet	$S_{max}$		N, kilocycles	Sheet	$S_{max}$		N, kilocycles
	ksi	MN/m <sup>2</sup>			ksi	MN/m <sup>2</sup>	
K <sub>T</sub> = 1; S <sub>mean</sub> = 40 ksi (276 MN/m <sup>2</sup> )				Spot-weld; S <sub>mean</sub> = 40 ksi (276 MN/m <sup>2</sup> )			
4	160	1104	20	3	75	518	24
4	160	1104	26	3	75	518	26
4	160	1104	26	3	75	518	30
4	155	1070	40	3	75	518	39
4	155	1070	43	3	70	483	43
4	155	1070	43	3	70	483	56
4	150	1035	46	3	65	449	87
4	150	1035	60	3	65	449	88
4	150	1035	68	3	65	449	88
4	140	966	57	3	65	449	91
4	140	966	80	3	65	449	98
4	140	966	96	3	60	414	191
4	130	897	147	3	60	414	240
4	130	897	170	3	60	414	249
4	130	897	188	3	60	414	250
1	125	863	92	3	55	380	429
1	125	863	220	3	55	380	510
1	125	863	572	3	55	380	610
1	125	863	691	3	55	380	643
4	125	863	1 372	3	55	380	844
4	120	828	427	3	53	366	830
1	120	828	587	3	53	366	1 296
1	120	828	1 197	3	51	352	>300
1	115	794	272	3	51	352	1 402
4	115	794	453	3	51	352	1 590
4	115	794	684	3	49	338	>10 000
4	112	773	211	3	48	331	9 152
4	112	773	708				
4	112	773	1 019	Fusion-weld; S <sub>mean</sub> = 40 ksi (276 MN/m <sup>2</sup> )			
1	110	759	1 048	7	115	794	16
4	110	759	>10 000	7	115	794	17
4	110	759	>10 000	7	115	794	20
K <sub>T</sub> = 4; S <sub>mean</sub> = 40 ksi (276 MN/m <sup>2</sup> )				7	110	759	21
4	85	587	11	7	110	759	32
4	85	587	11	7	110	759	33
4	85	587	11	7	105	725	52
4	80	552	16	7	105	725	59
4	80	552	16	7	105	725	59
4	80	552	22	7	100	690	131
4	72	497	23	7	100	690	141
4	72	497	23	7	100	690	163
4	72	497	28	7	100	690	180
4	65	449	38	7	100	690	204
4	65	449	41	7	95	656	239
4	65	449	49	7	95	656	261
4	65	449	53	7	95	656	677
4	65	449	62	7	92	635	141
4	60	414	67	7	92	635	1 764
4	60	414	67	7	92	635	2 895
4	60	414	94	7	90	621	379
4	58	400	71	7	90	621	959
1	58	400	87	7	90	621	1 315
1	58	400	>10 000	7	90	621	3 220
4	57	393	84	7	87	600	243
1	57	393	1 245	7	87	600	>10 000
1	57	393	1 792	7	87	600	>10 000
4	55	380	110	7	85	587	>10 000
1	55	380	174	7	85	587	>10 000
4	55	380	1 026	7	85	587	>10 000
4	55	380	1 862	7	83	572	>10 000
4	52	359	4 002				
1	52	359	>10 000				
1	52	359	>10 000				

TABLE IV.- RESULTS OF PREEXPOSURE FATIGUE TESTS - Continued

(c) AM 350 double-aged steel

Sheet	S <sub>max</sub>		N, kilocycles	Sheet	S <sub>max</sub>		N, kilocycles
	ksi	MN/m <sup>2</sup>			ksi	MN/m <sup>2</sup>	
K <sub>T</sub> = 1; S <sub>mean</sub> = 40 ksi (276 MN/m <sup>2</sup> )				K <sub>T</sub> = 4; S <sub>mean</sub> = 40 ksi (276 MN/m <sup>2</sup> )			
				Concluded			
3	160	1104	13	3	65	449	47
3	160	1104	15	3	65	449	54
3	160	1104	17	1	65	449	87
1	150	1035	26	3	62	428	71
1	150	1035	27	3	62	428	85
1	150	1035	37	3	62	428	9 141
3	140	966	37	3	60	414	66
1	140	966	37	1	60	414	>10 000
3	140	966	43	1	60	414	>10 000
1	140	966	45	3	60	414	>10 000
3	140	966	74	3	52	359	>10 000
3	140	966	96	3	50	345	>10 000
3	140	966	96	Spot-weld; S <sub>mean</sub> = 40 ksi (276 MN/m <sup>2</sup> )			
1	135	932	116	6	75	518	18
3	135	932	259	6	75	518	24
3	130	897	95	6	75	518	21
3	130	897	170	6	70	483	34
3	130	897	177	6	70	483	38
3	130	897	354	6	70	483	43
3	125	863	565	6	70	483	47
1	125	863	612	6	65	449	71
3	125	863	1 398	6	65	449	83
1	125	863	2 925	6	65	449	86
1	125	863	>10 000	6	60	414	111
3	120	828	164	6	60	414	159
3	120	828	165	6	60	414	176
1	120	828	>10 000	6	60	414	231
3	120	828	>10 000	6	57	393	255
1	115	794	3 571	6	57	393	273
1	115	794	>10 000	6	57	393	289
K <sub>T</sub> = 4; S <sub>mean</sub> = 40 ksi (276 MN/m <sup>2</sup> )				6	57	393	326
3	80	552	9	6	55	380	289
3	80	552	10	6	55	380	330
3	80	552	14	6	55	380	960
3	76	524	14	6	55	380	>10 000
3	76	524	18	6	53	366	5 336
3	76	524	20	6	52	359	3 489
3	72	497	20	6	52	359	4 554
3	72	497	25	6	52	359	8 089
1	72	497	38	6	51	352	1 942
1	68	469	22	6	51	352	2 112
3	68	469	25	6	50	345	>10 000
1	68	469	49				

TABLE IV.- RESULTS OF PREEXPOSURE FATIGUE TESTS - Continued

(c) AM 350 double-aged steel - Concluded

Sheet	S <sub>max</sub>		N, kilocycles	Sheet	S <sub>max</sub>		N, kilocycles
	ksi	MN/m <sup>2</sup>			ksi	MN/m <sup>2</sup>	
Fusion-weld; welded after heat treatment; S <sub>mean</sub> = 40 ksi (276 MN/m <sup>2</sup> )				Fusion-weld; welded prior to heat treatment; S <sub>mean</sub> = 40 ksi (276 MN/m <sup>2</sup> )			
8	125	863	5	7	140	966	11
8	125	863	8	7	140	966	25
8	120	828	8	7	140	966	26
8	120	828	9	7	140	966	29
8	120	828	11	7	130	897	27
8	115	794	12	7	130	897	30
8	115	794	13	7	130	897	32
8	115	794	25	7	130	897	34
8	110	759	20	7	130	897	35
8	110	759	33	7	125	863	44
8	110	759	47	7	125	863	117
8	105	725	69	7	120	828	45
8	105	725	70	7	120	828	49
8	105	725	71	7	120	828	62
8	105	725	137	7	120	828	89
8	100	690	75	7	115	794	107
8	100	690	154	7	115	794	154
8	100	690	159	7	115	794	202
8	100	690	180	7	110	759	135
8	100	690	188	7	110	759	141
8	100	690	275	7	110	759	238
8	97	669	75	7	105	725	334
8	97	669	246	7	105	725	366
8	97	669	251	7	100	690	151
8	97	669	278	7	100	690	366
8	95	656	136	7	100	690	487
8	95	656	457	7	97	669	787
8	95	656	524	7	97	669	2 823
8	95	656	550	7	96	662	624
8	95	656	738	7	96	662	>10 000
8	92	635	306	7	92	635	>10 000
8	92	635	383				
8	92	635	700				
8	90	621	705				
8	90	621	994				
8	90	621	1 293				
8	90	621	1 590				
8	90	621	>10 000				
8	87	600	1 571				
8	87	600	>10 000				
8	85	587	1 501				
8	85	587	>10 000				
8	85	587	>10 000				
8	85	587	>10 000				
8	80	552	>10 000				
8	80	552	>10 000				

TABLE IV.- RESULTS OF PREEXPOSURE FATIGUE TESTS - Continued

(d) AISI 301, 50 percent CR steel

Sheet	S <sub>max</sub>		N, kilocycles	Sheet	S <sub>max</sub>		N, kilocycles
	ksi	MN/m <sup>2</sup>			ksi	MN/m <sup>2</sup>	
K <sub>T</sub> = 1; S <sub>mean</sub> = 40 ksi (276 MN/m <sup>2</sup> )				Spot-weld; S <sub>mean</sub> = 40 ksi (276 MN/m <sup>2</sup> )			
2	140	966	18	7	70	483	18
2	140	966	21	7	70	483	19
2	140	966	23	7	70	483	19
2	140	966	36	7	65	449	30
2	140	966	37	7	65	449	32
2	140	966	51	7	65	449	36
1	130	897	32	7	65	449	54
2	130	897	33	7	60	414	71
2	130	897	37	7	60	414	71
3	122	842	1 741	7	60	414	76
2	120	828	47	7	60	414	125
2	120	828	51	7	57	393	110
2	120	828	63	7	57	393	126
2	120	828	68	7	57	393	145
1	120	828	73	7	55	380	137
2	120	828	81	7	55	380	167
2	120	828	87	7	55	380	186
1	120	828	167	7	55	380	332
1	120	828	425	7	53	366	256
1	120	828	841	7	53	366	257
1	120	828	>10 000	7	53	366	294
1	110	759	72	7	52	359	290
1	110	759	228	7	52	359	387
1	110	759	1 964	7	52	359	437
1	110	759	>8 046	7	52	359	>10 000
2	110	759	>10 000	7	51	352	387
2	110	759	>10 000	7	51	352	422
1	105	725	3 693	7	51	352	608
1	100	690	75	7	50	345	695
1	100	690	106	7	50	345	777
2	100	690	176	7	48	331	>10 000
1	100	690	210	7	48	331	>10 000
2	100	690	1 720	Fusion-weld; S <sub>mean</sub> = 40 ksi (276 MN/m <sup>2</sup> )			
2	100	690	6 770	6	87	600	61
1	100	690	>10 000	6	87	600	66
K <sub>T</sub> = 4; S <sub>mean</sub> = 40 ksi (276 MN/m <sup>2</sup> )				6	87	600	115
2	70	483	17	6	85	587	39
2	70	483	18	6	85	587	48
2	70	483	21	6	85	587	103
2	65	449	20	6	83	573	309
1	65	449	28	6	83	573	312
1	65	449	30	6	83	573	573
2	60	414	43	6	82	566	86
2	60	414	52	6	82	566	108
2	60	414	59	6	82	566	9 991
1	60	414	>10 000	6	82	566	>10 000
2	57	393	62	6	80	532	114
1	57	393	103	6	80	532	198
1	57	393	7 529	6	80	532	>10 000
2	57	393	>10 000	6	80	532	>10 000
1	57	393	>10 000	6	78	538	>10 000
1	57	393	>10 000	6	78	538	>10 000
1	55	380	94	6	75	518	>10 000
2	55	380	108	6	75	518	>10 000
2	55	380	271	6	75	518	>10 000
2	55	380	425				
2	55	380	9 879				
1	52	359	506				
2	52	359	630				
1	52	359	5 265				
1	52	359	>10 000				
2	50	345	2 018				
2	50	345	7 904				
1	50	345	>10 000				
1	48	331	>10 000				
2	48	331	>10 000				
2	48	331	>10 000				

TABLE IV.- RESULTS OF PREEXPOSURE FATIGUE TESTS - Continued

(e) Ti-6Al-4V annealed titanium

Sheet	S <sub>max</sub>		N, kilocycles	Sheet	S <sub>max</sub>		N, kilocycles
	ksi	MN/m <sup>2</sup>			ksi	MN/m <sup>2</sup>	
K <sub>T</sub> = 1; S <sub>mean</sub> = 25 ksi (173 MN/m <sup>2</sup> )				Spot-weld; S <sub>mean</sub> = 25 ksi (173 MN/m <sup>2</sup> )			
1	79	120	16	7	48	331	21
1		120	22	7	48	331	28
2		120	28	7	48	331	28
2	77	110	14	7	45	311	32
2		110	52	7	45	311	35
2		110	54	7	45	311	51
1	75	100	46	7	45	311	58
2		100	94	7	42	290	55
2		100	145	7	40	276	49
1	74	96	117	7	40	276	72
2		95	78	7	40	276	86
2		95	113	7	40	276	132
2		95	321	7	40	276	133
2		95	691	7	38	262	222
2	72	90	615	7	37	255	99
2		90	902	7	37	255	124
2	71	85	62	7	37	255	175
1		85	587	7	37	255	178
2		85	587	7	35	242	334
2		85	847	7	35	242	415
2		85	1 058	7	35	242	592
2	67	80	342	7	34	235	>10 000
2		80	901	7	34	235	>10 000
1		80	1 925	7	33	228	>10 000
1		80	2 116	7	33	228	>10 000
1		80	2 512	7	30	207	>10 000
1		76	2 091	7	30	207	>10 000
1	67	76	2 176	7	30	207	>10 000
1		76	3 087	Fusion-weld; S <sub>mean</sub> = 25 ksi (173 MN/m <sup>2</sup> )			
1	66	72	2 910	3	90	621	19
2		72	6 526	3	90	621	24
2		72	9 081	3	90	621	32
1	64	70	483	3	90	621	32
1		70	2 648	3	85	587	18
1		70	2 695	3	85	587	22
1		68	4 345	3	85	587	23
1	63	68	5 360	3	80	552	26
1		68	7 049	3	80	552	36
K <sub>T</sub> = 4; S <sub>mean</sub> = 25 ksi (173 MN/m <sup>2</sup> )				3	80	552	66
1	58	60	414	3	75	518	55
1		55	380	3	75	518	80
1	55	55	380	3	75	518	98
2		55	380	3	70	483	41
1		50	345	3	70	483	58
1	50	50	345	3	70	483	107
1		50	345	3	70	483	277
1		45	311	3	70	483	537
1	44	45	311	3	68	469	503
1		45	311	3	68	469	1 453
2		40	276	3	68	469	3 293
1	37	40	276	3	65	449	112
1		40	276	3	65	449	1 026
1		40	276	3	65	449	7 327
2		40	276	3	65	449	>10 000
2	34	38	262	3	63	435	404
2		38	262	3	63	435	1 061
1		37	255				
1	32	37	255				
1		36	248				
2		36	248				
2	31	36	248				
2		35	242				
2		35	242				
2	29	34	235				
2		34	235				
2		34	235				
2		34	235				
2		34	235				
2		34	235				
2		33	228				
2		33	228				
2		33	228				
2		32	221				
2	22	32	221				

