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EFFECT OF OUTDOOR EXPOSURE AT ELEVATED TEMPERATURE ON THE FATIGUE LIFE OF Ti-8Al-1Mo-1V TITANIUM ALLOY AND AM 350 STAINLESS STEEL SHEET

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16. Abstract

Constant-amplitude bending fatigue tests were conducted outdoors on central-hole (stress concentration factor of 1.6) and fusion-welded sheet specimens of duplex-annealed Ti-8Al-1Mo-1V titanium alloy and cold-rolled and tempered AM 350 stainless steel. The specimens were maintained at 550° F (561° K) during most of the exposure period to approximate the operating environment of a Mach 3 transport aircraft. The heating was interrupted when cyclic loads were applied, any time rain or snow was falling, and for a 4-hour period each night to allow dew to form. A static load was applied continuously for the duration of the tests. For comparison, tests were also conducted indoors at room temperature at the same stress levels. The results indicate that the outdoor test environment reduced the fatigue life of all materials tested. Based on the number of load cycles to produce the first failures, outdoor life was never reduced to less than 1/2 the indoor life; but the median outdoor life of the central-hole AM 350 specimen was reduced to 1/5 the median indoor life.

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EFFECT OF OUTDOOR EXPOSURE AT ELEVATED TEMPERATURE ON THE FATIGUE LIFE OF Ti-8Al-1Mo-1V TITANIUM ALLOY AND AM 350 STAINLESS STEEL SHEET

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SUMMARY

Constant-amplitude bending fatigue tests were conducted outdoors on central-hole (stress concentration factor of 1.6) and fusion-welded sheet specimens of duplex-annealed Ti-8Al-1Mo-1V titanium alloy and cold-rolled and tempered AM 350 stainless steel. The specimens were maintained at 550° F (561° K) during most of the exposure period to approximate the operating environment of a supersonic transport aircraft which will cruise at Mach 3. The heating was interrupted for a 4-hour period each night to allow dew to form, for a short period twice a week when cyclic loads were applied, and any time rain or snow was falling. A static load was applied continuously for the duration of the tests. The exposure period for individual specimens ranged from 7 to 23 months. For comparison, tests were also conducted indoors at room temperature, at the same stress levels as outdoors.

The results indicate that the outdoor environment reduced the fatigue life of all materials tested. Based on the number of load cycles to produce the first failures, outdoor life was never reduced to less than 1/2 the indoor life; but the median outdoor life of the central-hole AM 350 specimen was reduced to 1/5 the median indoor life. Median life was not obtained for the outdoor titanium-alloy specimens because most specimens failed out of the test section at small spotwelding-induced arc spots. The reductions in life to first failures observed for the materials in this investigation compare favorably with those observed previously for bare 2024-T3 and 7075-T6 aluminum alloys exposed outdoors at ambient temperature.

INTRODUCTION

Aircraft are exposed to the corrosive action of precipitation and airborne corrodents almost continuously during their service lives. Intuitively, one would expect this corrosive action to have a degrading effect upon the fatigue behavior of structural metals. To assess the magnitude of this effect, several investigations have been conducted on aluminum alloys used in subsonic aircraft (refs. 1 to 3). With the establishment of a tentative design speed of Mach 3 for the commercial supersonic transport in about 1960, it became clear that the prime structural materials would not be aluminum alloys because skin temperatures would range from 450° to 600° F (505° to 589° K). Early materials research in support of the supersonic transport program indicated that titanium and stainless steel alloys showed the greatest promise for this application on the basis of tests in noncorrosive environments (ref. 4).

In the present investigation, constant-amplitude bending fatigue tests of central-hole and fusion-welded specimens were conducted outdoors to obtain data on the effect of atmospheric corrosion on the fatigue life of duplex-annealed Ti-8Al-1Mo-1V titanium alloy and cold-rolled and tempered AM 350 stainless steel sheet. Because the structure of a supersonic-cruise transport will experience elevated temperatures during most of the flight time and because it was known that the corrosive effects of airborne salt on the titanium alloy would be heightened at elevated temperature (ref. 5), the specimens were maintained at 550° F (561° K) during most of the outdoor exposure. The specimens were allowed to cool to ambient temperature when alternating loads were applied to them and any time that rain or snow was falling. This was done because most of the atmospheric turbulence and precipitation encountered by a supersonic transport is expected to occur at low altitudes when the aircraft is flying subsonically. The specimens were also allowed to cool to ambient temperature for a 4-hour period every night to allow dew to form on them. A static load was applied continuously for the duration of the tests. The tests were conducted under atmospheric conditions prevalent at the Langley Research Center, which is located near the Chesapeake Bay.

The physical quantities in this paper are given both in U.S. Customary Units and in the International System of Units (SI) (ref. 6). Appendix A presents factors relating these two systems of units.

TESTS

Materials and Specimens

Specimens were fabricated from sheets of duplex-annealed Ti-8Al-1Mo-1V titanium alloy and cold-rolled and tempered (CRT condition) AM 350 stainless steel, nominally 0.050 in. (1.3 mm) thick. All specimens of each material were fabricated from a single 36- by 96-in. (0.91- by 2.44-m) sheet. Chemical analyses and processing histories furnished by the manufacturer are given in table I. The average longitudinal tensile properties of the parent materials and fusion welds were obtained at the Langley fatigue laboratory and are given in table II.

The two bending-specimen configurations used in the fatigue tests are shown in figure 1. The dashed lines indicate the shape of a constant-stress cantilever. Maximum bending stress occurs in the section at which these lines are tangent to the boundary of the specimen. The specimen contained either a drilled hole of 1/4-in. (6.35-mm) diameter or a transverse fusion weld in the maximum-stress section. The stress concentration factor K_T for the central-hole specimen loaded in bending is approximately 1.6 (ref. 7). The holes were drilled with the specimens in stacks of 10 and the edges of the holes were deburred with a rubber-matrix abrasive stick which was rotated in a drill press. The fusion-welded specimens were machined from blanks containing a weld 2.75 in. (69.8 mm) long in such a manner that the finished specimen contained the central 1 in. (25.4 mm) of the weld. No filler wire was added to the welds. The weld beads were not removed, nor were the welds thermally or mechanically treated before testing.

After fabrication, all specimens were chemically cleaned according to the procedures given in appendix B. After cleaning, each specimen that was to be tested outdoors had a thermistor and a thermocouple attached for temperature control and monitoring purposes.

Because the specimens were to be exposed outdoors in a horizontal position under a continuous static loading, the temperature sensors were spotwelded to the bottom surface so that the top (tensile mean stress) surface would be free of spotwelds and would not be cluttered by sensor leads. A metal clip to shield the sensors and tie-down straps to prevent vibration of the sensor leads relative to the specimen during fatigue cycling were also spotwelded to the specimen. The locations of the sensors, shielding clip, and tie-down straps are shown in figure 2. All spotwelding was accomplished by placing the top surface of the specimen against a copper grounding block and placing a hand-held electrode on the bottom surface at the point where a spotweld was desired. In addition to producing the desired spotwelds on the bottom surface, this procedure inadvertently produced small undesirable arc spots on the top surface which were not detected prior to fatigue testing.

Test Apparatus

Outdoor tests.- The outdoor fatigue tests were conducted with a machine that accommodates 76 specimens at one time (fig. 3). This machine was located in an open area and was not protected from the elements in any way. It was within 100 ft (30 m) of buildings that house chemical milling, plating, and foundry operations; within 300 ft (90 m) of a building where large quantities of fuel oil are burned; and within 3 miles (5 km) of salt water in the Chesapeake Bay. A diagram of the testing machine is shown in figure 4. Basically, this machine consists of a vibrating table supported on coil springs and restricted to vertical motion by a system of flexure arms. The table has a natural frequency of vibration in the vertical direction of approximately 430 cpm (7.2 Hz) and was excited to vibrate at this frequency by an adjustable crank and a clutch mechanism. The machine was started with the clutch disengaged. When the motor reached operating speed, the clutch was engaged slowly until the table vibrated at an amplitude equal to the throw of the crank. A preset counter was used to stop the machine automatically after a predetermined number of load cycles had been applied to the specimen.

