NASA TECHNICAL NOTE

NASA TN D-5973

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NASA TN D-5973

EFFECT OF STRAIN-GAGE ATTACHMENT BY SPOTWELDING AND BONDING ON FATIGUE BEHAVIOR OF Ti-6Al-4V, RENÉ 41, AND INCONEL X

by L. A. Imig

Langley Research Center
Hampton, Va. 23365

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • OCTOBER 1970

1. Report No. NASA TN D-5973	2. Government Accession No.	3.
4. Title and Subtitle EFFECT OF STRAIN-GAGE ATTACHMENT BY SPOT-WELDING AND BONDING ON FATIGUE BEHAVIOR OF Ti-6Al-4V, RENÉ 41, AND INCONEL X		5. Report Date October 1970
		6. Performing Organization Code
7. Author(s) L. A. Imig		8. Performing Organization Report No. L-7165
		10. Work Unit No. 126-14-15-02
9. Performing Organization Name and Address NASA Langley Research Center Hampton, Va. 23365		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Note
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

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17. Key Words (Suggested by Author(s)) Fatigue (materials); Elevated temperature; Titanium alloy; Heat-resistant alloys; Strain gages; Spotwelds		18. Distribution Statement Unclassified – Unlimited	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 21	22. Price* $3.00

*For sale by the Clearinghouse for Federal Scientific and Technical Information Springfield, Virginia 22151

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SUMMARY

An experimental investigation was conducted to evaluate the effects of spotwelding and bonding, as used for instrumentation attachment, on the fatigue behavior of three alloys suitable for use in high-speed airplanes: a titanium alloy and two superalloys. The effects of spotwelding were evaluated by means of constant-amplitude fatigue tests conducted at room temperature for all three alloys and at 1500° F (1090 K) for the superalloys. Test results for the titanium alloy indicated much lower fatigue strengths for specimens having strain gages attached by spotwelding than for plain specimens. The superalloys were affected similarly but to a lesser extent. The losses of fatigue strength were attributed to local microstructural changes due to spotwelding. In contrast, specimens with strain gages attached by adhesive bonding had fatigue strength equal to that of smooth specimens.

INTRODUCTION

Strain gages are efficient instruments for use in load-measuring programs for airplanes. Some existing resistance strain gages and other types under development are attached by spotwelding. The tests of reference 1 showed that such spotwelds are potentially detrimental to the fatigue life of the structure because electrical arcing produces microstructural defects at which fatigue cracks can initiate. Therefore, a limited experimental investigation was conducted to evaluate the effects of spotwelding and bonding, as used for instrumentation attachment, on the fatigue behavior of three alloys suitable for use in high-speed airplanes: a titanium alloy and two superalloys. The effects of spotwelding were evaluated by means of constant-amplitude fatigue tests of specimens with and without strain gages. All three alloys were tested at room temperature (about 70° F (294 K)); the superalloys were also tested at 1500° F (1090 K).

The physical quantities used in this paper are given both in U.S. Customary Units and in the International System of Units (SI). Factors relating these two systems of units are given in reference 2 and those units pertinent to the present investigation are presented in appendix A.

MATERIALS

Alloys

The fatigue behavior of three alloys potentially useful in high-speed airplanes was studied in the present investigation. The alloy Ti-6Al-4V was considered representative of structural materials for supersonic airplanes. Two superalloys, René 41 and Inconel X, were considered representative of materials for use in hypersonic airplanes. The titanium alloy was in the duplex-annealed condition, the René 41 was solution treated, and the Inconel X was annealed. All three materials were in sheet form. The chemical compositions, tensile properties, and thicknesses of the sheet materials are given in table I. Tensile and fatigue specimens were machined from the alloys to the configurations shown in figure 1. Other details of specimen preparation are given in appendix B.

Strain Gages

For the titanium-alloy specimens, two kinds of commercially available resistance strain gages were used: a weldable gage with a metal back and a bonded gage. The resistance element for the weldable gage was embedded in compacted magnesium oxide powder and insulated from a small metal tube that was attached to the gage backing. The metal backs were made from three alloys: a titanium alloy, a gold alloy, and a stainless steel. For the more conventional bonded gage, two synthetic backing materials were used: a fiber glass and a resin. For the superalloys, weldable strain gages were simulated by metal foils spotwelded to the specimen. The foil alloy was the same as the specimen alloy in both cases. The strain gages, foils, and welding parameters are described more fully in appendix B.

PROCEDURES

Fatigue tests were conducted with constant-amplitude axial stresses in the ratio of minimum stress to maximum stress of 0.05 ($R = 0.05$). The stresses were based on the initial minimum cross-sectional area of each specimen, excluding the areas of strain gages and foils. As indicated in table II, Ti-6Al-4V specimens with and without strain gages were tested at room temperature (taken as 70° F (294 K)) and superalloy specimens with and without simulated strain gages were tested at room temperature and at 1500° F (1090 K). Descriptions of testing machines and elevated-temperature equipment are provided in appendix B.