*annealed*

TABLE IV.- RESULTS OF PREEXPOSURE FATIGUE TESTS - Continued

(f) Ti-4Al-3Mo-1V aged titanium

Sheet	S <sub>max</sub>		N, kilocycles	Sheet	S <sub>max</sub>		N, kilocycles
	ksi	MN/m <sup>2</sup>			ksi	MN/m <sup>2</sup>	
K <sub>T</sub> = 1; S <sub>mean</sub> = 25 ksi (173 MN/m <sup>2</sup> )				Spot-weld; S <sub>mean</sub> = 25 ksi (173 MN/m <sup>2</sup> )			
1	110	759	11	3	48	331	27
1	110	759	14	3	48	331	31
1	110	759	15	5	48	331	36
1	100	690	14	5	45	311	34
1	100	690	16	5	45	311	40
1	100	690	21	3	45	311	49
1	90	621	17	3	45	311	51
1	90	621	19	3	42	290	70
1	90	621	29	3	42	290	82
1	84	580	28	3	42	290	97
1	84	580	41	5	40	276	84
1	82	566	34	5	40	276	108
1	82	566	56	5	40	276	155
1	82	566	78	5	40	276	167
1	80	552	49	5	40	276	222
1	75	518	41	3	38	262	181
2	75	518	65	5	38	262	>10 000
1	75	518	67	5	38	262	>10 000
2	70	483	69	3	38	262	>10 000
2	70	483	80	3	38	262	>10 000
2	70	483	178	5	38	262	>10 000
1	70	483	200	5	35	242	>10 000
1	68	469	126	5	35	242	>10 000
1	68	469	193	Fusion-weld; S <sub>mean</sub> = 25 ksi (173 MN/m <sup>2</sup> )			
1	68	469	316	6	75	518	16
1	68	469	>10 000	6	75	518	17
1	66	455	201	6	75	518	19
1	66	455	213	5	70	483	26
1	66	455	>10 000	5	70	483	30
2	65	449	>10 000	5	70	483	39
1	63	435	>10 000	5	70	483	39
1	60	414	>10 000	6	65	449	27
K <sub>T</sub> = 4; S <sub>mean</sub> = 25 ksi (173 MN/m <sup>2</sup> )				6	65	449	29
2	45	311	10	5	65	449	56
2	42	290	13	6	62	428	32
2	42	290	13	6	62	428	36
2	42	290	16	6	62	428	91
2	42	290	16	6	62	428	169
2	40	276	18	5	60	414	47
2	40	276	19	6	60	414	78
2	40	276	23	6	60	414	80
2	37	255	28	6	60	414	>10 000
2	37	255	31	6	58	400	48
2	37	255	32	6	58	400	73
2	35	242	44	5	55	380	61
2	35	242	51	5	55	380	66
2	35	242	63	5	55	380	>10 000
2	33	228	79	6	53	366	2 032
2	33	228	82	5	53	366	>10 000
2	33	228	145	6	53	366	>10 000
2	32	221	182	5	50	345	>10 000
2	32	221	199	6	50	345	>10 000
2	32	221	201				
1	32	221	>10 000				
2	32	221	>10 000				
2	31	214	476				
2	31	214	>10 000				
2	31	214	>10 000				
2	31	214	>10 000				

TABLE IV.- RESULTS OF PREEXPOSURE FATIGUE TESTS - Concluded

(g) Ti-8Al-1Mo-1V annealed titanium

Sheet	S <sub>max</sub>		N, kilocycles	Sheet	S <sub>max</sub>		N, kilocycles
	ksi	MN/m <sup>2</sup>			ksi	MN/m <sup>2</sup>	
K <sub>T</sub> = 1; S <sub>mean</sub> = 25 ksi (173 MN/m <sup>2</sup> )				Spot-weld; S <sub>mean</sub> = 25 ksi (173 MN/m <sup>2</sup> )			
8	110	759	21	3	48	331	24
8	110	759	22	3	48	331	25
8	110	759	28	3	48	331	32
8	100	690	19	3	48	331	81
8	100	690	23	3	45	311	32
8	100	690	57	3	45	311	58
8	95	656	24	3	45	311	80
8	95	656	27	3	45	311	109
8	95	656	45	6	45	297	46
8	95	656	64	6	43	297	47
8	90	621	38	6	43	297	57
8	90	621	59	6	43	297	97
8	90	621	80	3	43	297	139
8	90	621	89	3	40	276	73
8	90	621	127	3	40	276	105
8	85	587	46	3	40	276	226
8	85	587	71	6	38	262	107
8	85	587	97	3	38	262	155
8	85	587	979	3	38	262	196
8	85	587	1 365	3	36	248	351
8	85	587	9 420	3	36	248	439
8	80	552	122	6	35	242	185
8	80	552	124	3	35	242	289
8	80	552	138	3	35	242	432
8	80	552	505	3	35	242	659
8	80	552	1 471	3	34	235	7 987
8	80	552	1 522	3	34	235	8 864
8	77	531	2 960	6	34	235	>10 000
8	77	531	4 435	6	33	228	593
8	75	518	262	6	33	228	>10 000
8	75	518	319	Fusion-weld; S <sub>mean</sub> = 25 ksi (173 MN/m <sup>2</sup> )			
8	75	518	2 804	5	90	621	25
8	72	497	3 275	5	90	621	26
8	72	497	>10 000	5	90	621	27
8	72	497	1 840	5	85	587	24
8	70	483	7 921	5	85	587	32
8	70	483	9 955	5	85	587	33
8	70	483	1 595	5	85	587	28
8	70	483	>10 000	5	80	552	29
8	70	483	>10 000	5	80	552	38
8	66	455	>10 000	5	80	552	55
8	66	455	>10 000	5	78	538	80
8	66	455	>10 000	5	78	538	31
K <sub>T</sub> = 4; S <sub>mean</sub> = 25 ksi (173 MN/m <sup>2</sup> )				5	76	524	104
7	50	345	15	5	76	524	1 374
7	50	345	19	5	75	518	49
7	50	345	26	5	75	518	74
7	47	324	15	5	75	518	96
7	47	324	20	5	75	518	173
7	47	324	21	5	74	511	262
7	45	311	24	5	72	497	54
7	45	311	58	5	72	497	62
7	45	311	221	5	72	497	75
7	43	297	24	5	72	497	620
7	43	297	71	5	70	483	664
7	43	297	444	5	70	483	893
7	42	290	75	5	70	483	2 212
7	42	290	562	5	68	469	91
7	40	276	429	5	68	469	1 693
7	40	276	453	5	68	469	2 801
7	40	276	459	5	65	449	1 932
7	40	276	635	5	64	442	548
7	40	276	642	5	64	442	1 905
7	37	255	110	5	64	442	5 760
7	37	255	569	5	62	428	2 896
7	37	255	695	5	62	428	5 066
7	35	242	1 167	5	62	428	5 985
7	35	242	1 691	5	62	428	6 588
7	33	228	733	5	60	414	4 227
7	33	228	1 651	5	60	414	5 365
7	33	228	1 796	5	60	414	>10 000
7	32	221	3 571	5	58	400	4 943
7	32	221	9 252	5	58	400	5 615
7	32	221	>10 000	5	58	400	8 599
7	30	207	>10 000				
7	30	207	>10 000				
7	30	207	>10 000				

TABLE V.- STATIC STRENGTH OF FUSION-WELDED FATIGUE  
 SPECIMENS AFTER EXPOSURE TO 550° F (561° K)

[One specimen per period]

Material	S <sub>u</sub> , ksi, after exposure to 550° F (561° K) for -		
	0 hr	2200 hr	4400 hr
PH 15-7 Mo*	139	140	148
PH 15-7 Mo**	208	205	208
AM 350 CRT	139	132	103
AM 350 DA*	125	131	131
AM 350 DA**	187	182	184
AISI 301	130	122	123
Ti-6Al-4V	160	162	163
Ti-4Al-3Mo-1V	146	148	150
Ti-8Al-1Mo-1V	159	160	163

\*Welded after heat treatment.

\*\*Welded before heat treatment.

TABLE VI.- RESULTS OF EXPOSURE TO 550° F (561° K) FATIGUE TESTS

[Specimens which did not fail were excluded from calculation of geometric mean]

(a) PH 15-7 Mo;  $S_{mean} = 40 \text{ ksi (276 MN/m}^2\text{)}$

0 hours exposed	2200 hours exposed		4400 hours exposed		8800 hours exposed	
$N_f$ , kilocycles	Sheet	$N_f$ , kilocycles	Sheet	$N_f$ , kilocycles	Sheet	$N_f$ , kilocycles
$K_T = 1; S_{max} = 113 \text{ ksi (780 MN/m}^2\text{)}$						
400	3	240	7	106	7	261
	3	338	7	159	7	825
	3	348	7	208	7	908
	3	459	7	258	7	1 203
	3	787	7	310	7	1 322
		400*		195*		792*
$K_T = 4; S_{max} = 62 \text{ ksi (428 MN/m}^2\text{)}$						
70	6	47	6	36	7	43
	6	49	6	45	7	46
	6	66	6	47	7	54
	6	67	6	58	7	54
	6	69	6	155	7	74
		59*		59*		53*
Spotweld; $S_{max} = 67 \text{ ksi (462 MN/m}^2\text{)}$						
50	10	46	10	59	10	74
	10	48	10	59	10	79
	10	51	10	68	10	101
	10	64	10	69	10	107
	10	72	10	98	10	111
		55*		71*		94*
Fusion-weld (welded after heat treatment); $S_{max} = 90 \text{ ksi (621 MN/m}^2\text{)}$						
150	14	173				
	14	174				
	14	196				
	14	239				
	14	260				
		205*				
Fusion-weld (welded before heat treatment); $S_{max} = 100 \text{ ksi (690 MN/m}^2\text{)}$						
	12	74	12	54		
	12	86	12	58		
	12	90	12	63		
	12	100	12	133		
	12	180	12	263		
		100*		93*		

\*Geometric mean.

TABLE VI.- RESULTS OF EXPOSURE TO 550° F (561° K) FATIGUE TESTS - Continued

(b) AM 350 (20 percent CRT);  $S_{mean} = 40$  ksi (276 MN/m<sup>2</sup>)

0 hours exposed	2200 hours exposed		4400 hours exposed		8800 hours exposed	
$N_i$ , kilocycles	Sheet	$N$ , kilocycles	Sheet	$N$ , kilocycles	Sheet	$N$ , kilocycles
$K_T = 1$ ; $S_{max} = 130$ ksi (897 MN/m <sup>2</sup> )						
170	1 1 4 4 1	42 71 149 229 286  124*	1 1 1 4 4	93 126 261 278 364  198*	1 1 1 4	53 117 139 200  115*
$K_T = 4$ ; $S_{max} = 65$ ksi (449 MN/m <sup>2</sup> )						
40	4 4 1 1 1	38 41 44 48 7 690  43*	1 1 1 1 1	36 43 45 50 6 629  43*	1 4 1 4 4	32 37 38 39 43  38*
Spotweld; $S_{max} = 55$ ksi (380 MN/m <sup>2</sup> )						
500	3 3 3 3 3	579 652 695 1 233 1 795  945*	3 3 3 3 3	687 803 884 1 312 1 547  1 002*	3 3 3 3 3	620 690 817 1 161 1 666  1 000*
Fusion-weld; $S_{max} = 100$ ksi (690 MN/m <sup>2</sup> )						
140	7 7 7 7 7	72 90 111 118 155  106*	7 7 7 7 7	65 69 85 87 90  83*		

\* Geometric mean.

TABLE VI.- RESULTS OF EXPOSURE TO 550° F (561° K) FATIGUE TESTS - Continued

(c) AM 350 (double aged);  $S_{mean} = 40 \text{ ksi} (276 \text{ MN/m}^2)$

0 hours exposed	2200 hours exposed		4400 hours exposed		8800 hours exposed	
$N_i$ , kilocycles	Sheet	N, kilocycles	Sheet	N, kilocycles	Sheet	N, kilocycles
$K_T = 1; S_{max} = 140 \text{ ksi} (966 \text{ MN/m}^2)$						
60	1	54	3	52	1	28
	3	61	3	55	3	46
	3	78	3	56	1	61
	3	98	1	57	1	67
	3	102	3	80	3	89
		76*		60*		54*
$K_T = 4; S_{max} = 65 \text{ ksi} (449 \text{ MN/m}^2)$						
50	1	22	3	35	3	22
	3	33	3	36	3	25
	3	39	3	38	3	26
	1	63	3	50	3	30
	3	132	1	88	1	33
		47*		55*		26*
Spot-weld; $S_{max} = 57 \text{ ksi} (393 \text{ MN/m}^2)$						
300	6	227	6	217	6	249
	6	263	6	262	6	298
	6	306	6	277	6	329
	6	322	6	329	6	339
			6	392	6	375
		277*		295*		315*
Fusion-weld (welded after heat treatment); $S_{max} = 100 \text{ ksi} (690 \text{ MN/m}^2)$						
130	8	40	8	30		
	8	49	8	36		
	8	64	8	43		
	8	81	8	47		
	8	117	8	55		
		65*		41*		
Fusion-weld (welded before heat treatment); $S_{max} = 115 \text{ ksi} (794 \text{ MN/m}^2)$						
120	7	81	7	61		
	7	96	7	72		
	7	116	7	85		
	7	196	7	125		
	7	228	7	129		
		143*		90*		

\*Geometric mean.

TABLE VI.- RESULTS OF EXPOSURE TO 550° F (561° K) FATIGUE TESTS - Continued

(d) AISI 301 (50 percent CR);  $S_{mean} = 40$  ksi (276 MN/m<sup>2</sup>)

0 hours exposed	2200 hours exposed		4400 hours exposed		8800 hours exposed	
$N_i$ , kilocycles	Sheet	$N$ , kilocycles	Sheet	$N$ , kilocycles	Sheet	$N$ , kilocycles
$K_T = 1; S_{max} = 120$ ksi (828 MN/m <sup>2</sup> )						
80	2	114	2	113	2	50
	2	282	2	114	2	55
	1	>8 853	1	201	1	71
	1	>12 600	1	>10 650	2	113
	1	>14 540			1	>10 200
		660*		139*		58*
$K_T = 4; S_{max} = 60$ ksi (414 MN/m <sup>2</sup> )						
55	1	37	1	34	1	38
	2	38	1	52	1	46
	1	48	1	62	2	53
	1	66	2	>10 230	1	2 036
	2	>15 000	2	>10 446	2	6 828
		46*		48*		264*
Spot-weld; $S_{max} = 57$ ksi (393 MN/m <sup>2</sup> )						
120	7	115	7	106	7	108
	7	120	7	125	7	113
	7	126	7	134	7	125
	7	128	7	135	7	130
	7	129	7	155	7	134
		123*		131*		123*
Fusion-weld; $S_{max} = 82$ ksi (566 MN/m <sup>2</sup> )						
300	6	61	6	68		
	6	93	6	92		
	6	129	6	115		
	6	143	6	134		
				141		
		101*		106*		

\*Geometric mean.

TABLE VI.- RESULTS OF EXPOSURE TO 550° F (561° K) FATIGUE TESTS - Continued

(e) Ti-6Al-4V;  $S_{mean} = 25$  ksi (173 MN/m<sup>2</sup>)

0 hours exposed	2200 hours exposed		4400 hours exposed		8800 hours exposed	
$N_i$ , kilocycles	Sheet	$N$ , kilocycles	Sheet	$N$ , kilocycles	Sheet	$N$ , kilocycles
$K_T = 1$ ; $S_{max} = 100$ ksi (690 MN/m <sup>2</sup> )						
130	2	78	2	73	2	68
	1	91	2	89	2	79
	1	105	1	128	1	240
	2	132	1	182	1	1 110
	1	534	1	1 119		
		139*		176*		194*
$K_T = 4$ ; $S_{max} = 40$ ksi (276 MN/m <sup>2</sup> )						
50	2	33	1	33	1	36
	1	35	1	38	1	36
	2	41	2	40	2	47
	1	50	1	45	2	48
	1	51	2	1 255	1	67
		41*		78*		46*
Spot-weld; $S_{max} = 40$ ksi (276 MN/m <sup>2</sup> )						
90	7	127	7	155	7	88
	7	165	7	160	7	123
	7	167	7	220	7	125
	7	189	7	225	7	157
	7	229	7	261	7	189
		172*		187*		134*
Fusion-weld; $S_{max} = 75$ ksi (518 MN/m <sup>2</sup> )						
70	3	53	3	43		
	3	56	3	51		
	3	83	3	53		
	3	89	3	107		
	3	133	3	228		
		78*		78*		

\*Geometric mean.