The magnitude of the stresses induced in the specimens by the vibrating table was controlled by the adjustment of two masses which were attached to the specimen. One mass was rigidly attached to the free end of the specimen. Adjustment of the magnitude of this mass was the primary method of adjusting the alternating stress in the specimen. Another mass was suspended from the first by a soft coil spring. The suspended mass was adjusted so that the sum of the two masses produced the desired mean stress in the specimen. The spring was soft enough so that the vibration of the cantilever was not significantly affected by the suspended mass. The suspended mass was submerged in oil to damp out transient vibrations during starting and stopping. A correction for the buoyant force of the oil was made when the weight of the suspended mass was computed.

Each specimen had a separate and complete heating and temperature-control system. The system was composed of two 200-watt quartz tube lamps and a reflector, a thermistor temperature sensor on the specimen, and a solid-state temperature controller. Each specimen also had a thermocouple attached to it for temperature monitoring purposes. The temperature of each specimen was sampled and recorded every 16 minutes by a central temperature monitoring system.

In addition to the radiant heating from the quartz lamps, the specimens were heated in the gripped area by conduction from cartridge heaters which were inserted into drilled holes in the mounting plates. Heating the gripped portion of the specimen reduced the load on the quartz lamps and thus helped to achieve long lamp life and closer temperature control on windy days.

All the quartz lamp heating units on each side of the fatigue machine were mounted on a common structure which could be raised or lowered. This feature was desirable since the lamps needed to be close to the specimens to achieve long lamp life but had to be moved away from the specimens during the cyclic loading.

A precipitation sensor was developed which automatically turned off the heat when rain or snow was falling and turned it back on when the precipitation ended. The heating system also had a programer so that the heat could be automatically turned off or on at any time of the day.

Indoor tests.- The indoor tests were conducted with a small nonresonant vibration table which accommodated only one specimen at a time. The stresses induced in the specimen were controlled by the same mass-adjustment procedure that was used in the outdoor tests. The tests were conducted at a frequency of 600 cpm (10 Hz).

Procedure

The loads to produce the desired stresses in the critical cross section in each specimen were computed by using the flexure formula with section measurements taken to the nearest 0.0001 in. (3 μm). These loads were applied statically to the specimens by deadweight loading and the specimen deflections were measured. The deflections were then reproduced in the tests by adjustment of the masses attached to the specimen. Deflections were measured with a stroboscope, a scale graduated in 0.01-in. (0.3-mm) increments, and a low-power microscope. The large deflections of 1.1 to 1.4 in. (28 to 36 mm) associated with the maximum stress levels facilitated adjustment to within ±2 percent of the desired level.

The following outer-fiber net-section stresses were applied in the test program:

Material	Type of specimen	Stress applied	
		ksi	MN/m^2
Ti-8Al-1Mo-1V	Central hole	25 ± 67	172 ± 462
Ti-8Al-1Mo-1V	Weld	25 ± 53	172 ± 365
AM 350	Central hole	40 ± 82	276 ± 565
AM 350	Weld	27 ± 68	186 ± 469

The mean stress levels were selected on the basis of published information on these materials (ref. 8) which indicated that the levels were realistic 1g design stresses for a transport aircraft. The alternating stresses were chosen to produce failures in approximately 10^5 cycles on the basis of a few preliminary indoor tests.

Outdoor tests.- A temperature of 550° F (561° K) was desired at the test section on the top surface. Since the temperature sensors were located on the bottom surface, a correspondence had to be established between thermocouple readings on the two surfaces. To do this, specimens having the usual instrumentation on the bottom surface and an array of thermocouples on the top surface were mounted on the machine. The temperature indication of the bottom thermocouple corresponding to a 550° F indication on the top surface was recorded for each specimen mounting location and used as the control set point in the ensuing test. Temperatures of the test sections were controlled to within ±30° F (±20° K) of the desired 550° F (561° K) temperature on calm days. Temperature fluctuations due to wind were generally no more than an additional 30° F (20° K) and lasted only a few seconds.

In setting up the tests to achieve the desired stress levels, specimens were clamped to the machine one at a time; the masses attached to the specimens were adjusted to produce the desired deflections; and then the specimens were removed from the machine and stored indoors. Approximately 2000 cycles were applied to each specimen during the mass-adjustment process. When this process had been completed, all 76 specimens were mounted on the machine so that every fourth position around the periphery was occupied by the same kind of specimen. An additional 1600 cycles were applied to the specimens while checks were made on specimen deflections. The first day of outdoor test exposure was January 20, 1966.

The specimen temperature was maintained at 550° F (561° K) except when rain or snow was falling, when fatigue cycles were being applied, and for a 4-hour period each night to allow dew to form on the specimens. An average of about 16 hot-hours per day was actually experienced by the specimens during the test. Approximately 1100 fatigue cycles were applied to the specimens at ambient temperature on Tuesday and Friday of each week. The mean load was applied continuously for the duration of the test.

Meteorological data for the duration of the tests were taken from records of the NASA Langley weather station and are summarized in table III. The rain sensor malfunctioned several times during the test period, with the result that heating of the specimens continued during approximately 15 percent of the precipitation that occurred.

Indoor tests.- For comparison with the outdoor tests, 16 specimens of each type were tested indoors at room temperature under the same stresses. The specimens were cycled to failure without interruption if failure occurred in less than about 800 000 cycles. If a specimen was not cracked at 800 000 cycles, it was removed from the machine and the test was continued at a later date after all the specimens had undergone an initial test period. This procedure was adopted after it was found that some tests would last in excess of 10 million cycles and would occupy the test machine for as much as 3 weeks. Tests were scheduled so that every fourth test was on the same kind of specimen.

RESULTS AND DISCUSSION

Test Results

The results of the indoor tests are presented in table IV. The number of load cycles required to produce failure (separation into two pieces) is listed for each specimen.

The results of the outdoor tests are presented in table V. For each specimen the number of load cycles required to produce failure, the number of hours exposed at 550° F (561° K), and the date of failure are listed.

The fatigue lives obtained in both the indoor and outdoor tests are plotted in figures 5 and 6 for the AM 350 and Ti-8Al-1Mo-1V specimens, respectively.

Discussion of Test Results

AM 350 central-hole specimens.- The indoor tests of the AM 350 central-hole specimens resulted in a wide range of fatigue lives. While it is not unusual to observe large scatter in the long-life region of the stress-cycle (S-N) curve, an interesting feature of the data from the present investigation is the apparent division into short-life and long-life groups. A review of specimen fabrication and test procedures revealed no apparent correlation between the two life groups and specimen-blank location in the sheet, or the drilling of the holes in the specimens in stacks of 10. Similar life behavior has been reported for other materials and specimen configurations in references 9 and 10. In these references, it is hypothesized that the two life groups exist only at stresses near the knee in the S-N curve and are produced as the result of two fatigue failure mechanisms – one predominant at stresses above the knee, the other below the knee, and both operative at the knee.

All the specimens failed through the hole, as expected. In general, a crack initiated on one side of the hole and grew until that side fractured before a crack was initiated on the other side of the hole. Examination of the fracture surfaces with a 60-power microscope revealed that many of the specimens from each life group did not crack initially at the edge of the hole. The cracks appear to have initiated in the top surface 0.01 to 0.04 in. (0.3 to 1.0 mm) from the edge of the hole. Determination of the location of the crack initiation sites was based on the texture of the fracture surface. In some cases it was not possible to determine whether the crack initiated at the edge of the hole or a short distance from it. In some of the aluminum specimens of reference 1 that had the same configuration as the specimens of the present investigation, cracks initiated some distance from the edge of the hole. The reason for this behavior has not been determined.