Two of the titanium specimens with weldable strain gages were annealed after spotwelding to evaluate potentially beneficial effects of stress-relief treatments at elevated temperatures on structural material. One specimen was heated to 1350° F (1000 K) for

4 hours and the other was heated to 1500° F (1090 K) for 6 hours; the annealing treatments were carried out at 10^{-5} torr (1.33 mN/m^2) and the specimens were furnace cooled.

As an aid to understanding the effects of spotwelding, some of the specimens were examined metallographically. A photomicrograph was made from a failed specimen of each material and from one of the titanium specimens that had been stress relieved.

Information about the fatigue resistances of the strain gages was obtained from a sideline investigation. The gages were connected into a full-bridge circuit, the output of which was recorded continuously. Separation of the gage element or lead wire caused a loss of signal to the recorder and thereby indicated gage failure. In some tests of Ti-6Al-4V specimens with bonded gages the adhesive failed. The number of cycles required for failure of the bond or the gage circuit was taken as the gage life.

RESULTS AND DISCUSSION

Tests

Tensile properties of the sheet materials used in this investigation are indicated in table I. Fatigue data are listed in tables III, IV, and V and are plotted in figures 2, 3, and 4 for Ti-6Al-4V, René 41, and Inconel X, respectively. Each symbol in the figures represents the fatigue life of an individual specimen. All curves in the figures were faired through the data.

Ti-6Al-4V specimens.- The fatigue limit for plain Ti-6Al-4V specimens was not precisely determined, but a short extrapolation of the curve (see fig. 2) indicates the fatigue strength at 10^7 cycles to be above 110 ksi (760 MN/m^2). That fatigue strength is much higher than would have been anticipated from the data in reference 3. Thus, the fatigue strength of the present material appears to be unusually high.

Strain gages attached by bonding had no apparent effect on the fatigue strength. However, in one test, specimen failure due to a surface flaw occurred in only 115 000 cycles at 70 ksi (480 MN/m^2). Optical examination of the specimen indicated that the flaw probably resulted from an electrical arc generated by an electrical discharge instrument used to number the specimens. Thus, as reported in reference 1, arcing between electrical equipment and titanium structures can be very detrimental to fatigue strength.

At 10^7 cycles the fatigue strength of Ti-6Al-4V specimens with weldable gages was less than one-eighth of that for plain specimens, as shown in figure 2. That effect is much larger than would be expected for stress concentrations resulting from manufacture of typical airplane structures. Thus, especially for titanium-alloy structures, the detrimental effect of spotwelding should be carefully considered when the use of weldable strain gages is contemplated.

In most tests of Ti-6Al-4V specimens with weldable gages, fatigue cracks initiated from the end weld in each row of spotwelds at one end of the gage. The two cracks thus formed subsequently joined into a single crack which propagated until the specimen failed. (As indicated in table III, four of the specimens failed as a result of cracks that initiated at spotwelds interior to the end spotwelds.)

Two specimens were subjected to stress-relief annealing to determine whether such treatments could alleviate the severe effects of spotwelding. Both specimens were tested at a maximum stress of 80 ksi (550 MN/m^2). As shown in figure 2, the fatigue lives for the two stress-relieved specimens were longer than those for specimens tested as welded. Thus, heat treatment after welding might be a way to minimize the detrimental effect of spotwelding on fatigue life. However, before stress-relief annealing would be practical, an efficient method of heat treating a small region of a structure and the reaction of the strain gage to the heat treatment would have to be determined. Such determinations were beyond the scope of the present effort.

Continuity measurements on the gages indicated that the bonded gages remained electrically continuous throughout 10^7 cycles for specimen stresses up to 60 ksi (410 MN/m^2). (See table III for the gage lives.) At the highest stress level, the gages with resin backs became unbonded and the measuring elements of the gages with fiber glass backs failed in relatively few cycles. For both the bonded and spotwelded gages, large shifts in gage output occurred prior to electrical failure of the gage, especially at the higher stress levels. The fatigue characteristics of the strain gages, which were of secondary interest, were studied only incidentally in the present investigation; however, these results suggest that the fatigue characteristics should be determined before selecting strain gages for a particular application.

René 41 specimens.- As shown in figure 3, the fatigue lives of plain specimens tested at room temperature and at 1500° F (1090 K) were about the same. At 10^7 cycles specimens with simulated weldable gages tested at the two temperatures had the same fatigue strength. For stresses higher than that fatigue strength, the tests at elevated temperature resulted in much shorter fatigue lives than the tests at room temperature. At both temperatures, the fatigue strengths at 10^7 cycles for specimens with simulated weldable gages were about two-thirds of the value for plain specimens. That effect is more nearly equal to that expected from stress concentrations in fabricated structures than the large effect observed for the titanium alloy.

In René 41 specimens tested at both room and elevated temperature, fatigue cracks leading to specimen failure initiated at spotwelds at one end of the simulated gages. Many of the spotwelds failed in tests at 1500° F (1090 K); thus, strain gages would have become inactive under such circumstances.