TABLE VI.- RESULTS OF EXPOSURE TO 550° F (561° K) FATIGUE TESTS - Continued

(f) Ti-4Al-3Mo-1V;  $S_{mean} = 25$  ksi (173 MN/m<sup>2</sup>)

0 hours exposed	2200 hours exposed		4400 hours exposed		8800 hours exposed	
$N_i$ , kilocycles	Sheet	$N$ , kilocycles	Sheet	$N$ , kilocycles	Sheet	$N$ , kilocycles
$K_T = 1; S_{max} = 70$ ksi (483 MN/m <sup>2</sup> )						
120	1 1 1	42 119 246	1 1 1 1 1	70 202 >10 072 >12 715 >14 643	2 2 2 2 2	120 141 194 >10 414 >15 092
		107*		120*		147*
$K_T = 4; S_{max} = 33$ ksi (228 MN/m <sup>2</sup> )						
100	2 2 2 2 2	69 74 89 92 104	2 2 2 2 2	67 92 110 186 563	1 1 1 1 1	112 117 530 >10 000 >12 800
		85*		148*		191*
Spot-weld; $S_{max} = 40$ ksi (276 MN/m <sup>2</sup> )						
120	5 5 3 3 3	82 90 97 116 133	5 3 3 3 3	60 75 85 103 103	5 5 5 3 3	52 59 61 62 74
		103*		83*		61*
Fusion-weld; $S_{max} = 62$ ksi (428 MN/m <sup>2</sup> )						
50	6 6 5 6 5	40 41 43 50 52	5 6 6 6 5	30 34 56 65 75		
		45*		51*		

\* Geometric mean.

TABLE VI.- RESULTS OF EXPOSURE TO 550° F (561° K) FATIGUE TESTS - Concluded

(g) Ti-8Al-1Mo-1V;  $S_{mean} = 25$  ksi (173 MN/m<sup>2</sup>)

0 hours exposed	2200 hours exposed		4400 hours exposed		8800 hours exposed	
$N_1$ , kilocycles	Sheet	N, kilocycles	Sheet	N, kilocycles	Sheet	N, kilocycles
$K_T = 1; S_{max} = 90$ ksi (621 MN/m <sup>2</sup> )						
70	8	49	8	59	8	86
	8	78	8	60	8	155
	8	90	8	94	8	1 268
	8	92	8	151	8	4 401
	8	361	8	216		
			103*		102*	
$K_T = 4; S_{max} = 40$ ksi (276 MN/m <sup>2</sup> )						
200	7	44	7	33	7	35
	7	46	7	40	7	35
	7	48	7	59	7	56
	7	48	7	493	7	60
	7	56	7	59	7	43
			48*		74*	
Spot-weld; $S_{max} = 38$ ksi (262 MN/m <sup>2</sup> )						
200	6	121	3	139	6	140
	3	141	6	153	6	168
	6	186	3	204	3	419
	3	290	3	208	3	503
	3	575	6	217	3	559
			221*		181*	
Fusion-weld; $S_{max} = 75$ ksi (518 MN/m <sup>2</sup> )						
100	5	42	5	47		
	5	67	5	74		
	5	89	5	115		
	5	156	5	116		
	5	323	5	156		
			135*		113*	

\*Geometric mean.

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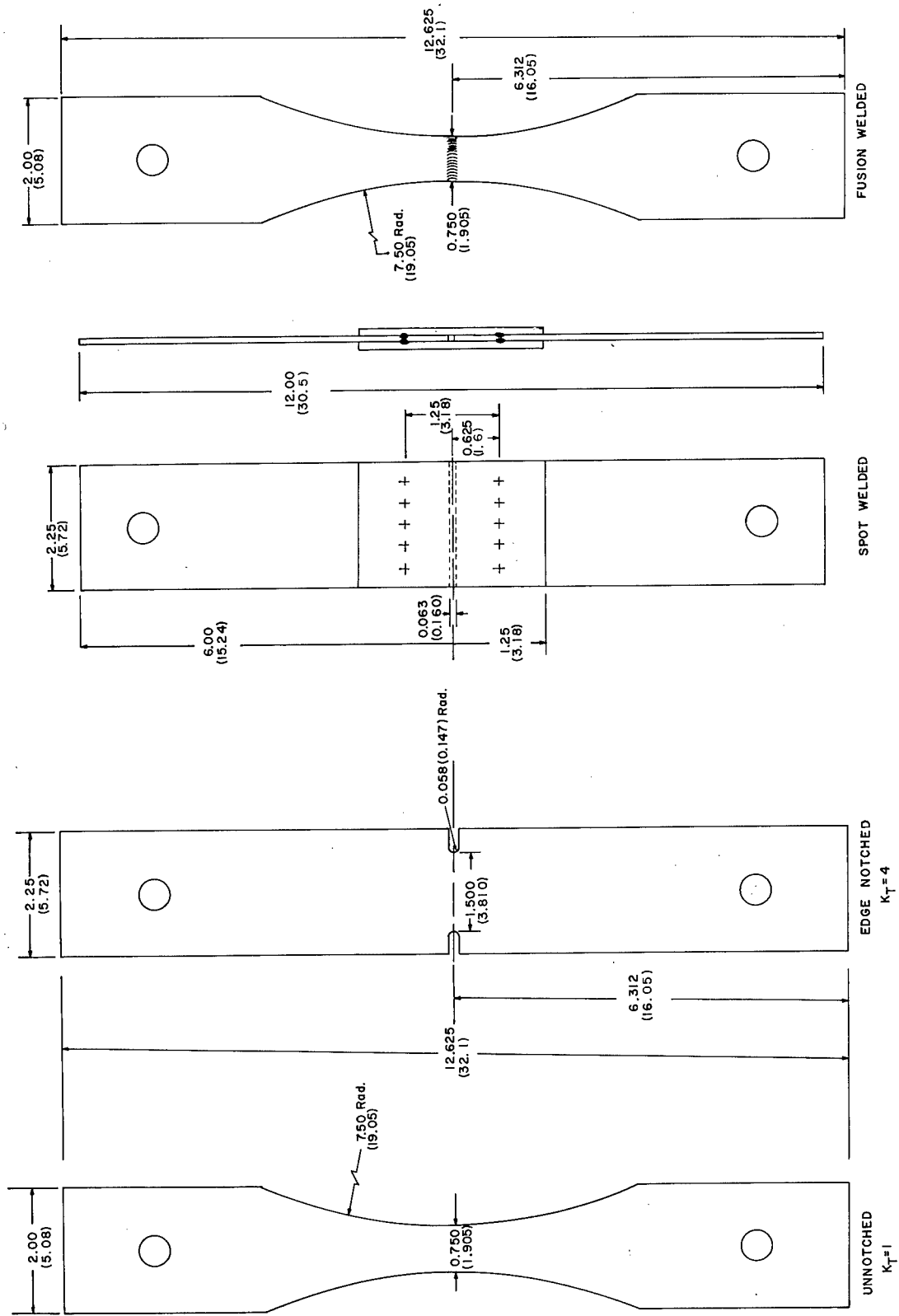


Figure 1.- Fatigue specimens. All dimensions are in inches (centimeters).

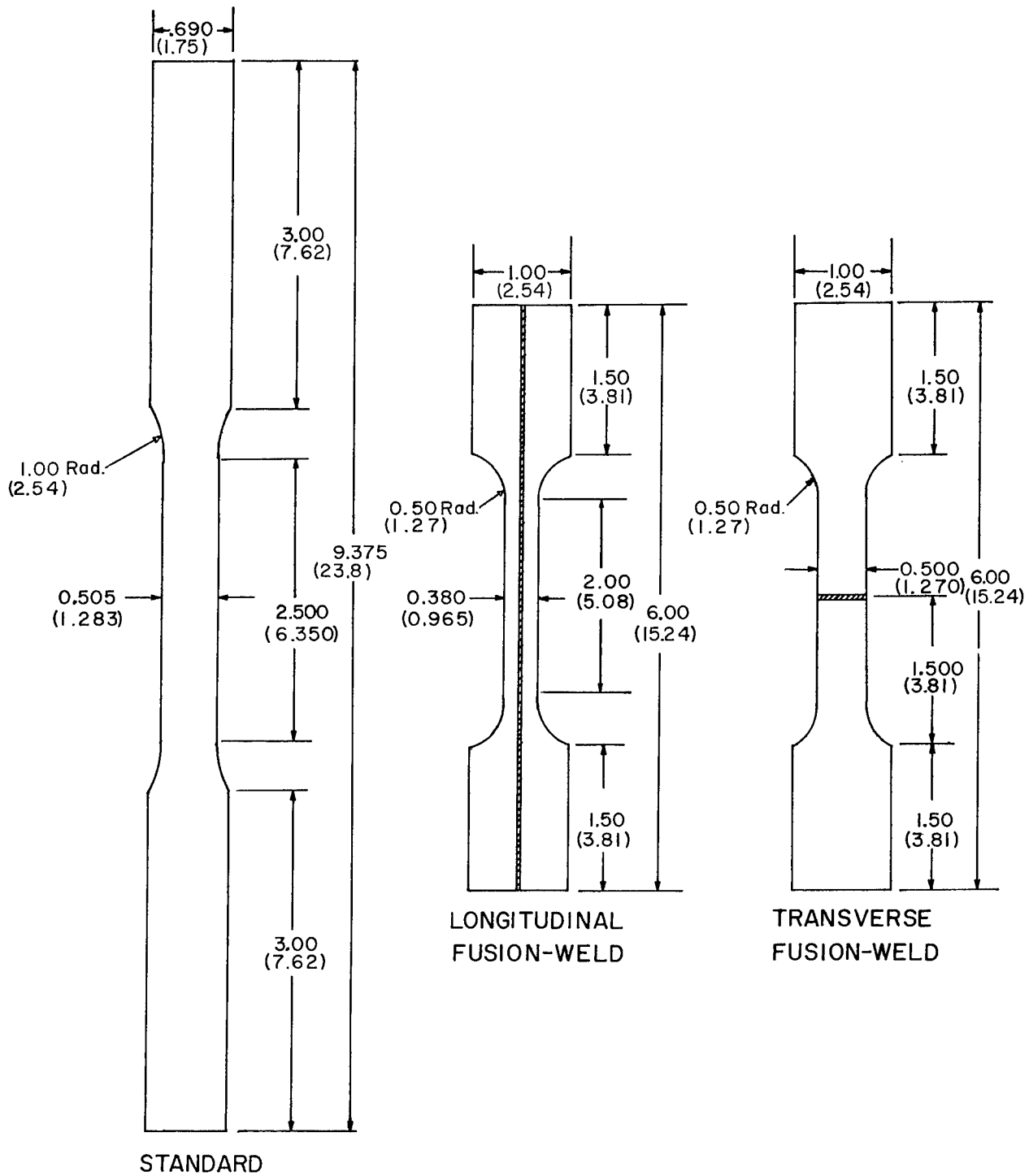


Figure 2.- Tensile specimens. All dimensions are in inches (centimeters).

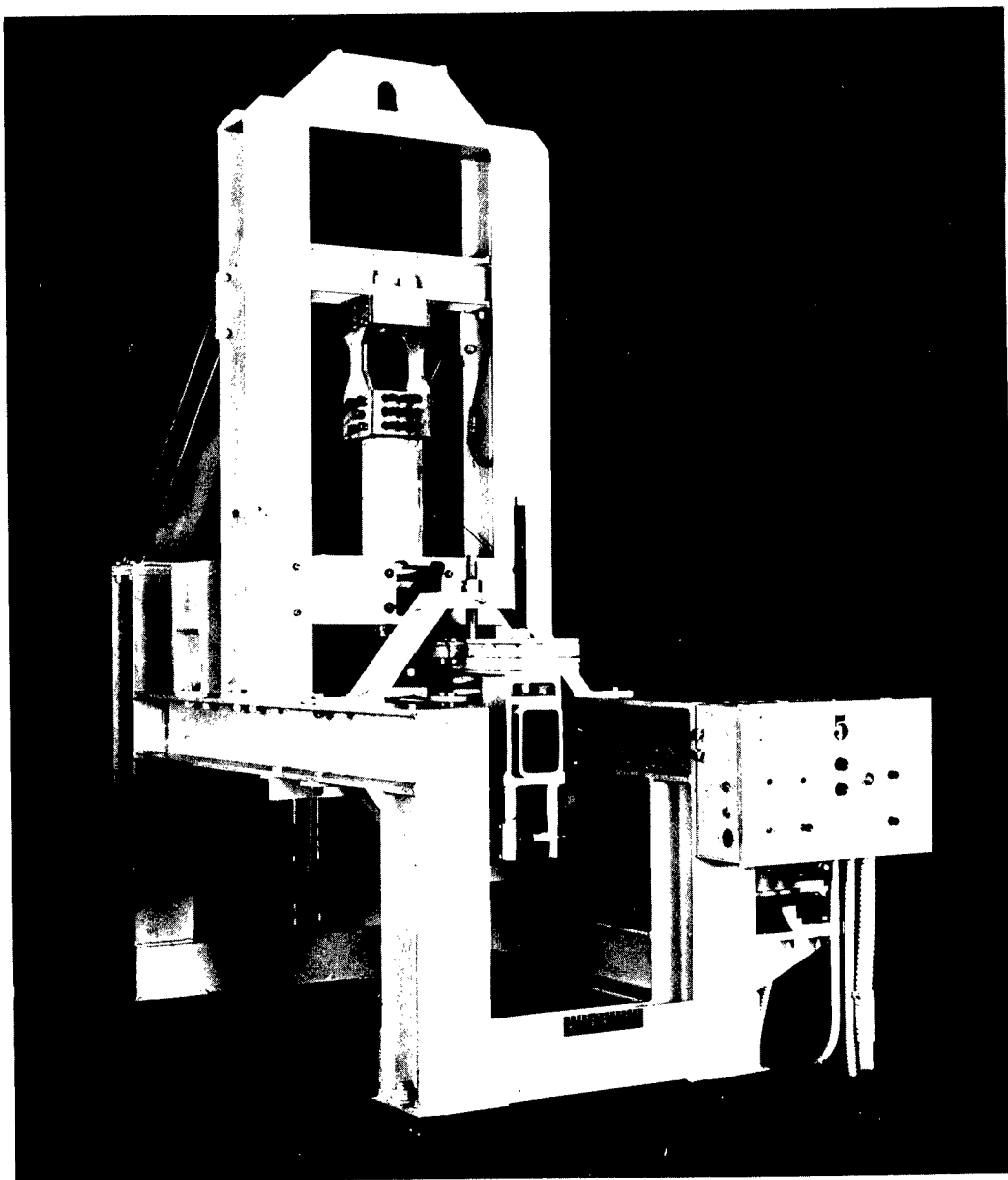


Figure 3.- Subresonant axial-load fatigue testing machine.