In the outdoor tests, specimens began failing after approximately 7 months of exposure and after sustaining approximately half the number of load cycles required to produce the first failures in the indoor tests. Scatter in test lives was dramatically lower than in the indoor tests, and the data fell into a single life group. The median life in the outdoor tests was less than 1/5 of that in the indoor tests.

All of the specimens tested outdoors failed through the hole, as did the indoor specimens. In the outdoor specimens, however, there was a greater tendency to crack equally on each side of the hole. Also, in most of the specimens, secondary cracks initiated ahead of the main crack in slightly different cross sections. Crack initiation sites were easily identified on the outdoor specimens because of the discoloration of the fracture surface due to the elevated-temperature exposure. Examination of these specimens revealed that the cracks initiated 0.01 to 0.04 in. (0.3 to 1.0 mm) from the edge of the hole, as was noted for the indoor specimens. The location of a crack initiation site with respect to the hole is shown in the photograph of figure 7.

AM 350 fusion-welded specimens.- In 14 of the 16 AM 350 fusion-welded specimens tested indoors, the fatigue cracks leading to failure initiated at the edge of the weld bead.

In general, failure occurred in these 14 specimens by the linking of two or more cracks. In two of the specimens tested indoors, cracks initiated and grew to failure in the weld bead.

In the outdoor tests, specimens began failing after approximately 7 months of exposure and after sustaining slightly more than half the number of load cycles required to produce the first failures indoors. Scatter in test lives was about the same as for the indoor tests, with the result that the median life outdoors was also reduced to about half the indoor life. All the outdoor specimens failed as a result of fatigue cracks which initiated along the edge of the weld bead. There was only a slight tendency toward the initiation of more cracks in the outdoor tests than in the indoor tests.

Ti-8Al-1Mo-1V central-hole specimens.- The indoor tests of the titanium alloy central-hole specimens resulted in an even wider range of fatigue lives than that observed for the AM 350 central-hole specimens. The titanium data also exhibit a tendency toward division into short-life and long-life groups, although the division is not as obvious as in the case of the AM 350 specimens. All the specimens failed through the hole, and failure was generally characterized by the growth of a single crack from one side of the hole. It was not possible to locate the crack initiation sites with any degree of certainty, but in a few cases the crack may have initiated 0.01 to 0.02 in. (0.3 to 0.5 mm) from the edge of the hole rather than at the edge.

In the outdoor tests, 11 of the 16 specimens failed as a result of cracks that initiated in arc spots which were inadvertantly produced on the specimens when the temperature sensors were spotwelded to the bottom surface. The arc spots were generally less than 0.01 in. (0.3 mm) in diameter and could not be detected with the unaided eye prior to the elevated-temperature exposure. During the elevated-temperature exposure, the arc spots were preferentially oxidized and discolored, and eventually were detectable with the unaided eye. The arc spots were concentrated in the area between the test section and the grip line, and consequently most of the fractures did not occur through the test section. Some failures occurred in cross sections at which the nominal stress was as low as 60 percent of that at the test section. A metallurgical examination revealed that cracking in the arc spots was related to the local metallurgical transformation and to the slight pitting of the surface which occurred. The outdoor test environment apparently was not a significant factor in the occurrence of these failures since similar failures were subsequently produced in unheated, unexposed specimens.

The specimen failures caused by the arc spots prevented the determination of the effects of the outdoor test environment on the median life of the sample. However, these failures may have provided useful information by indicating that titanium alloys may be unusually sensitive to such defects and that caution must be exercised when using equipment which might cause arcing near titanium alloy structures.

The five outdoor failures which were not influenced by arc spots occurred chronologically as failures 2 to 6. (See table V(b).) This being the case, the tests do provide an indication of the effect of the environment in producing the first failures, which generally are the failures of most interest. Failure number 1 can be disregarded because this specimen failed as the result of an arc spot at a fatigue life close to that of failure number 2. Hence, in the absence of the arc spot, this specimen probably would not have been the first to fail. Specimens began failing outdoors after slightly more than 7 months' exposure and after sustaining about 2/3 of the number of load cycles required to produce the first failures indoors. The cracks leading to failure initiated at or very near the edge of the hole. Although the fracture surfaces were slightly discolored because of the elevated-temperature exposure, it was not possible to pinpoint the initiation sites. Cracking occurred predominantly on one side of the hole, and no evidence of secondary cracking was observed.

Ti-8Al-1Mo-1V fusion-welded specimens.- The indoor tests of the titanium alloy fusion-welded specimens resulted in two widely separated fatigue-life groups which corresponded to two modes of failure. The failures in the short-life group initiated in the weld bead, whereas the failures in the long-life group did not. The latter failures apparently initiated just outside the heat-affected zone in an area where, because of the increased thickness in the weld area, the stresses were as high as, or higher than, in the weld bead. The reason for division into two life groups has not been determined.

In the outdoor tests, specimens began failing after approximately 9 months of exposure. Although nine of the 15 specimen failures were induced by arc spots, five of the first six failures were not influenced by arc spots and initiated in the weld bead, as did the short-life failures indoors. The first failures outdoors occurred at a fatigue life approximately 3/4 of that observed for the first failures indoors. The number of cracks initiated in the outdoor tests was similar to that observed in the indoor tests.

Comparison With Outdoor Tests on Aluminum Alloys

In a series of outdoor tests conducted at the Langley Research Center several years ago and documented in reference 1, specimens of bare 2024-T3 and 7075-T6 aluminum alloys were exposed at ambient temperatures for a period somewhat shorter than that in the present investigation. First failures outdoors in the aluminum series occurred at approximately 1/2 to 2/3 of the load cycles required to produce the first failures indoors. The average lifetime outdoors was about 1/3 of that observed indoors. Thus it appears that the effect of the elevated-temperature outdoor exposure on the fatigue life of the Ti-8Al-1Mo-1V and AM 350 alloys in the present investigation is of the same order as that observed for bare 2024-T3 and 7075-T6 aluminum alloys exposed at ambient temperatures. As in the case of the aluminum tests, the reduction in life observed in the outdoor tests of the present investigation is apparently due to corrosion effects because Healy et al. (ref. 11) found that the fatigue strength of Ti-8Al-1Mo-1V and AM 350 was unaffected by longtime stressed exposure at 550° F (561° K) in an oven.

CONCLUDING REMARKS

Constant-amplitude bending fatigue tests were conducted on central-hole (stress concentration factor of 1.6) and fusion-welded sheet specimens of duplex-annealed Ti-8Al-1Mo-1V titanium alloy and cold-rolled and tempered AM 350 stainless steel. The specimens were maintained at 550° F (561° K) during most of the exposure period to approximate the operating environment of a Mach 3 supersonic transport aircraft. The heating was interrupted for a 4-hour period each night to allow dew to form, for a short period twice a week when cyclic loads were applied, and any time rain or snow was falling. A static load was applied continuously for the duration of the tests. The exposure period for individual specimens ranged from 7 to 23 months. For comparison, tests were also conducted indoors at room temperature and at the same stress levels as outdoors. From the data presented, the following observations are made:

1. The outdoor test environment had a deleterious effect on the fatigue behavior of all the materials tested, as evidenced by the following:

Central-hole AM 350 specimens – life to first failures was reduced to 1/2 and the median life to 1/5 of the indoor life; a significantly greater number of fatigue cracks initiated in the outdoor specimens.

Fusion-welded AM 350 specimens – life to first failures and median life were reduced to 1/2 of the indoor life.

Central-hole Ti-8Al-1Mo-1V specimens – life to first failures was reduced to 2/3 of the indoor life.

Fusion-welded Ti-8Al-1Mo-1V specimens – life to first failures was reduced to 3/4 of the indoor life.

2. Most of the failures in the titanium specimens tested outdoors occurred outside the test section, sometimes through cross sections where the nominal stress was as low as 60 percent of that at the test section. The cracks leading to failure initiated at small arc spots (less than 0.01 in. (0.3 mm) in diameter) on the tension mean stress surface.

3. The reduction in life to first failures observed for all materials in this investigation is of the same order as that reported previously for bare 2024-T3 and 7075-T6

aluminum alloys exposed at ambient temperatures. The reduction in life was apparently due to corrosion effects rather than to heating effects.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., May 20, 1969,
129-03-06-04-23.

APPENDIX A

CONVERSION OF U.S. CUSTOMARY UNITS TO SI UNITS

The International System of Units (SI) was adopted by the Eleventh General Conference on Weights and Measures held in Paris in 1960 (ref. 6). Conversion factors required for units used herein are given in the following table:

Physical quantity	U.S. Customary Unit	Conversion factor (*)	SI Unit (**)
Force	lbf	4.448	newtons (N)
Length	in.	0.0254	meters (m)
Stress	ksi = 10^3 lbf/in^2	6.895×10^6	newtons per sq meter (N/m^2)
Temperature	(^oF + 459.67)	5/9	degrees Kelvin (^oK)
Volume	gallon	3.785×10^{-3}	cubic meters (m^3)
Frequency	cpm	1.67×10^{-2}	hertz (Hz)

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

**Prefixes to indicate multiple of units are as follows:

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

APPENDIX B

MATERIAL CLEANING PROCEDURES

Ti-8Al-1Mo-1V (duplex annealed)

1. Remove metal markings such as manufacturer's stamp, crayon, and so forth, with acetone or alcohol and cloth.

2. Perform alkaline cleaning consisting of six steps, using a separate tank for each solution or rinse as follows:

a. Immerse in sodium hydroxide base alkaline cleaner, 6 ozm per gallon (45 kg/m^3) water, at temperature of 180° to 200° F (360° to 370° K) for 10 minutes.

b. Rinse in hot water for 2 to 3 minutes.

c. Immerse in nitric acid solution, 20 percent nitric acid and 80 percent water by volume, for 30 seconds.

d. Rinse in agitated hot water.

e. Rinse in agitated cold water.

f. Rinse in agitated cold water with continuous supply of fresh water.

3. Dry with clean cloth or paper wipers.

AM 350 (CRT)

1. Remove metal markings such as manufacturer's stamp, crayon, and so forth, with acetone or alcohol and cloth.

2. Degrease with trichloroethylene vapor.

3. Rinse in hot water.

4. Immerse in nitric acid solution, 20 percent nitric acid and 80 percent water by volume, for approximately 5 minutes.

5. Wash thoroughly in hot water.

6. Rinse thoroughly in cold water.

7. Dry with clean cloth or paper wipers.

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TABLE I.- CHEMICAL ANALYSIS AND HEAT TREATMENT OF MATERIALS

Ti-8Al-1Mo-1V (duplex annealed)

Element	Percent by weight
C	0.026
Fe	.11
N	.011
Al	7.9
V	1.0
Mo	1.1
H	.003 to .006
Ti	Balance

Heat treatment:
1450° F (1060° K) for 8 hours, furnace cooled
1450° F for 15 minutes, air cooled

AM 350 (CRT)

Element	Percent by weight
C	0.096
MN	.75
P	.015
S	.010
Si	.27
Cr	16.64
Ni	4.30
Mo	2.79
N	.096
Fe	Balance

Heat treatment:
Annealed at 1950° F (1340° K)
Cold rolled 33%
Tempered in hot caustic at 900° to 950° F (760° to 780° K) for 5 minutes, air cooled

TABLE II.- AVERAGE[a] ROOM-TEMPERATURE LONGITUDINAL TENSILE PROPERTIES OF Ti-8Al-1Mo-1V (DUPLEX ANNEALED) AND AM 350 (CRT) IN THE WELDED AND UNWELDED CONDITIONS

Material	Ultimate tensile strength		Yield strength (0.2% offset)		Elongation in 2 in. (5 cm), percent	Modulus of elasticity	
	ksi	GN/m^2	ksi	GN/m^2		ksi	GN/m^2
AM 350 (CRT)	222	1.53	[b]219	[b]1.51	[b]15.1	28.8×10^3	199
AM 350, fusion welded	150	1.03	84	.58	3.3	---------	---
Ti-8Al-1Mo-1V (duplex annealed)	151	1.04	139	.96	13.1	17.6×10^3	121
Ti-8Al-1Mo-1V, fusion welded	[c]>140	[c]>0.96	----	----	----	---------	---

[a]Based on eight tests.

[b]Based on seven tests.

[c]The strengths of the welds were not determined because the cross-sectional area of the welds was greater than the area of the parent metal and all the specimens failed in the parent metal. The numbers shown are equal to the failing load in the parent metal divided by the cross-sectional area of the weld.

TABLE III.- METEOROLOGICAL DATA FOR TEST PERIOD

Month and year	Average temperature		Total precipitation		Days of precipitation
	°F	°K	in.	mm	
Jan. 1966	35	275	3.81	96.8	12
Feb.	39	277	4.08	103.6	11
Mar.	48	282	1.53	38.9	8
Apr.	54	285	2.68	68.1	10
May	63	290	5.48	139.2	13
June	72	296	5.14	130.6	10
July	78	299	5.39	136.9	5
Aug.	75	297	7.15	181.6	14
Sept.	69	294	6.31	160.3	11
Oct.	59	288	1.15	29.2	6
Nov.	50	283	.86	21.8	4
Dec.	41	278	3.43	87.1	10
Jan. 1967	44	280	2.82	71.6	7
Feb.	40	278	3.89	98.8	11
Mar.	49	283	1.78	45.2	7
Apr.	58	288	.91	23.1	3
May	60	289	3.86	98.0	15
June	70	294	1.20	30.5	4
July	75	297	6.13	155.7	13
Aug.	74	297	9.80	248.9	15
Sept.	66	292	3.23	82.0	8
Oct.	58	288	1.44	36.6	5
Nov.	46	281	1.99	50.5	5
Dec.	43	279	7.28	184.9	9
Jan. 1968	35	275	3.14	79.8	10
Feb.	34	274	1.41	35.8	3

TABLE IV.- RESULTS OF INDOOR FATIGUE TESTS ON AM 350 (CRT) AND Ti-8Al-1Mo-1V (DUPLEX ANNEALED)

(a) AM 350 (CRT)		(b) Ti-8Al-1Mo-1V (duplex annealed)	
Central-hole specimen tested at 40 ± 82 ksi (276 ± 565 MN/m^2)	Fusion-weld specimen tested at 27 ± 68 ksi (186 ± 469 MN/m^2)	Central-hole specimen tested at 25 ± 67 ksi (172 ± 462 MN/m^2)	Fusion-weld specimen tested at 25 ± 53 ksi (172 ± 365 MN/m^2)
Cycles to failure	Cycles to failure	Cycles to failure	Cycles to failure
110 900	108 300	93 800	110 900
119 900	115 100	101 400	123 500
134 200	124 600	101 700	131 200
142 600	134 000	134 200	135 700
151 100	162 000	159 400	139 500
163 200	162 600	174 100	139 700
214 900	171 100	240 800	166 900
235 500	180 200	246 700	168 500
688 200	205 200	[a]853 000	173 600
721 300	208 700	[a]1 058 800	276 900
850 600	209 600	[a]1 497 600	[a,c]6 393 800
[a]969 800	217 300	[a]2 755 700	[a,c]7 553 600
[a]1 005 200	266 400	2 785 400	[c]8 227 200
[a]1 413 100	[b]302 900	[a]3 894 000	[a,c]10 218 300
1 554 000	323 000	[a]4 652 700	[a,c]12 098 900
[a]2 027 800	[a,b]2 938 700	[a]10 635 000	[a,c]13 390 200
		[a]14 967 800	

[a]Test was interrupted and completed later.
[b]Failed through weld bead (other specimens failed along edge of weld bead).
[c]Failed in parent metal (other specimens failed through weld bead).