L-77926



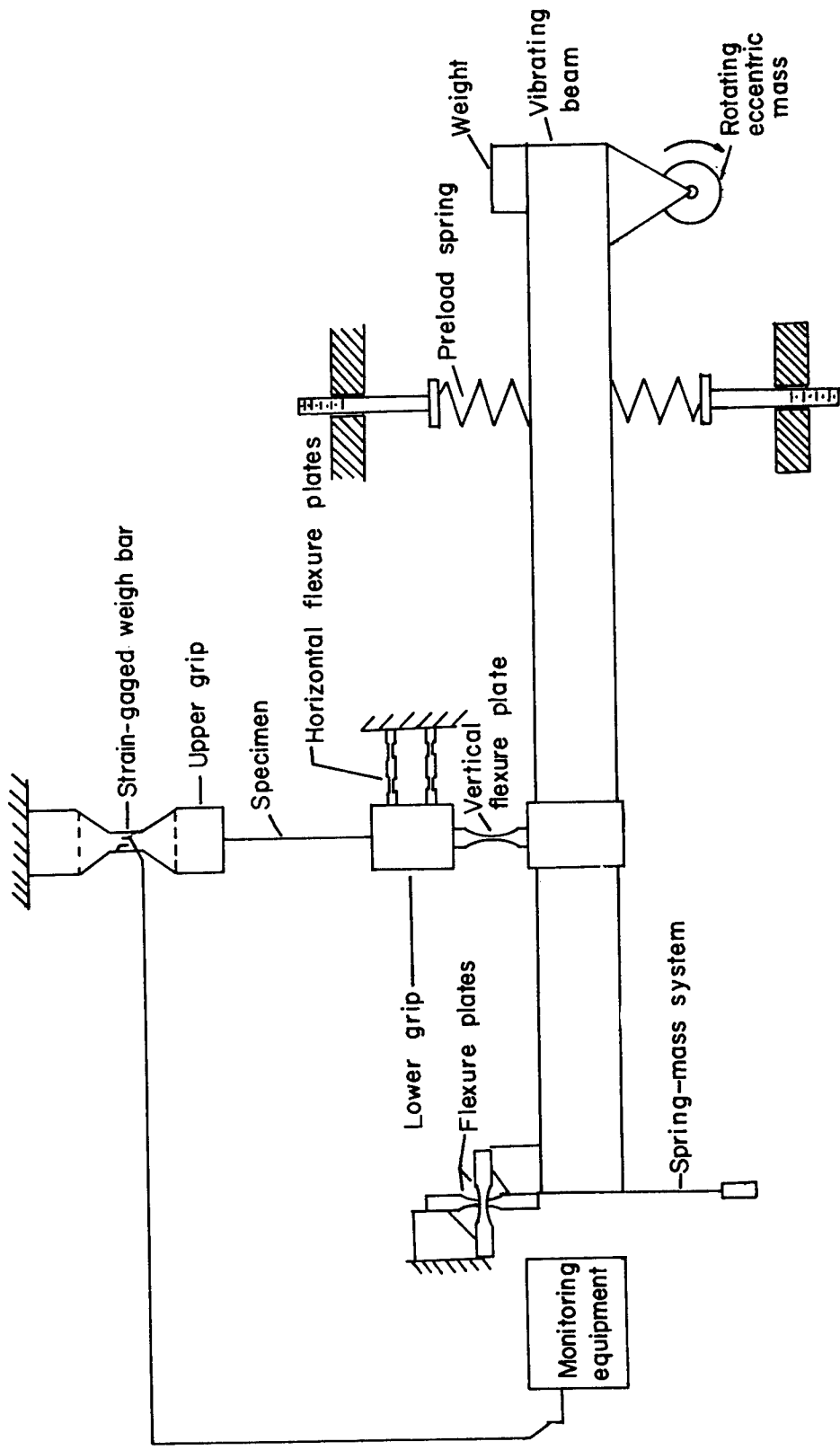
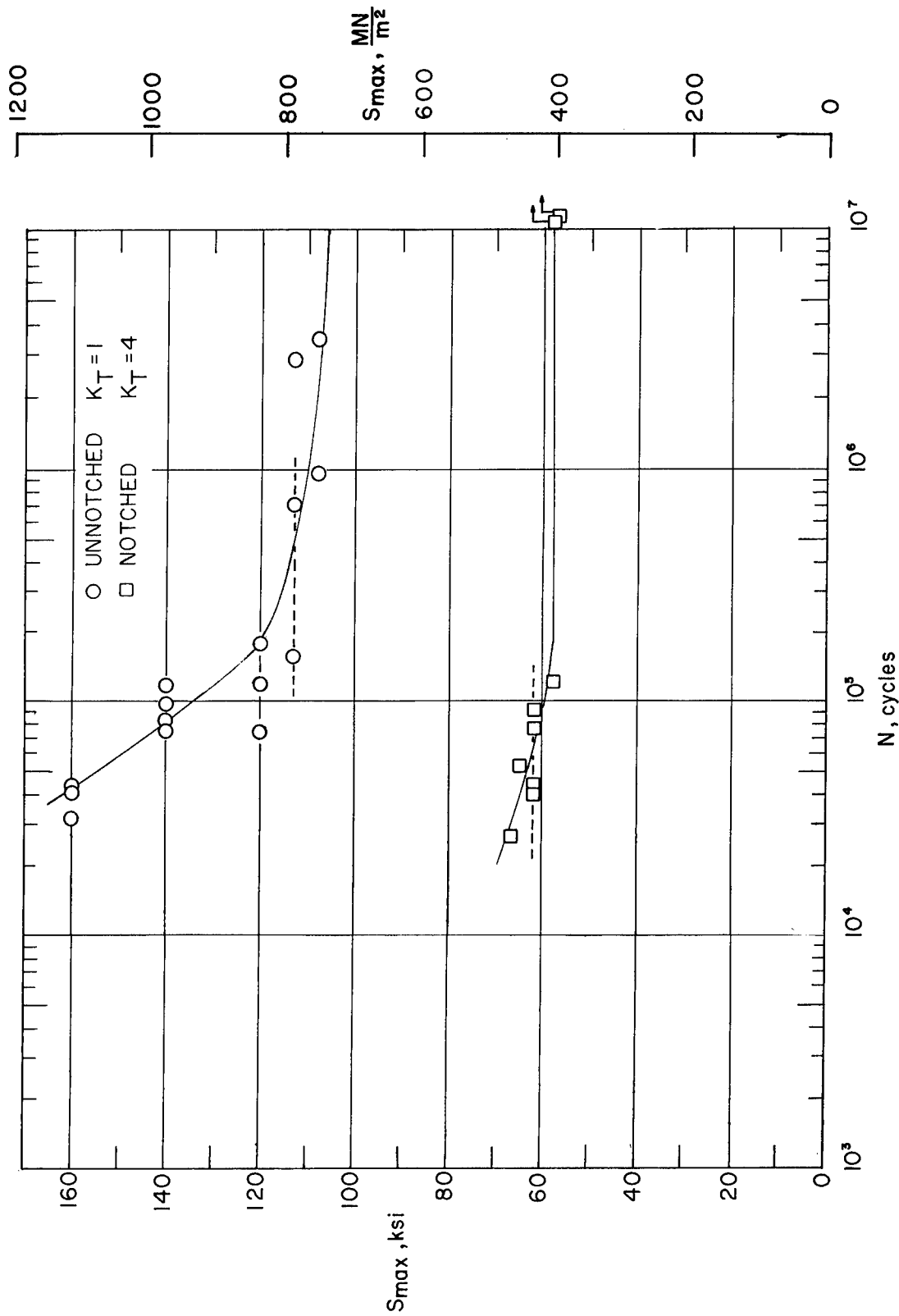
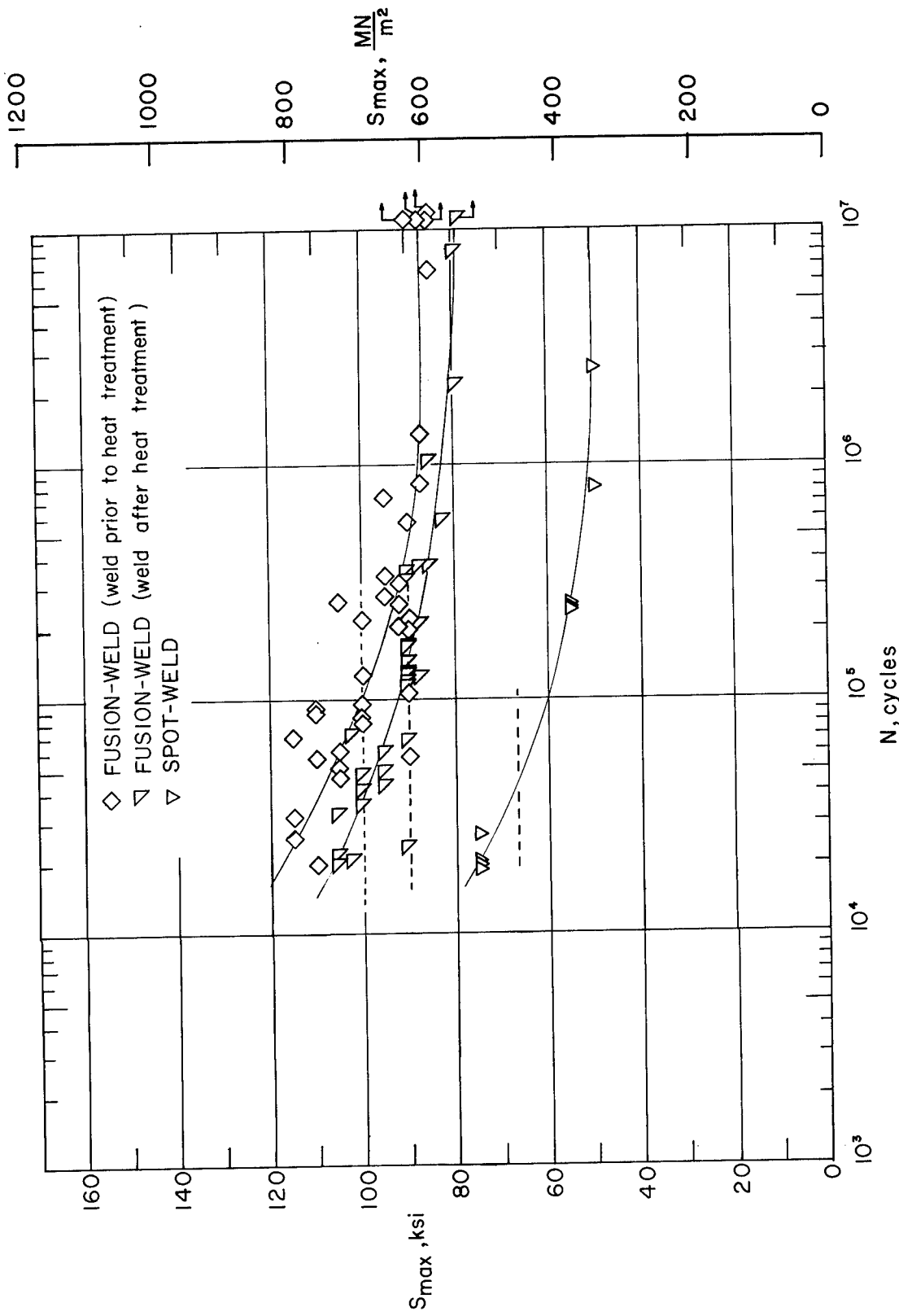


Figure 4.- Schematic of subresonant axial-load fatigue testing machine.



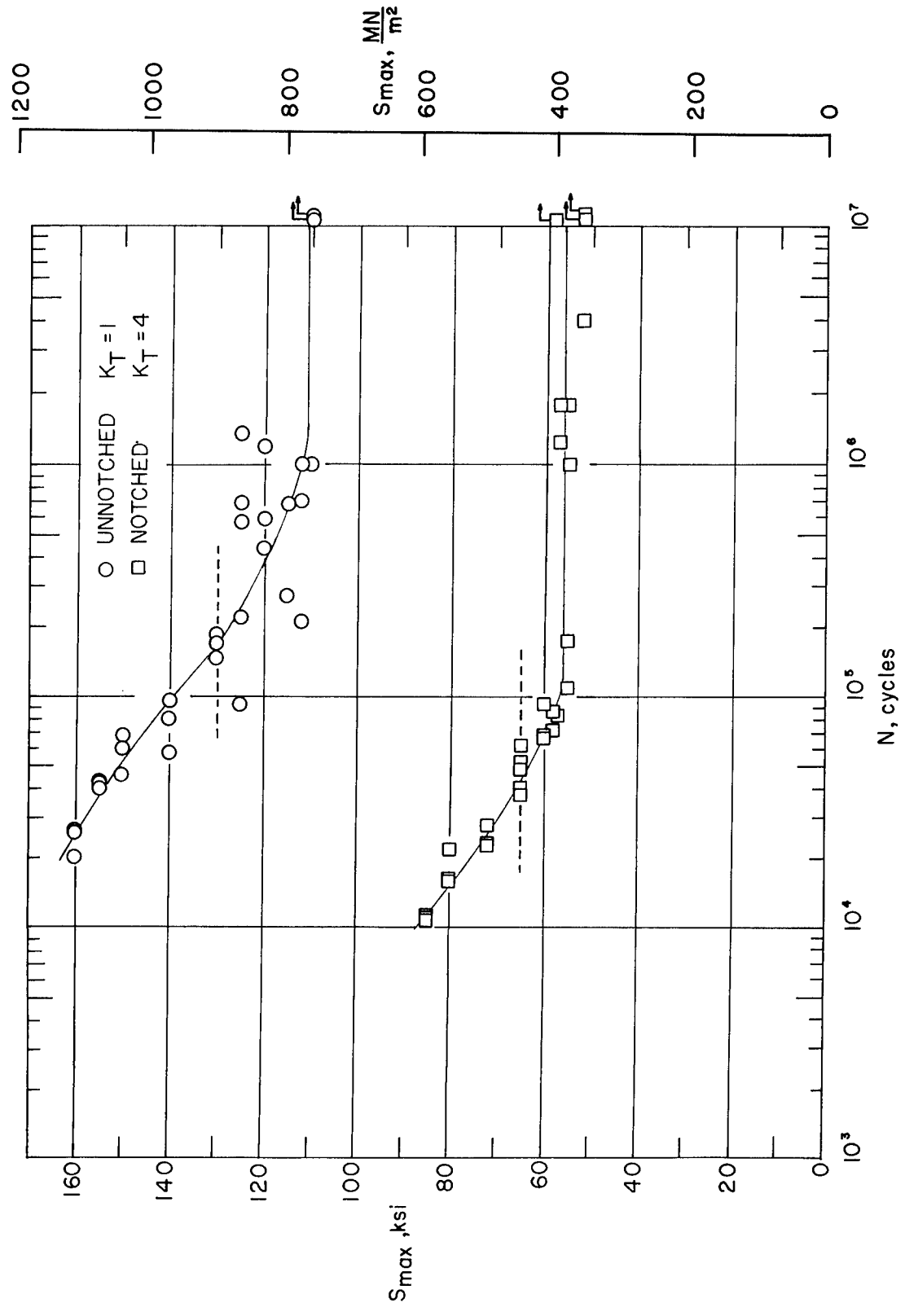
(a) PH 15-7Mo, condition TH 1050; mean stress, 40 000 psi (276 MN/m<sup>2</sup>).

Figure 5.- Results of axial-load tests. Dashed line represents postexposure stress level.



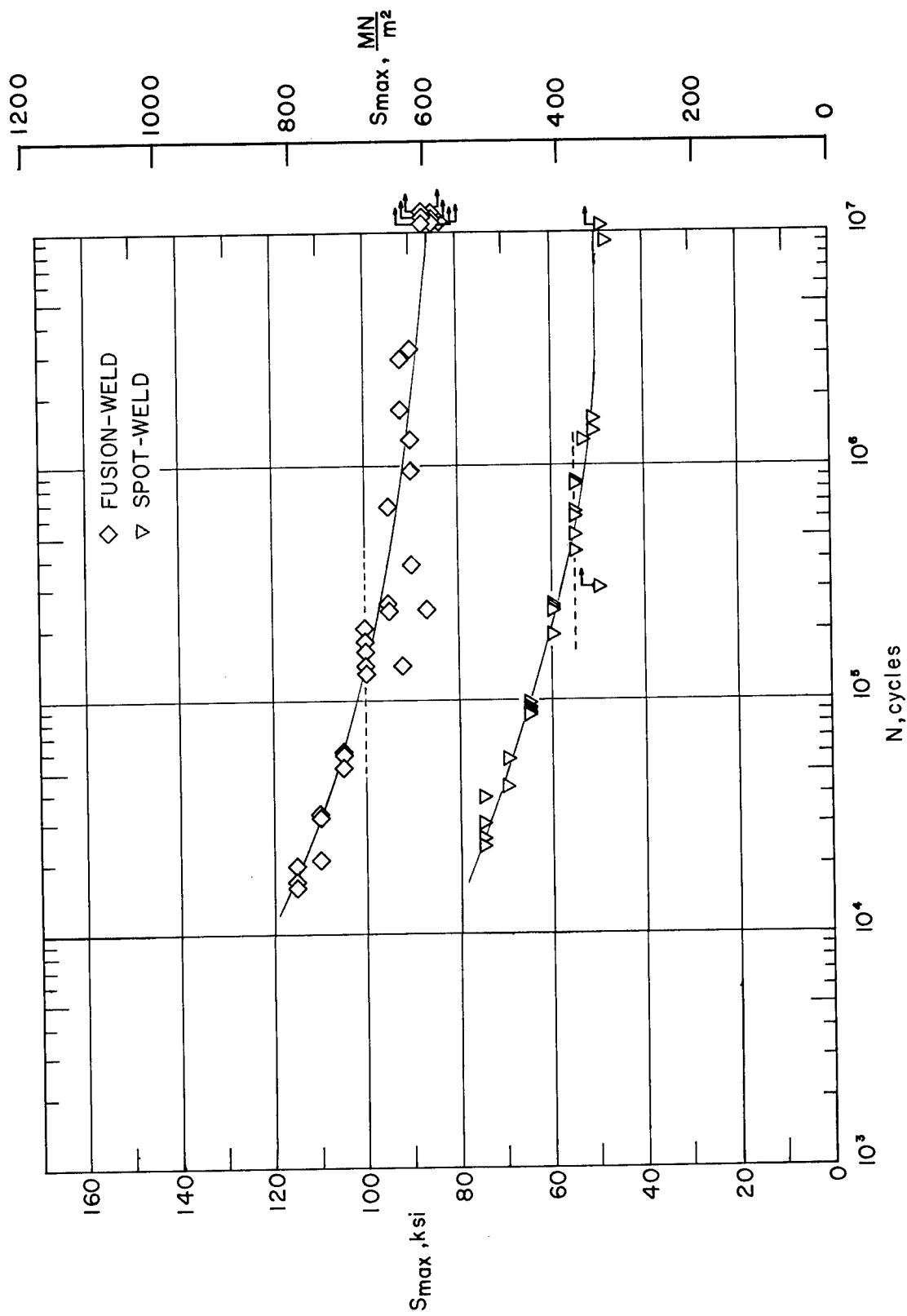
(a) PH 15-7Mo, condition TH 1050; mean stress, 40 000 psi ( $276 \text{ MN/m}^2$ ). Concluded.