TABLE V.- RESULTS OF OUTDOOR FATIGUE TESTS ON AM 350 (CRT) AND Ti-8Al-1Mo-1V (DUPLEX ANNEALED)

(a) AM 350 (CRT)

Central-hole specimens[a] tested at 40 ± 82 ksi (276 ± 565 MN/m²)			Fusion-weld specimens[b] tested at 27 ± 68 ksi (186 ± 469 MN/m²)		
Cycles to failure	Hours exposed at 550° F (561° K)	Date of failure[c]	Cycles to failure	Hours exposed at 550° F (561° K)	Date of failure[c]
61 700	3400	8-16-66	57 200	2 820	8-26-66
65 800	3580	8-26-66	65 600	3 540	8-30-66
70 700	3640	9-16-66	69 700	3 450	9-21-66
74 200	3660	11-10-66	71 900	3 830	10-14-66
76 800	3990	10-28-66	83 300	4 440	11-22-66
78 100	4050	10-11-66	85 800	4 600	11-4-66
81 400	4120	10-25-66	87 100	4 490	11-18-66
85 600	4270	11-10-66	88 200	4 750	11-15-66
87 900	4730	11-16-66	90 700	4 860	11-22-66
89 900	4740	11-25-66	97 100	5 060	12-23-66
90 200	4870	11-22-66	108 500	5 760	2-8-67
91 000	4740	11-29-66	116 100	5 820	3-7-67
93 400	5050	11-29-66	185 500	10 020	10-13-67
98 900	5440	12-20-66			
102 500	5300	1-24-67			
104 200	5500	3-3-67			
122 700	6270	3-14-67			

(b) Ti-8Al-1Mo-1V (duplex annealed)

Central-hole specimens[d] tested at 25 ± 67 ksi (172 ± 462 MN/m²)			Fusion-weld specimens[e] tested at 25 ± 53 ksi (172 ± 365 MN/m²)		
Cycles to failure	Hours exposed at 550° F (561° K)	Date of failure[c]	Cycles to failure	Hours exposed at 550° F (561° K)	Date of failure[c]
[f]59 700	3 190	8-16-66	81 600	4 110	10-25-66
67 700	3 690	9-1-66	90 700	4 760	11-22-66
71 700	3 850	9-21-66	125 700	6 900	3-28-67
81 600	4 260	11-10-66	[f]128 600	7 090	4-4-67
96 900	4 530	12-23-66	140 200	7 600	5-5-67
102 000	5 490	1-6-67	157 700	8 630	8-1-67
[f]134 300	7 160	4-21-67	[f]175 300	9 540	9-15-67
[f]137 600	7 300	6-2-67	[f]177 100	9 800	11-7-67
[f]145 100	7 740	6-13-67	[f]178 500	9 390	11-3-67
[f]151 000	8 130	6-16-67	181 000	9 630	12-26-67
[f]179 300	9 660	10-6-67	[f]197 200	10 710	12-29-67
[f,g]210 800	11 370	1-18-68	[f,g]219 400	10 260	1-18-68
[f,g]264 400	11 650	1-19-68	[f,g]285 100	11 530	2-1-68
[f,g]290 100	11 160	2-1-68	[f,g]303 500	11 730	2-1-68
[f,g]294 000	11 300	2-1-68	[f,g]487 600	10 820	3-5-68
[f,g]319 600	11 050	2-1-68			

[a]Two of the 19 specimens on test were inadvertently destroyed early in the test period.

[b]Six specimens destroyed.

[c]Test exposure initiated on 1-20-66 for all specimens.

[d]Three of 19 specimens destroyed.

[e]Four of 19 specimens destroyed.

[f]Failure initiated in arc spot.

[g]Schedule of applying 1100 cycles twice a week was abandoned on 1-18-68; thereafter, large numbers of cycles were applied on days when it was convenient to operate machine.

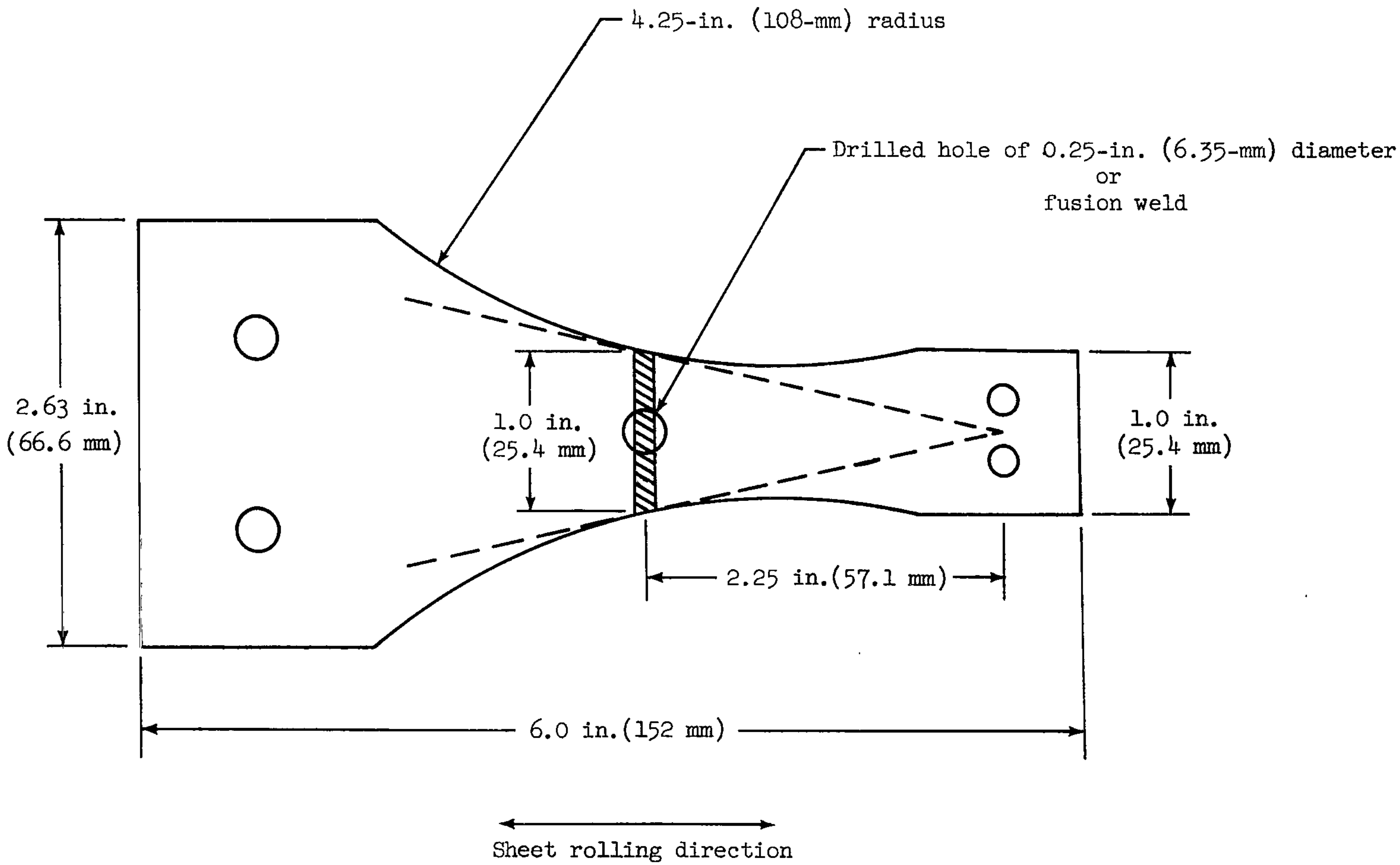

Figure 1.- Fatigue-specimen configurations.