Figure 5.- Continued.



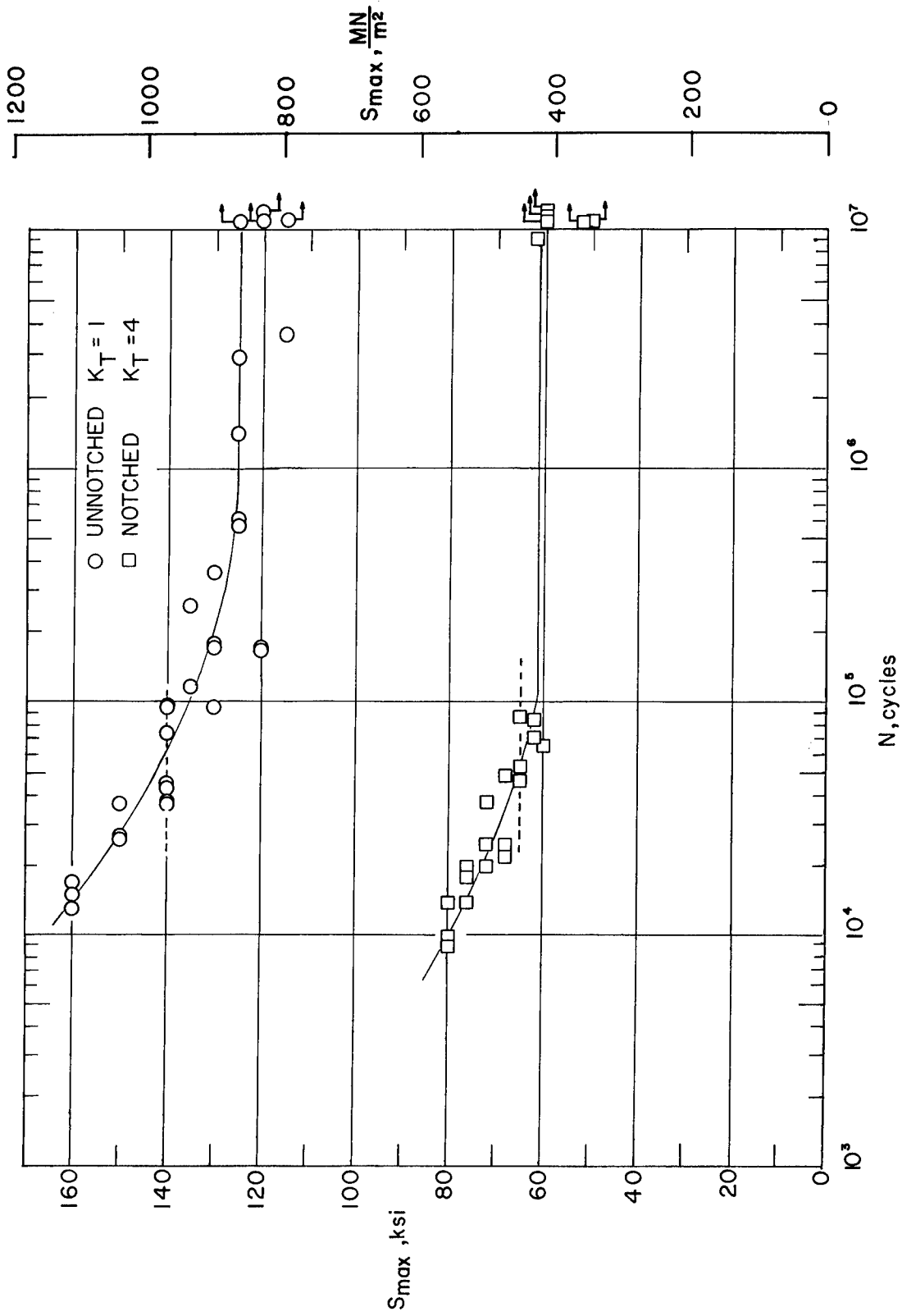
(b) AM 350 20 percent CRT; mean stress, 40 000 psi (276 MN/m<sup>2</sup>).

Figure 5.- Continued.



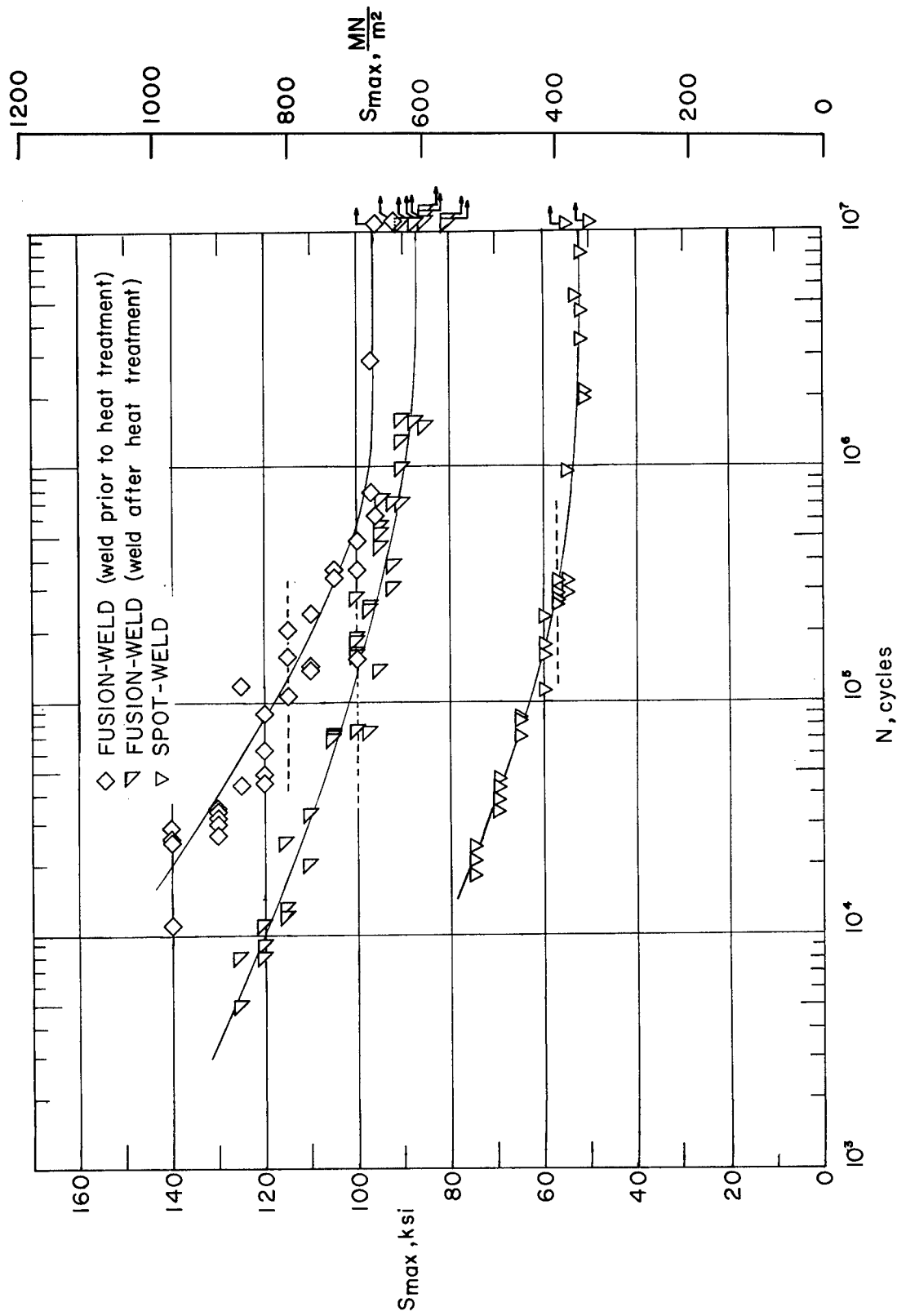
(b) AM 350 20 percent CRT; mean stress, 40 000 psi (276 MN/m<sup>2</sup>). Concluded.

Figure 5.- Continued.



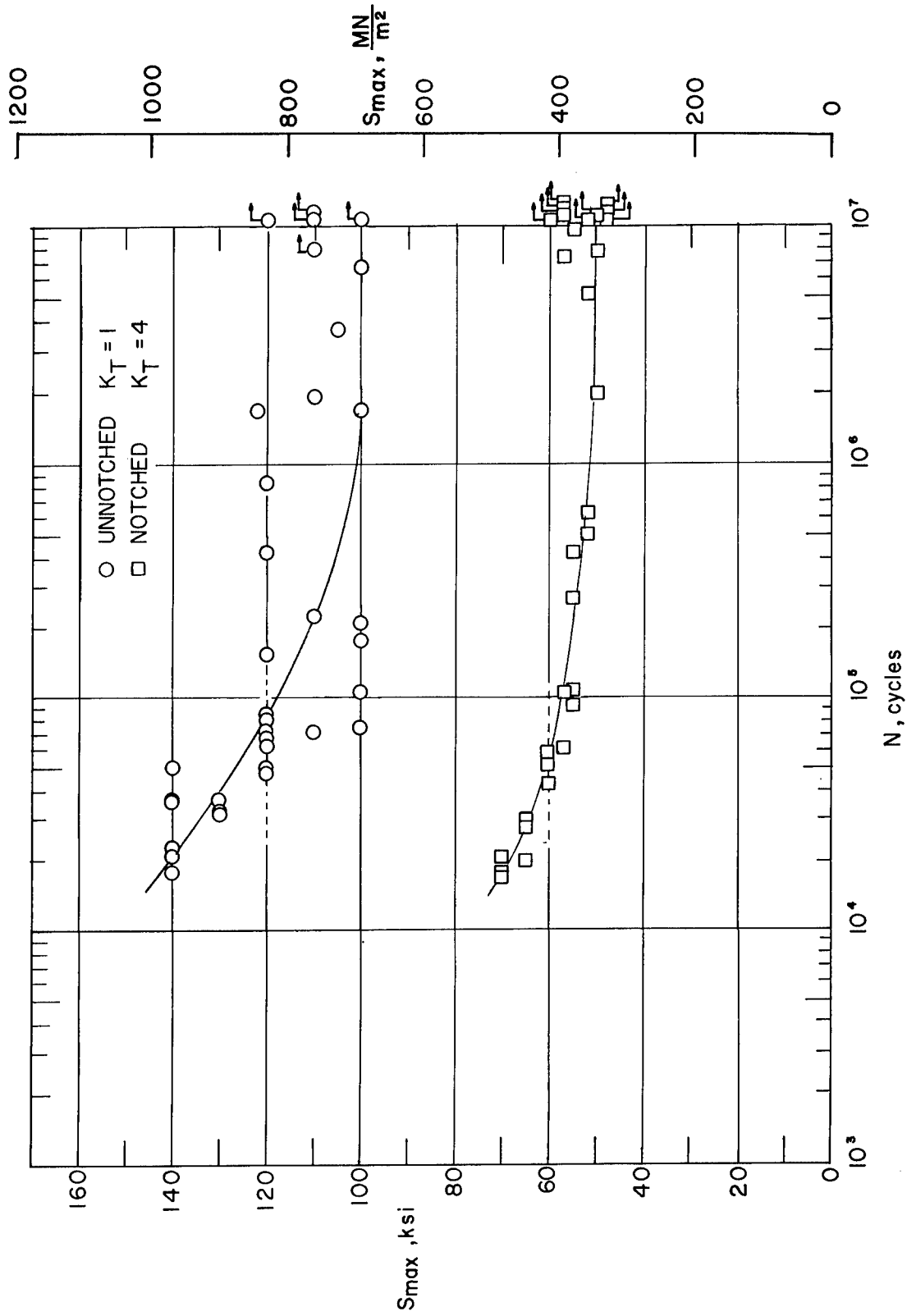
(c) AM 350 double aged; mean stress, 40 000 psi (276  $MN/m^2$ ).

Figure 5.- Continued.



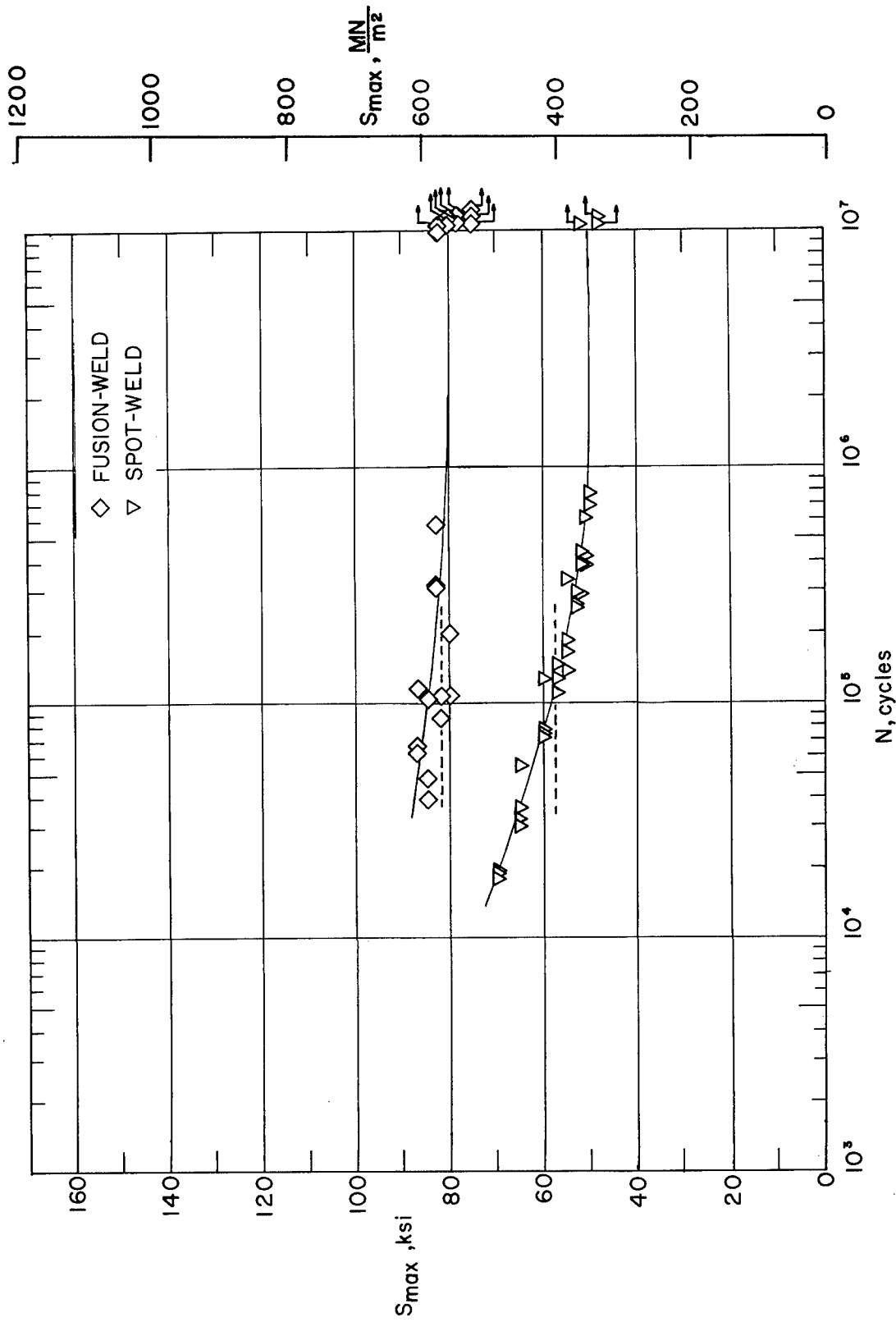
(c) AM 350 double aged; mean stress, 40 000 psi (276 MN/m<sup>2</sup>). Concluded.