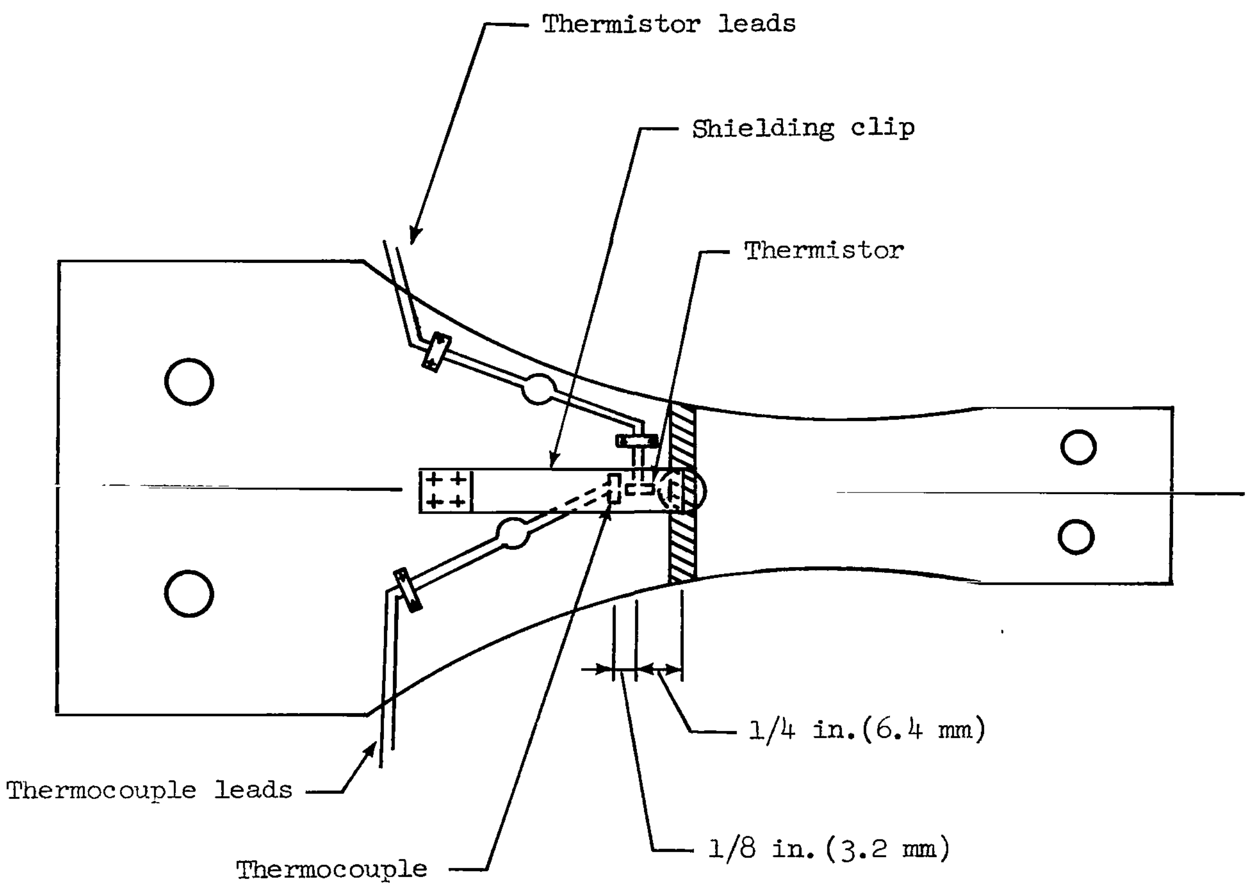

Figure 2.- Location of thermistor, thermocouple, and shielding clip on bottom surface of specimen.