Figure 5.- Continued.



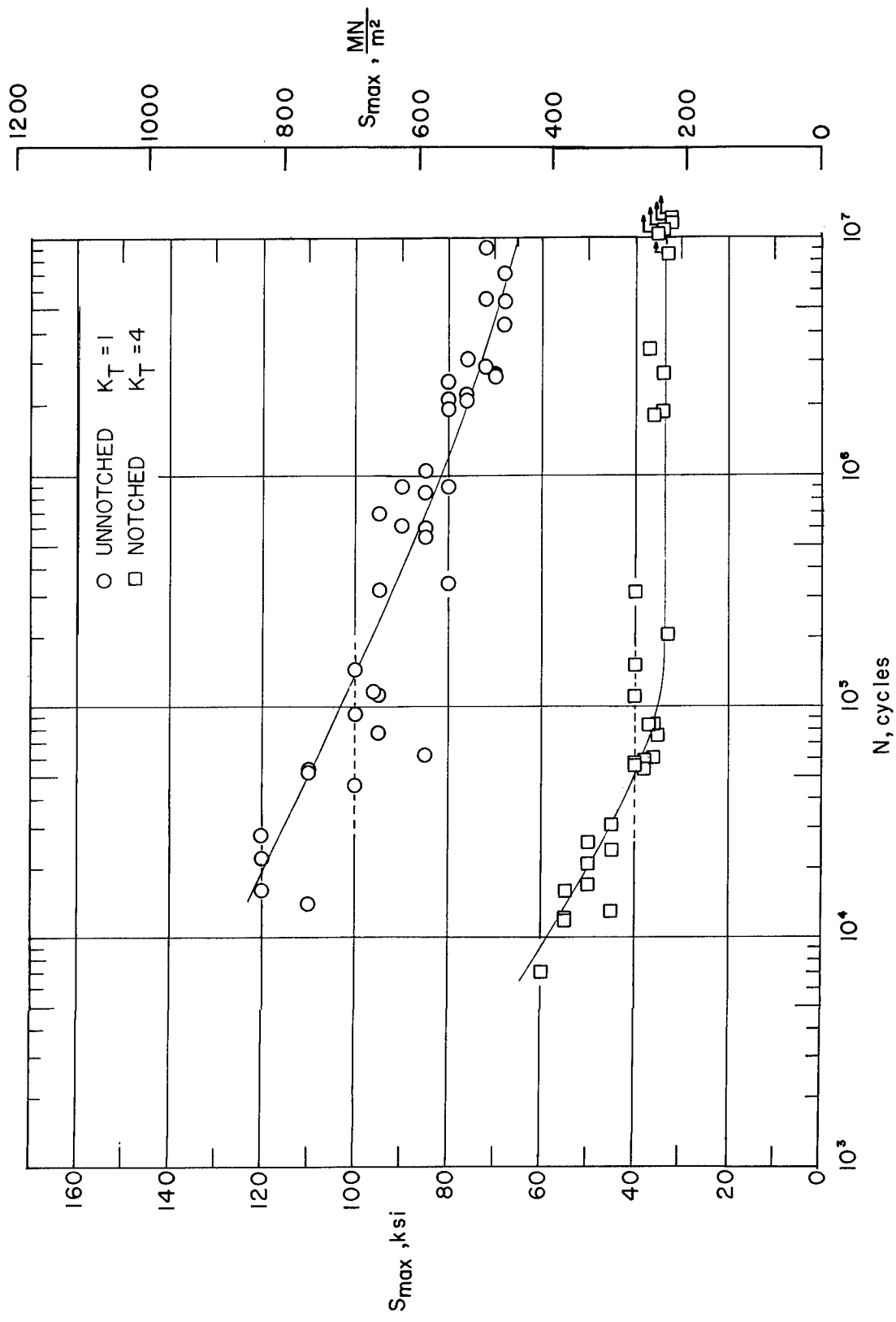
(a) AISI 301 50 percent CR; mean stress, 40 000 psi (276 MN/m<sup>2</sup>).

Figure 5.- Continued.



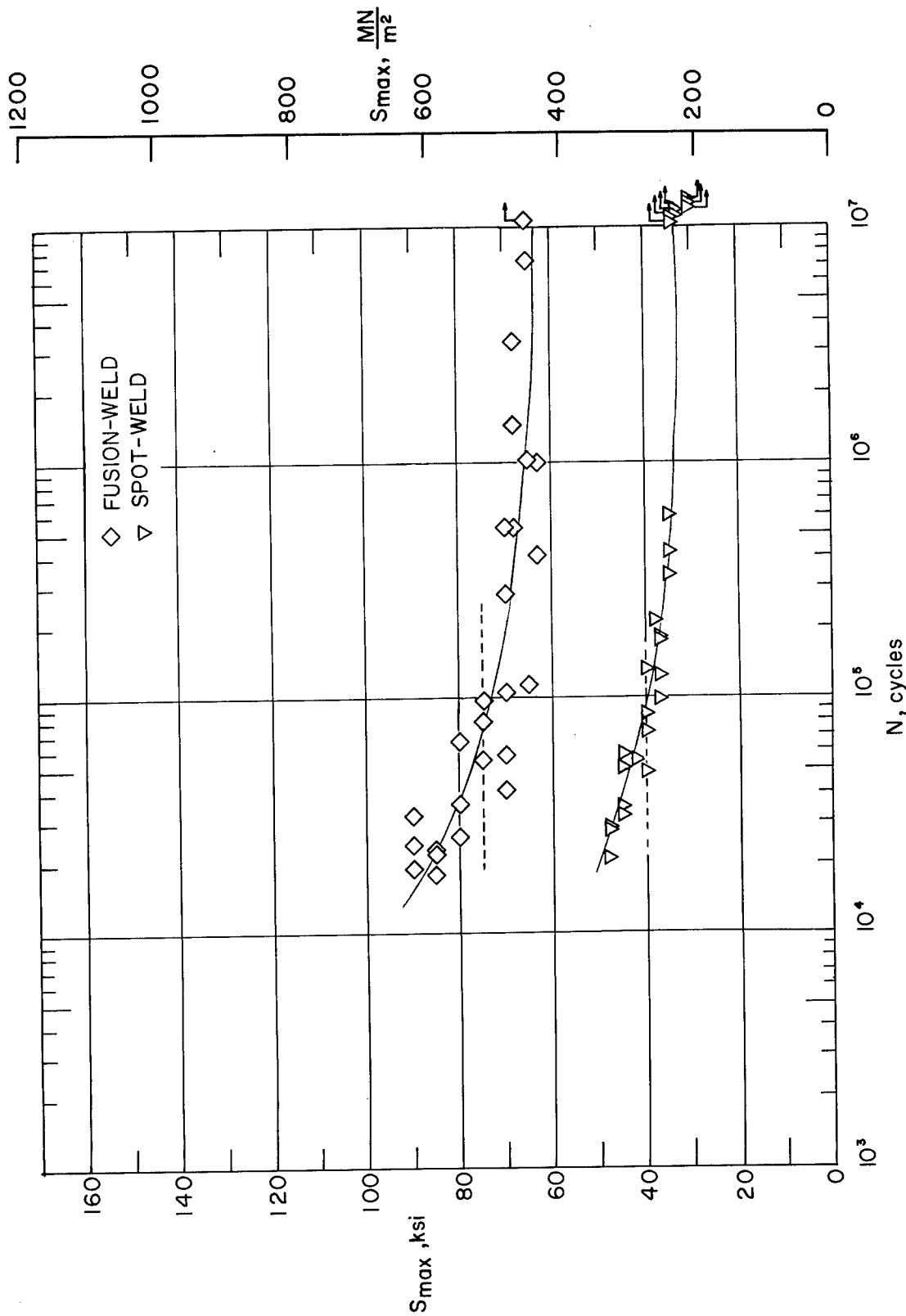
(d) AISI 301 50 percent CR, mean stress, 40 000 psi ( $276 \frac{MN}{m^2}$ ). Concluded.

Figure 5.- Continued.



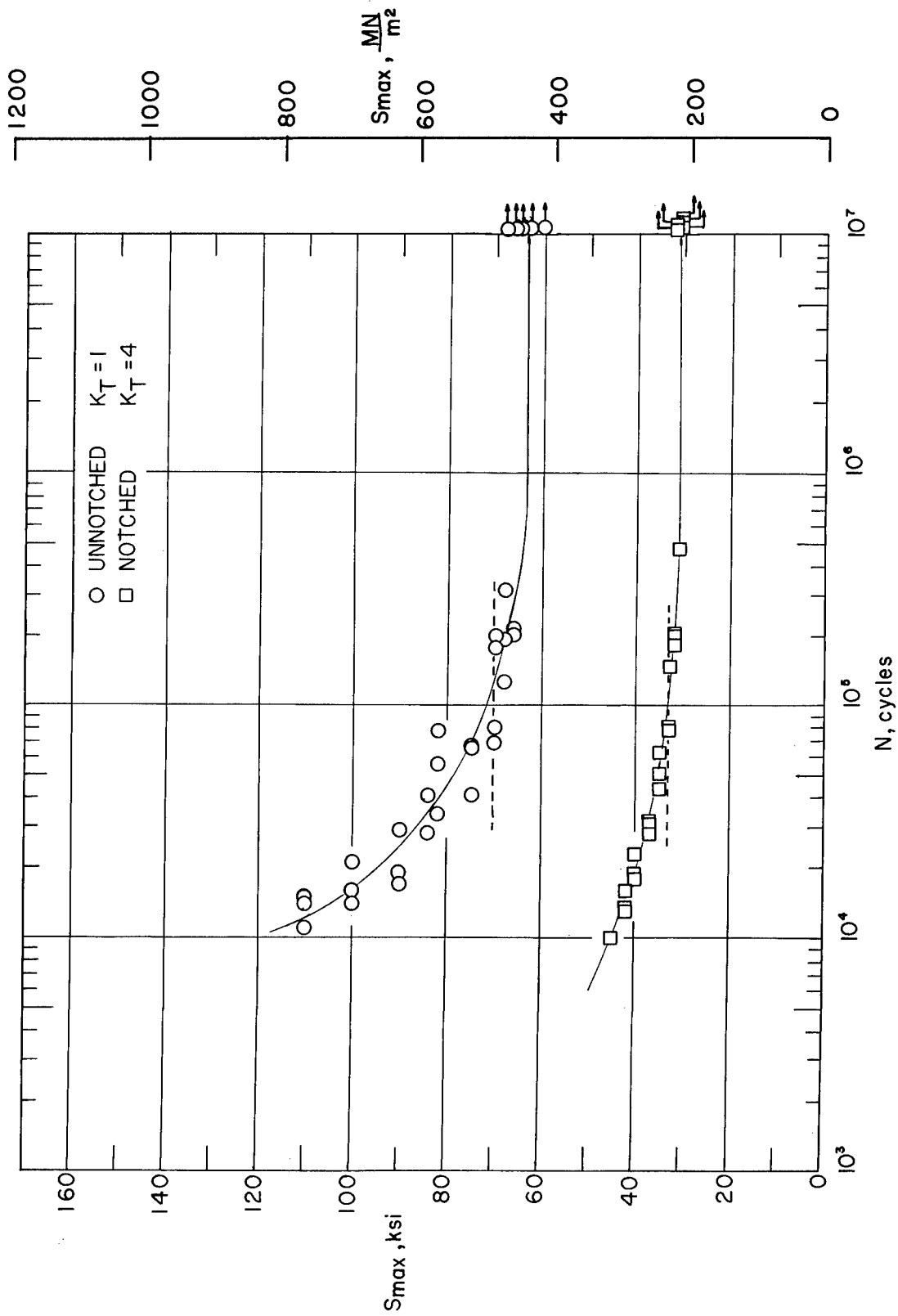
(e) Ti-6Al-4V, annealed; mean stress, 25 000 psi (173  $MN/m^2$ ).

Figure 5.- Continued.



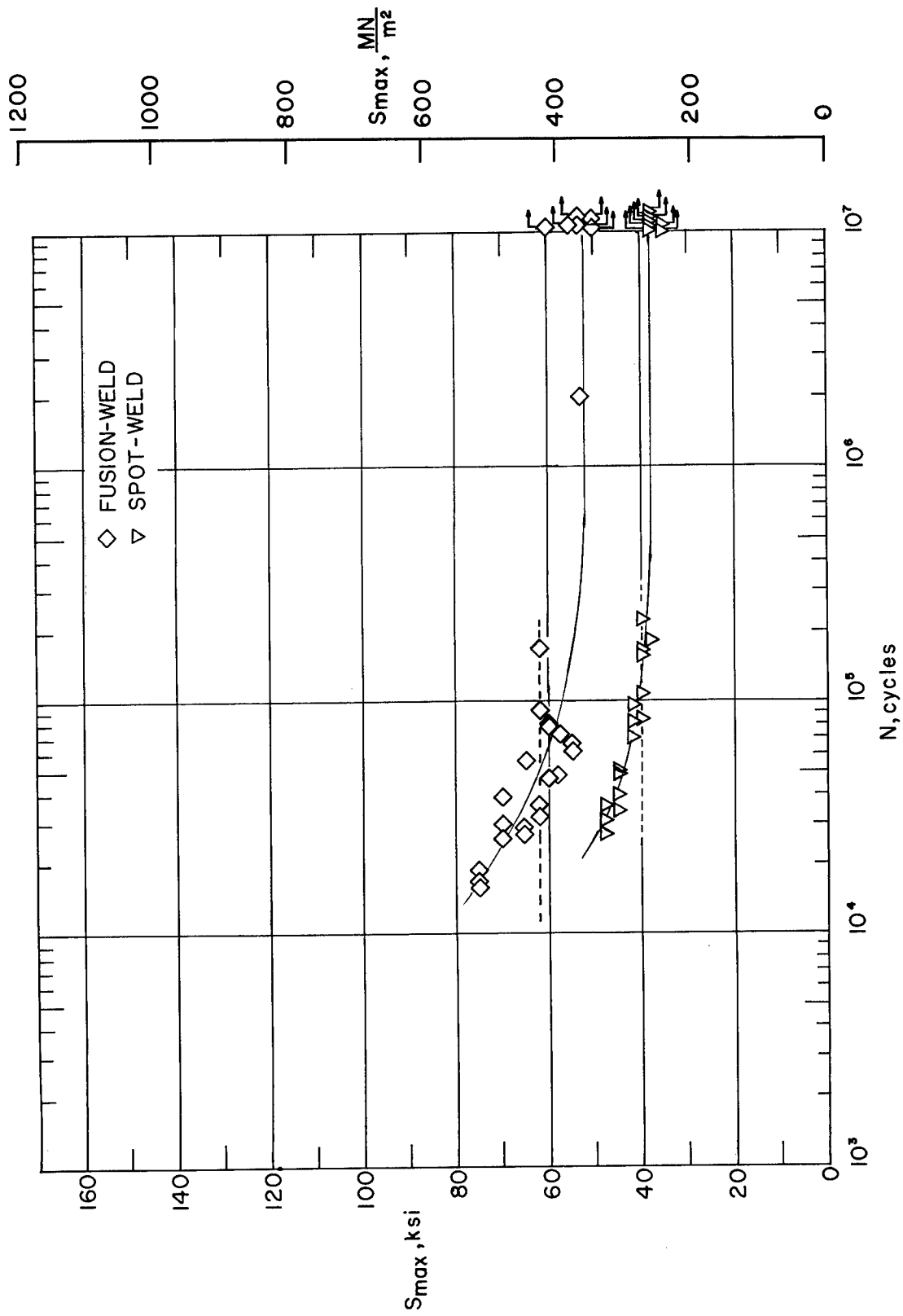
(e) Ti-6Al-4V, annealed; mean stress, 25 000 psi (173 MN/m<sup>2</sup>). Concluded.