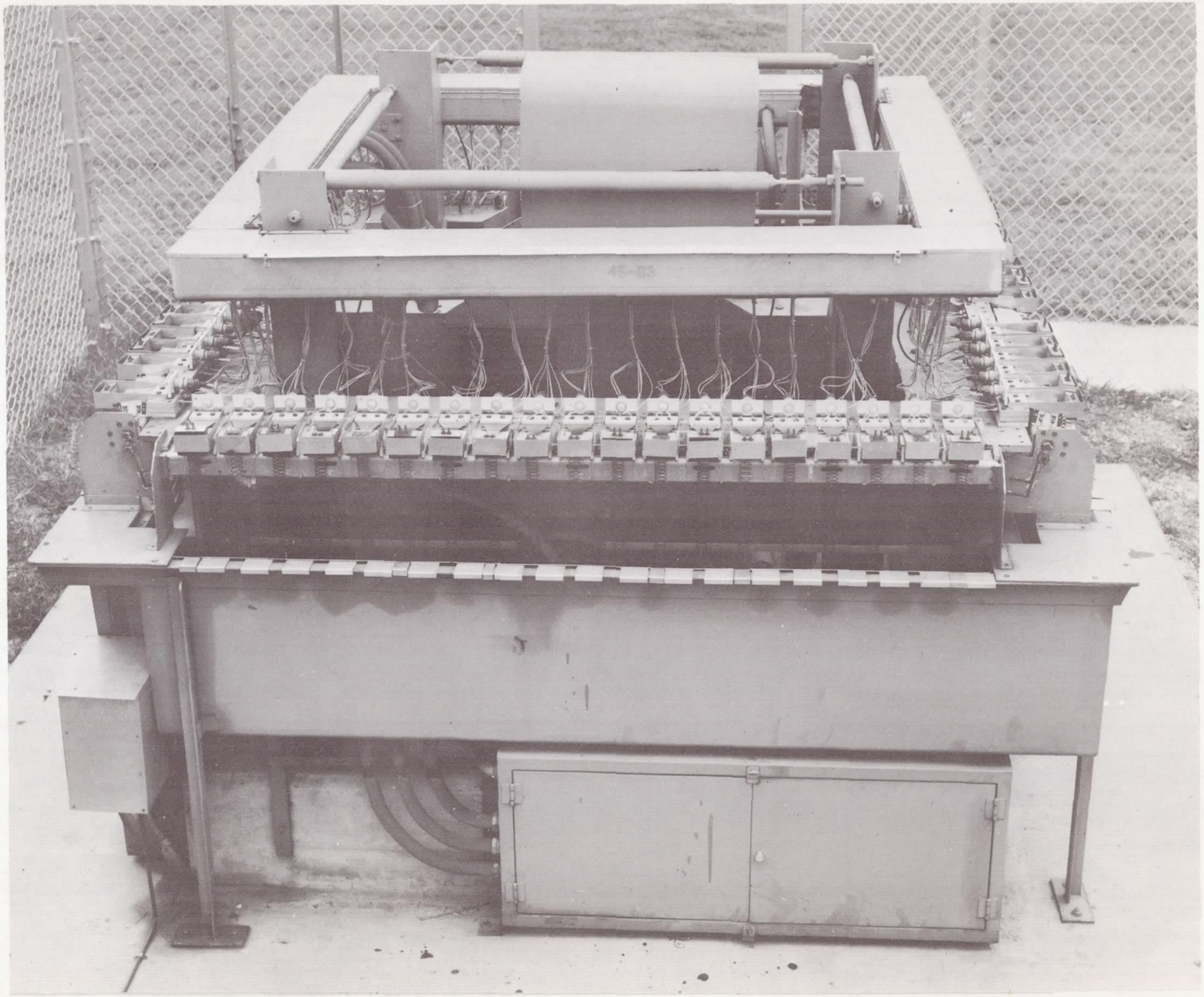

Figure 3.- Outdoor fatigue-testing machine. L-66-7230

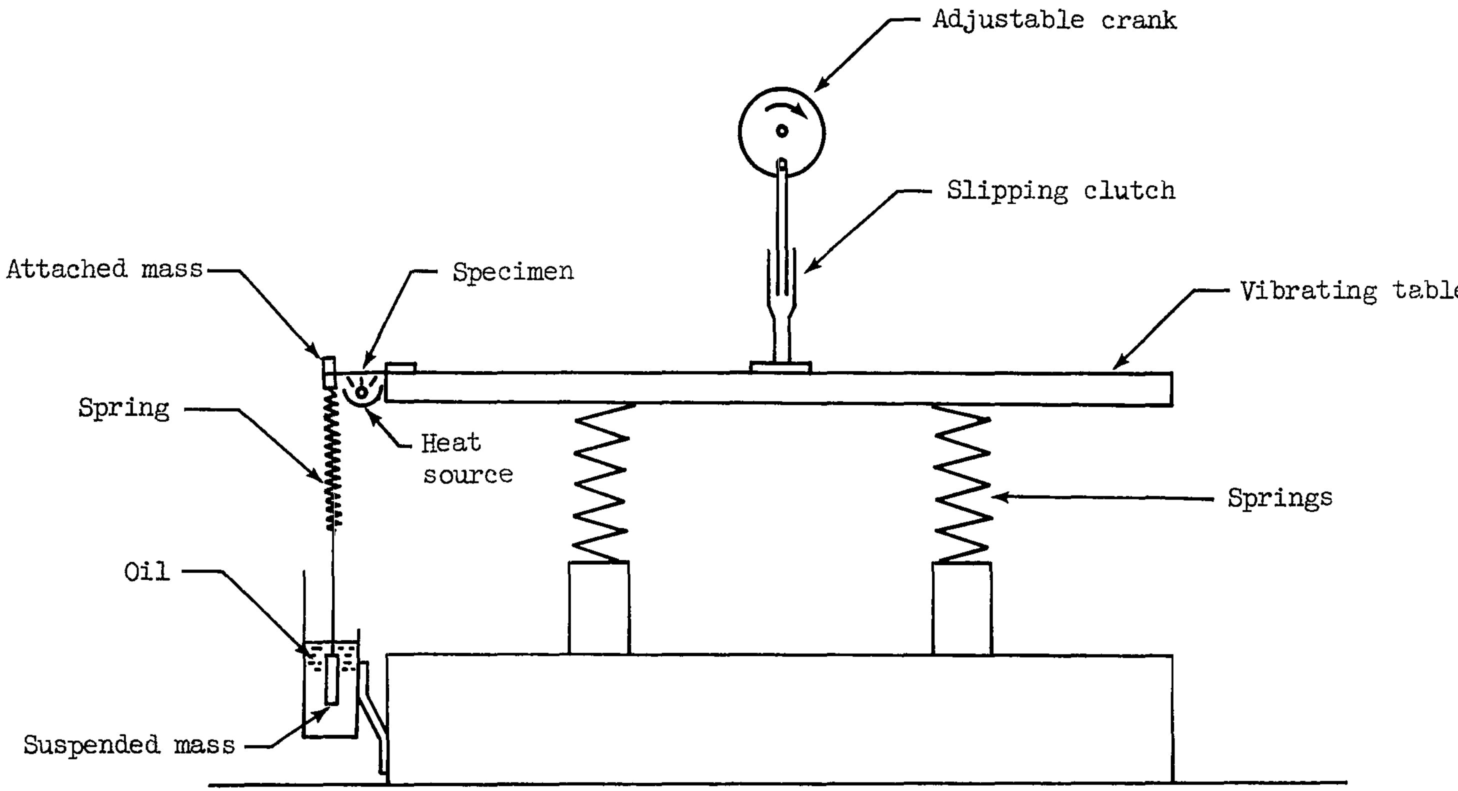

Figure 4.- Diagram of outdoor fatigue-testing machine.

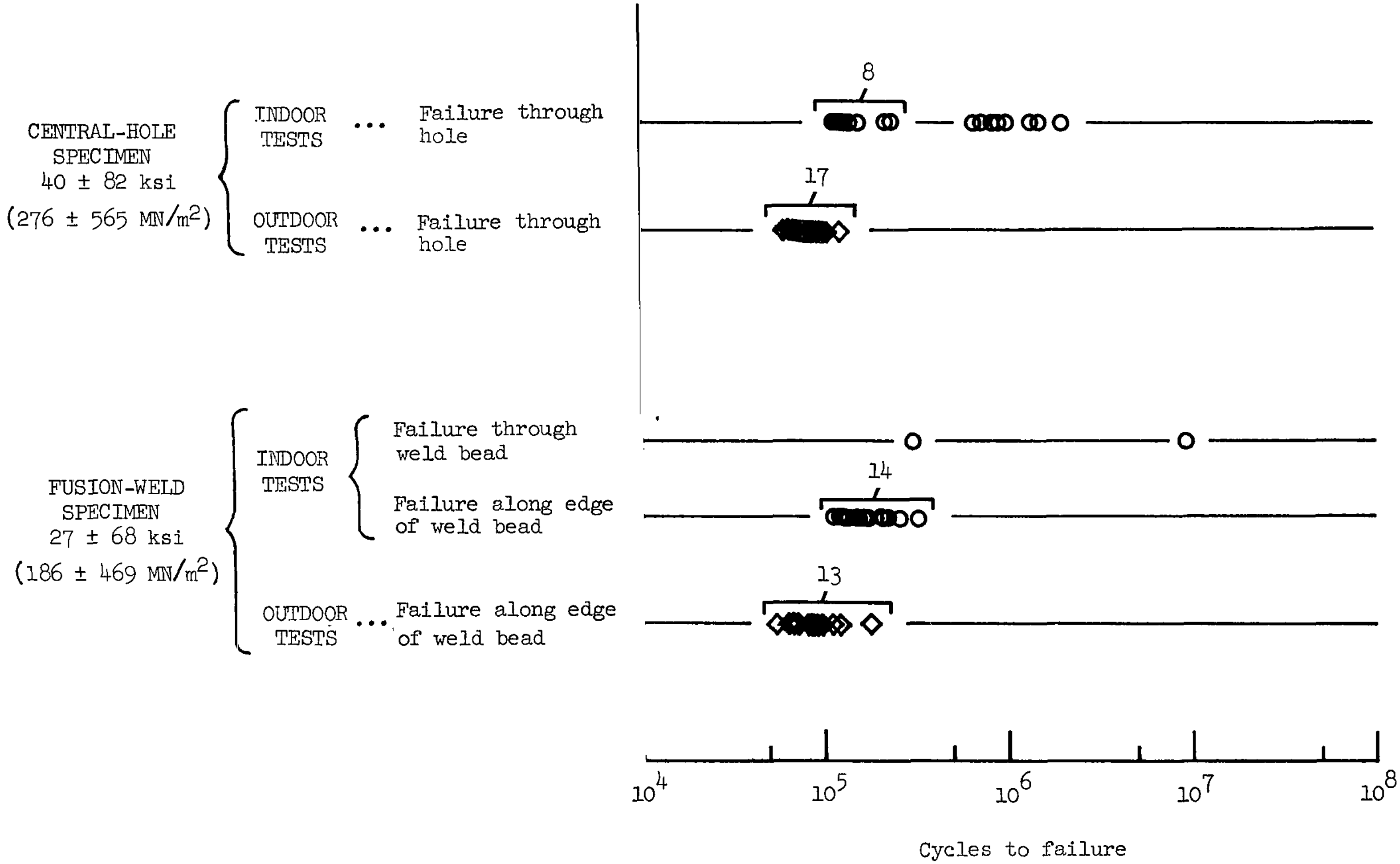

Figure 5.- Results of indoor and outdoor fatigue tests on central-hole and fusion-welded specimens of AM 350 (CRT) stainless steel.

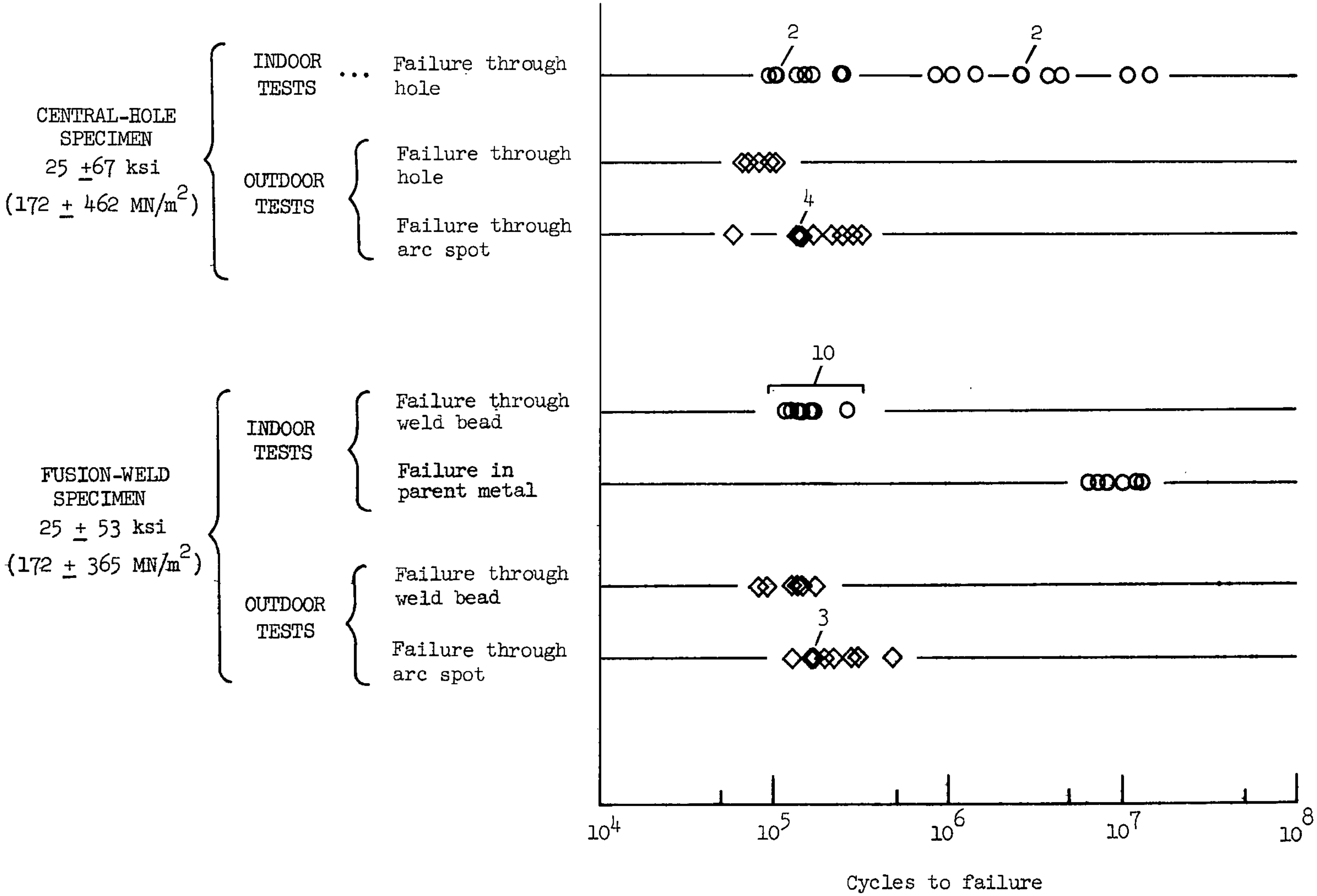

Figure 6.- Results of indoor and outdoor fatigue tests on central-hole and fusion-welded specimens of Ti-8Al-1Mo-1V (duplex annealed) titanium alloy.

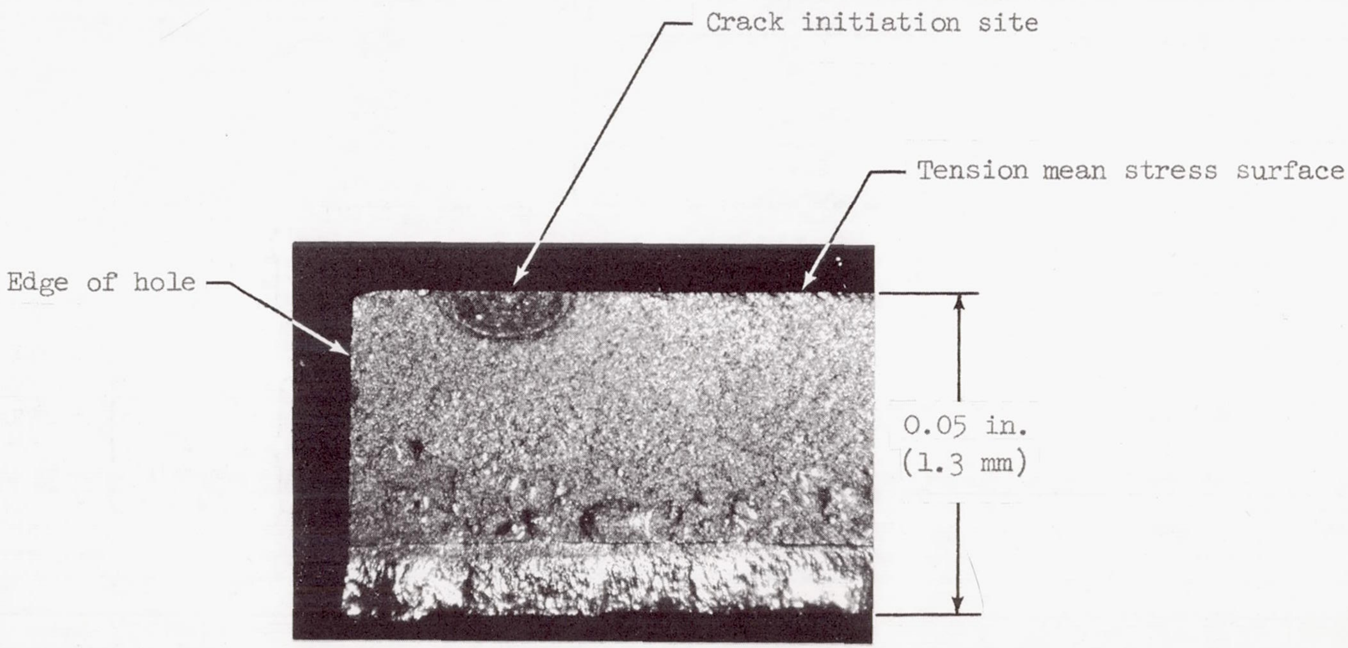

Figure 7.- Photograph of crack initiation site in central-hole AM 350 specimen tested outdoors. L-69-5215

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