Figure 5.- Continued.



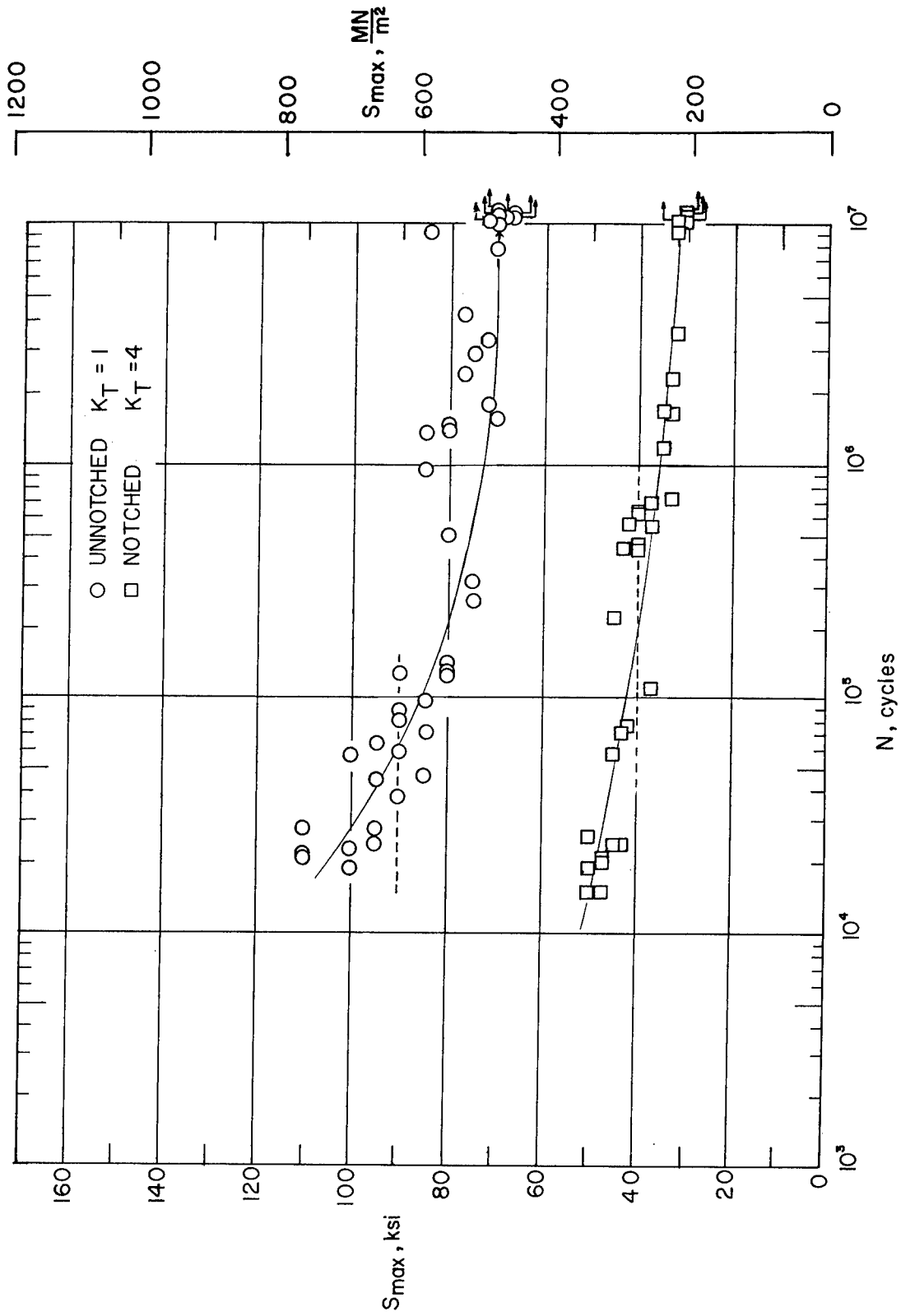
(f) Ti-4Al-3Mo-IV, aged; mean stress, 25 000 psi (173  $MN/m^2$ ).

Figure 5.- Continued.



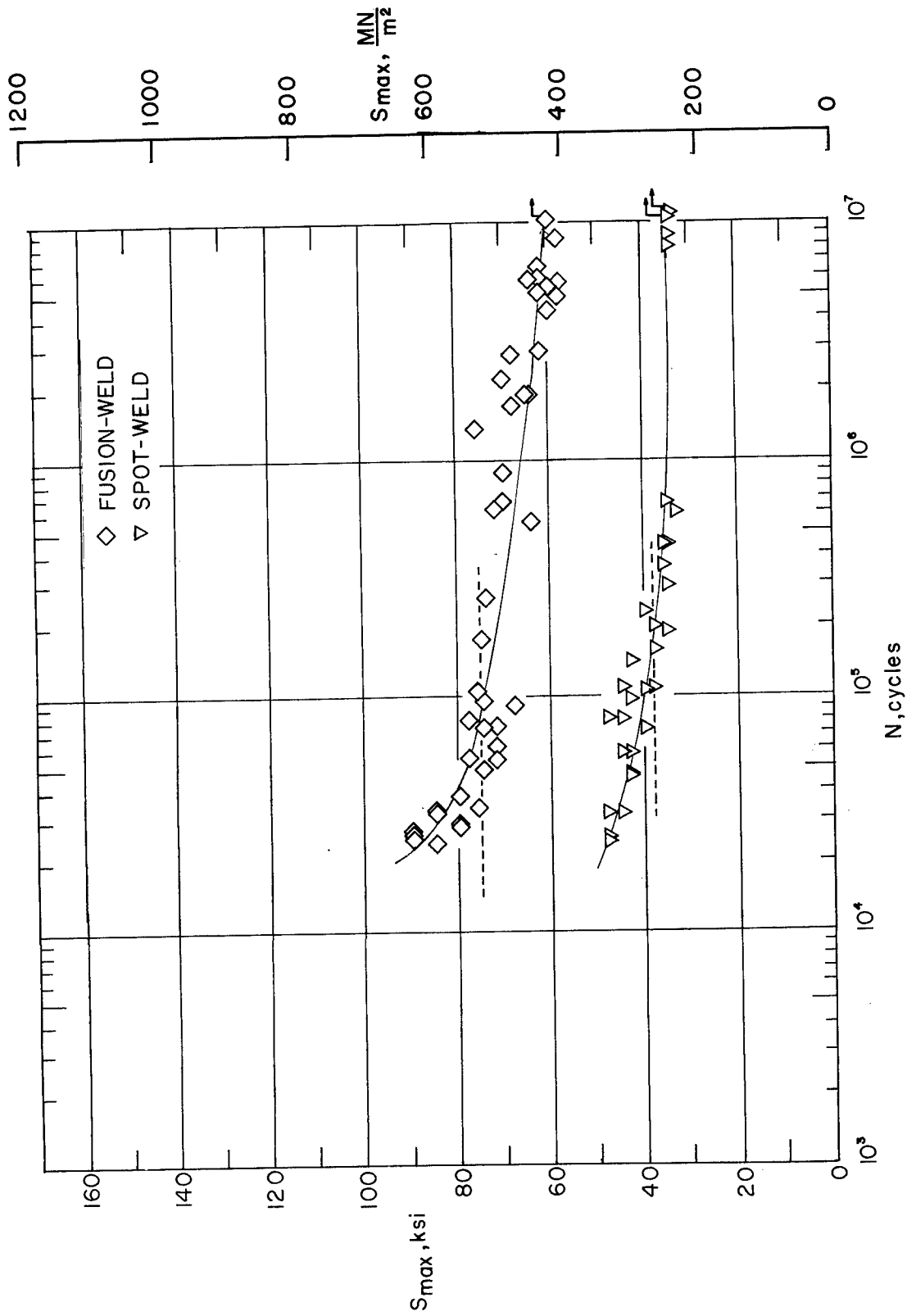
(F) Ti-4Al-3Mo-IV, aged; mean stress, 25 000 psi (1.73 MN/m<sup>2</sup>). Concluded.

Figure 5.- Continued.



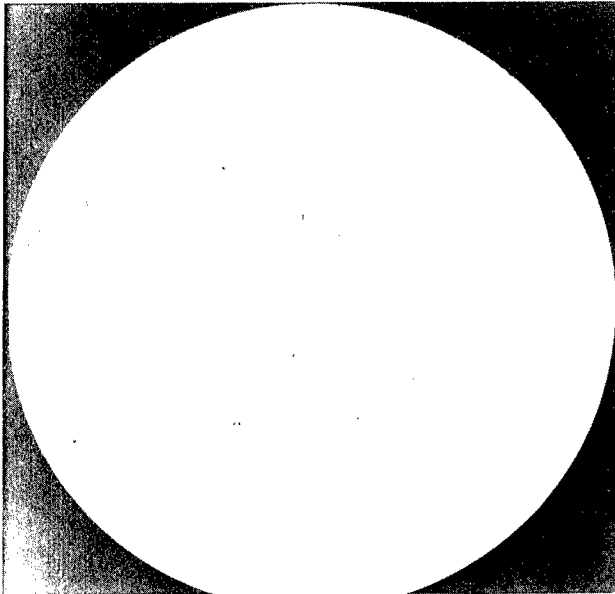
(g) Ti-8Al-1Mo-IV, single annealed; mean stress 25 000 psi (173 MN/m<sup>2</sup>).

Figure 5.- Continued.

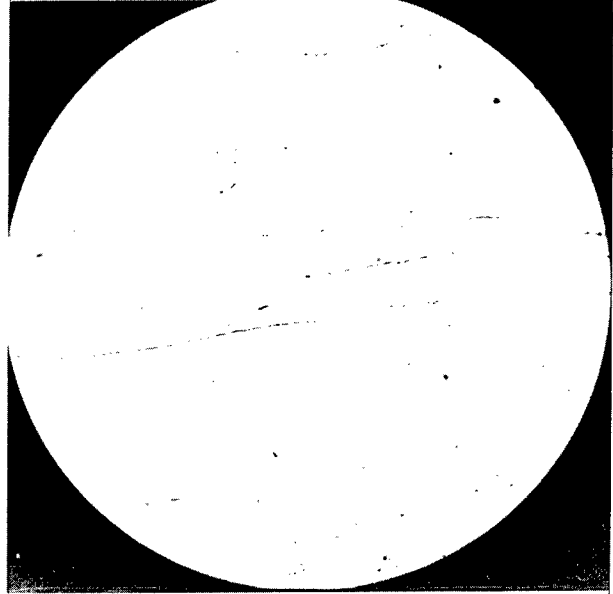


(g) TI-8Al-1Mo-IV, single annealed; mean stress 25 000 psi (173 MN/m<sup>2</sup>). Concluded.

Figure 5.- Concluded.



TRANSVERSE CROSS SECTION



LONGITUDINAL CROSS SECTION

SURFACE

Figure 6.- Photomicrographs of AISI 301 stainless steel 150X.

L-65-40

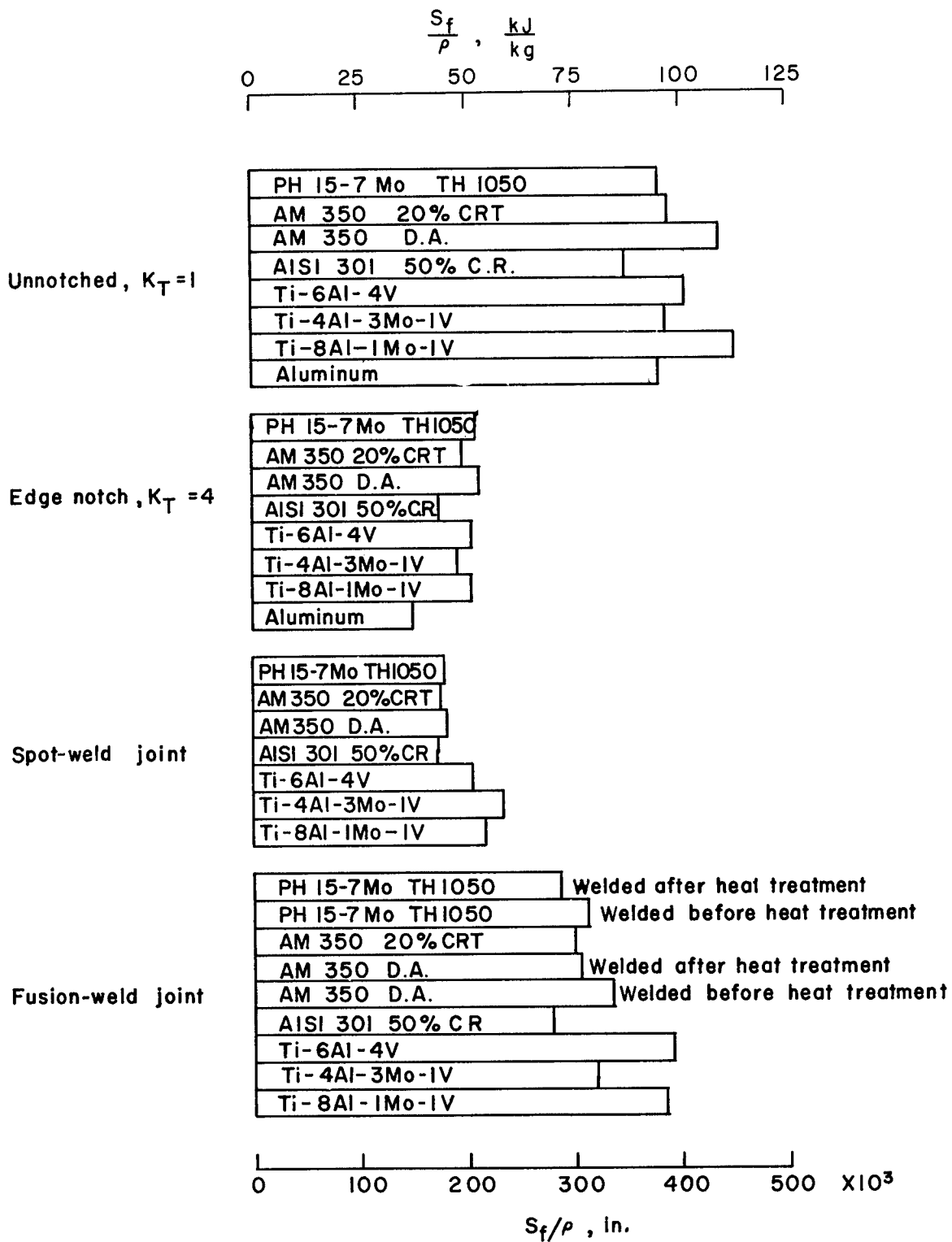
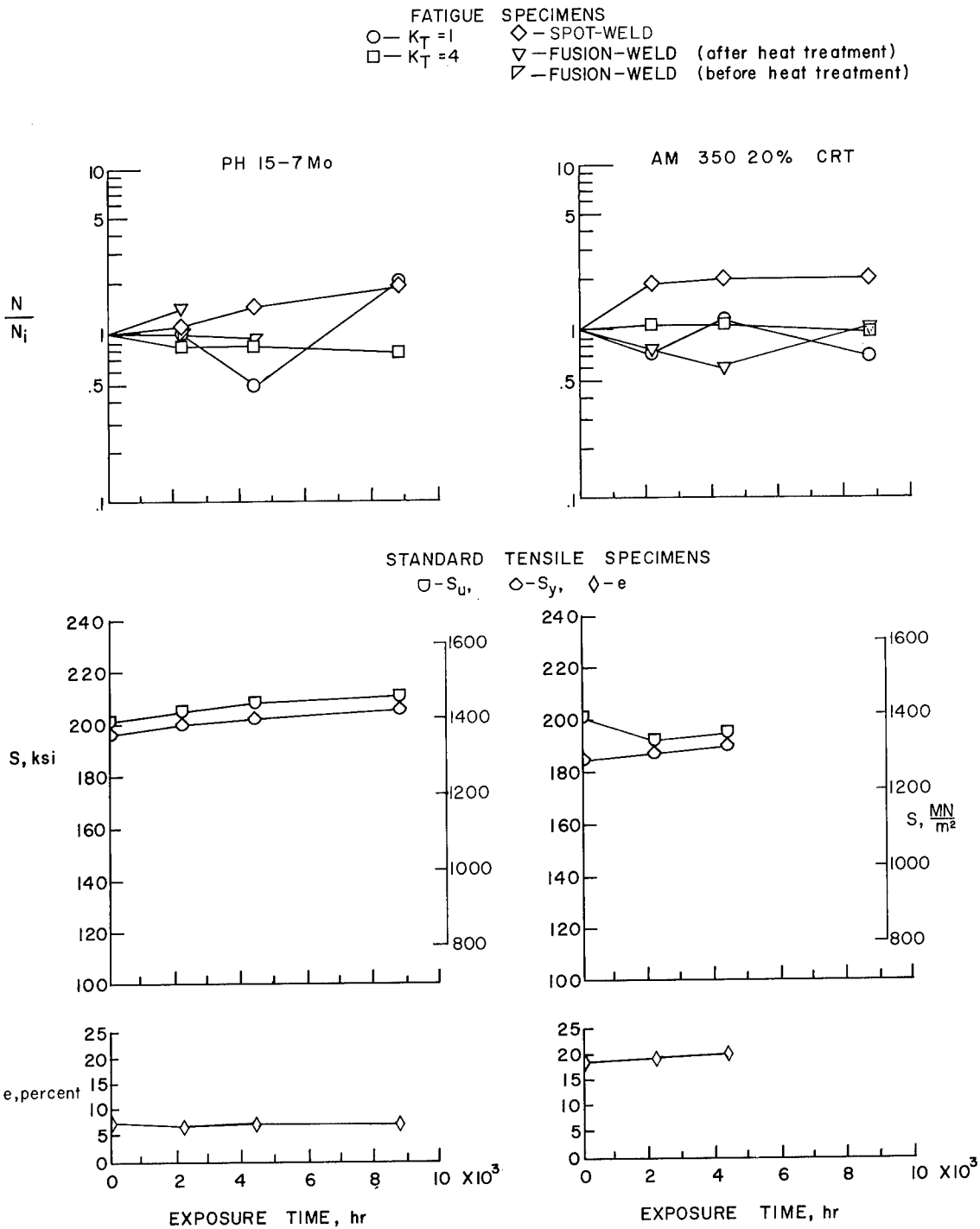


Figure 7.- Comparison of ratios of fatigue limit to density.

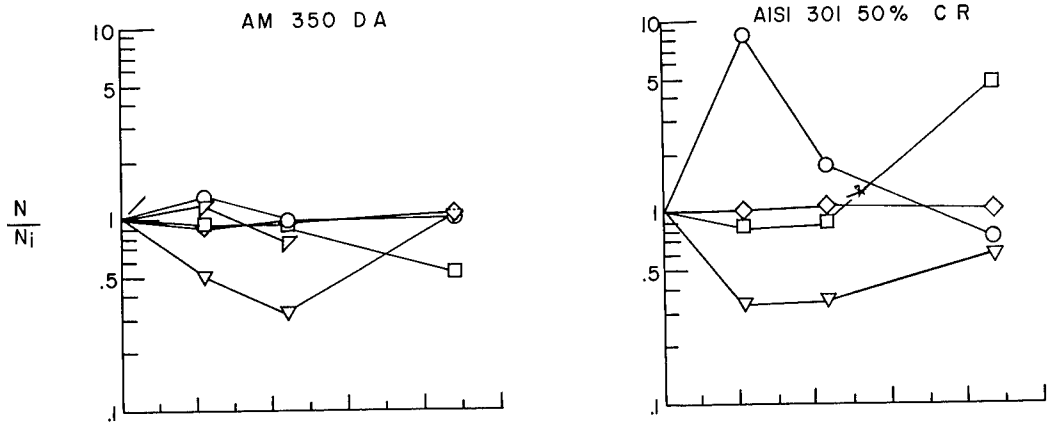


(a) PH 15-7Mo and AM 350 20 percent CRT.

Figure 8.- Results of exposure to 550° F (561° K) on fatigue limit, static strength, and elongation.

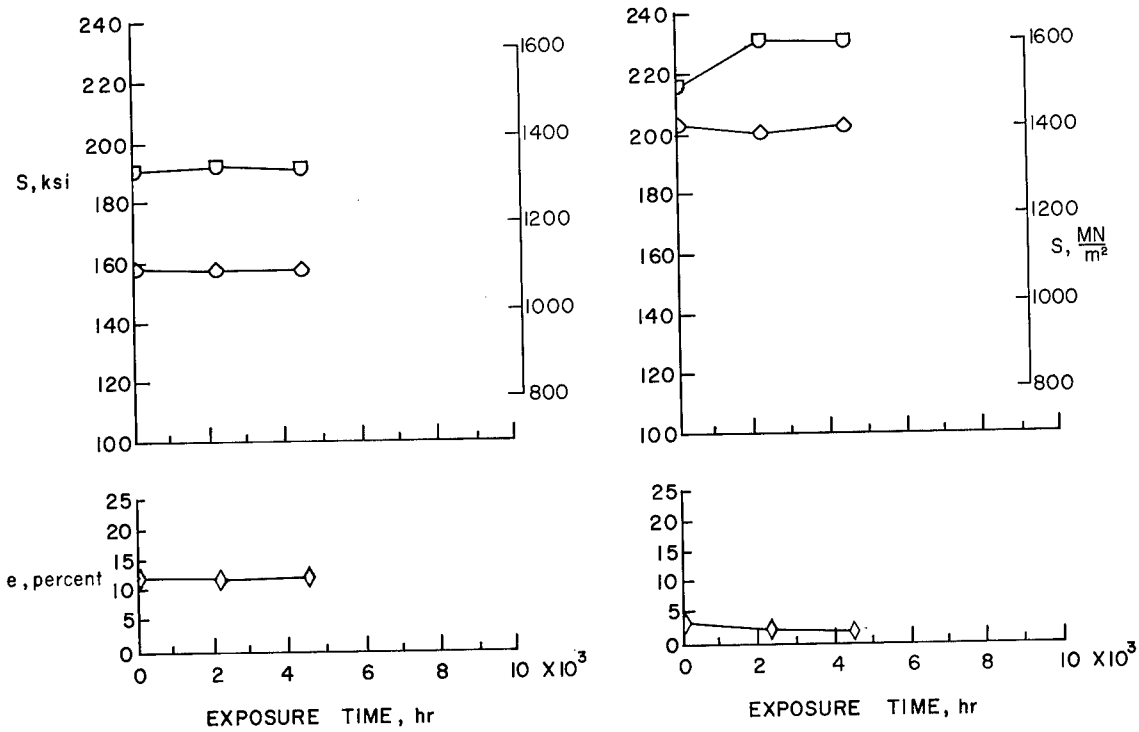
FATIGUE SPECIMENS

- —  $K_T = 1$
- ◇ — SPOT-WELD
- —  $K_T = 4$
- ▽ — FUSION-WELD (after heat treatment)
- ▽ — FUSION-WELD (before heat treatment)



STANDARD TENSILE SPECIMENS

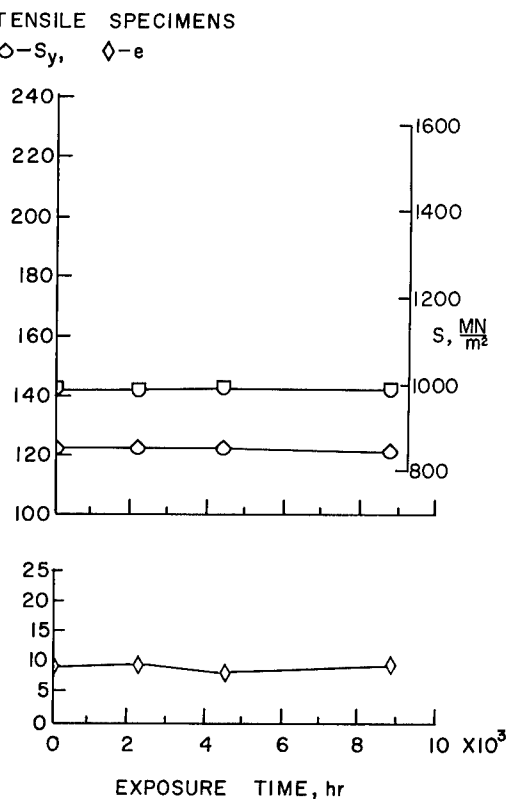
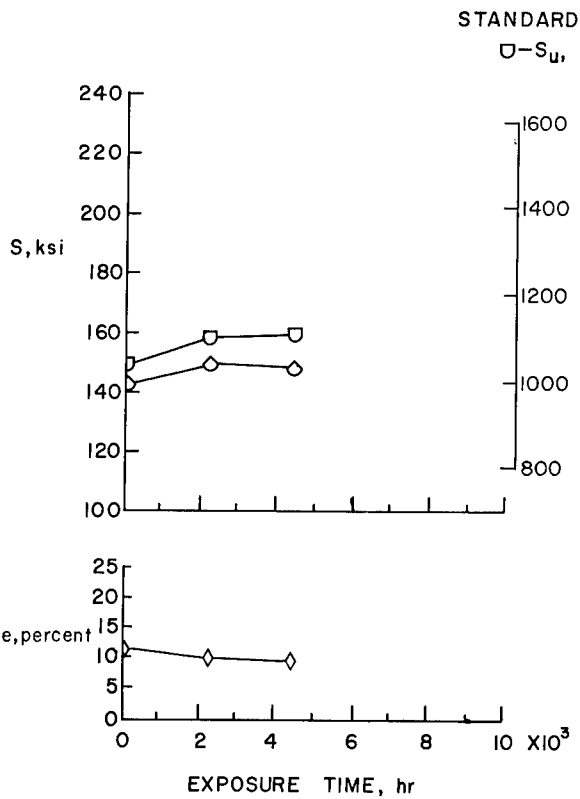
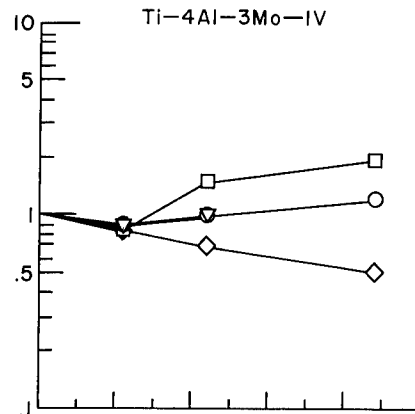
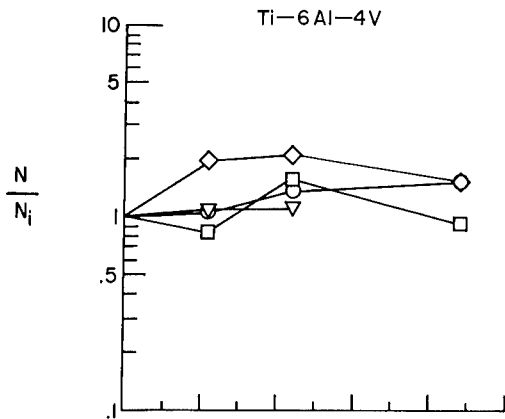
- —  $S_u$
- ◇ —  $S_y$
- ◇ —  $e$



(b) AM 350 double aged and AISI 301 50 percent CR.

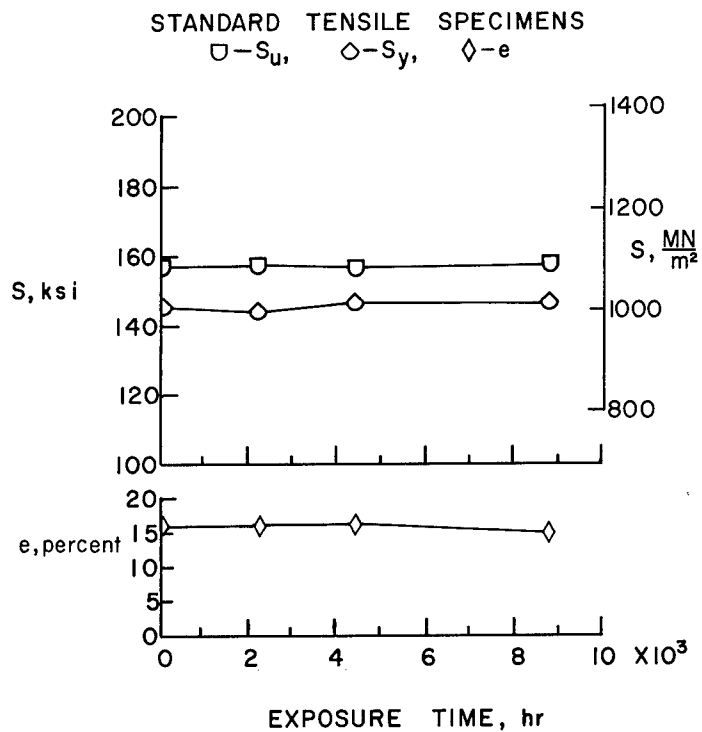
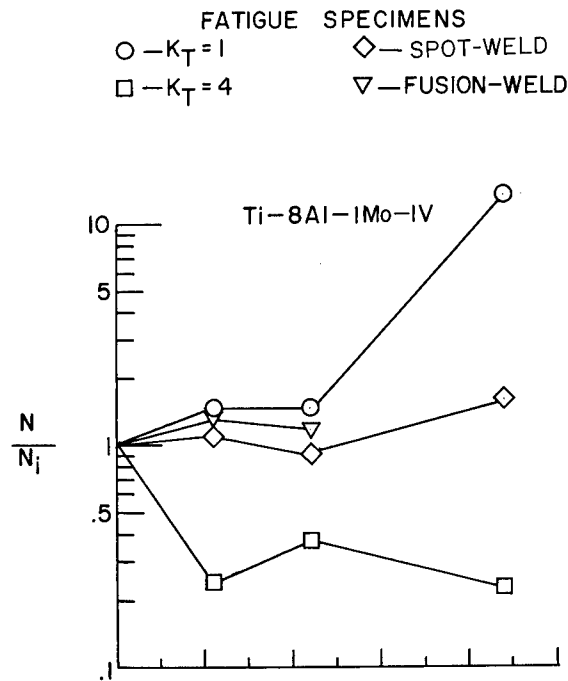
Figure 8.- Continued.

FATIGUE SPECIMENS  
 ○ -  $K_T = 1$       ◇ - SPOT-WELD  
 □ -  $K_T = 4$       ▽ - FUSION-WELD



(c) Ti-6Al-4V and Ti-4Al-3Mo-IV.

Figure 8.- Continued.



(d) Ti-8Al-1Mo-IV.

Figure 8.- Concluded.