During the course of the investigation, some of the René 41 specimens were observed to generate heat during room-temperature tests at 30 cps (30 Hz). By means of thermocouples, the temperatures of specimens were observed to vary systematically with stress level between 55 and 85 ksi (380 and 590 MN/m^2). The highest temperature recorded was 120° F (320 K) in a test at a maximum stress of 85 ksi (590 MN/m^2). No heating was recorded at stress levels of 55 ksi (380 MN/m^2) and lower. The generation of heat in specimens undergoing fatigue tests is a generally recognized phenomenon and is discussed in reference 4.

Inconel X specimens.- As shown in figure 4, the room-temperature fatigue strength at 10^7 cycles of Inconel X specimens with simulated weldable gages was about two-thirds that of the plain specimens. However, at 1500° F (1090 K) the fatigue strengths of the Inconel X specimens with and without the simulated gages were the same and were somewhat lower than the room-temperature strengths. These effects are of about the same magnitude as usually expected from fabrication effects in structures.

Inconel X specimens also generated measurable heat in room-temperature tests. Specimen temperatures were approximately the same as those observed for the René 41 specimens. Fatigue cracks leading to specimen failure initiated at end spotwelds as they had for the René 41 specimens, and all but three Inconel X specimens exhibited weld failures to varying degrees.

Metallographic Examination

The photomicrographs in figure 5 show partial cross sections through spotwelds for all the specimen materials. These photomicrographs of the entire heat-affected zone show that the effects of spotwelding were restricted to very small regions in all three alloys. As shown in figures 5(a) and 5(b), spotwelding produced nuggets 0.01 inch (0.25 mm) in diameter in the superalloys. Distinct nuggets were not formed in the titanium-alloy specimens, but as shown in figures 5(c) and 5(d), spotwelding produced microstructural changes within a heat-affected zone about 0.02 to 0.025 inch (0.50 to 0.60 mm) in diameter. As shown in figure 5(e), the microstructure of the titanium alloy after stress relieving indicates that annealing has occurred in the heat-affected zone, although the effects of spotwelding were not removed entirely. Even though the fatigue strength of the stress-relieved specimen was higher than that of the as-welded specimen, its strength was much less than that of the specimens without gages. Thus, stress relieving, if sufficient to alleviate the effects of spotwelding, would require optimization to achieve the maximum benefit. The microstructural changes produced by the spotwelding were undoubtedly responsible for the losses of fatigue strength.

CONCLUSIONS

Fatigue tests were conducted to investigate the effect of strain-gage attachment by spotwelding and bonding on the fatigue behavior of a titanium alloy and two superalloys. The following results of the investigation suggest that weldable strain gages should be used with caution on highly loaded structures of these alloys:

1. Strain gages attached to Ti-6Al-4V specimens by spotwelding reduced the fatigue strength at 10^7 cycles to less than one-eighth of the value for plain specimens.

2. Simulated strain gages attached to René 41 specimens by spotwelding reduced the fatigue strength at 10^7 cycles to approximately two-thirds of the value for plain specimens in tests at room temperature and at 1500° F (1090 K).

3. Simulated strain gages attached to Inconel X specimens by spotwelding reduced the fatigue strength at 10^7 cycles to approximately two-thirds of the value for plain specimens in tests at room temperature. At 1500° F (1090 K), the fatigue strengths of the Inconel X specimens with and without the simulated gages were about the same and were somewhat lower than the fatigue strengths at room temperature.

4. Changes in microstructure associated with spotwelding were undoubtedly responsible for the losses of fatigue strength.

5. A surface flaw in a titanium-alloy specimen, probably the result of an electrical arc, caused a fatigue failure at a stress less than two-thirds of the apparent fatigue limit.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., July 9, 1970.

APPENDIX A

CONVERSION OF U.S. CUSTOMARY UNITS TO THE INTERNATIONAL SYSTEM OF UNITS

The International System of Units (SI) was adopted by the Eleventh General Conference of Weights and Measures in Paris, October 1960. Conversion factors for the units used herein are taken from reference 2 and are presented in the following table:

Physical quantity	U.S. Customary Unit	Conversion factor (*)	SI Unit (**)
Energy	W-s	1.0	joule (J)
Force	lbf	4.448	newton (N)
Frequency	cps	1.0	hertz (Hz)
Length	in.	0.0254	meter (m)
Pressure	torr	133.22	newton/meter^2 (N/m^2)
Stress	ksi = 1000 lbf/in^2	6.895×10^6	newton/meter^2 (N/m^2)
Temperature . . .	$^\circ$F	$\frac{5}{9}(^\circ F + 459.67)$	kelvin (K)

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

**Prefixes to indicate multiples of SI Units are as follows:

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

APPENDIX B

EQUIPMENT AND TEST PROCEDURES

Specimen Preparation

The specimens were made by clamping stacks of at least six specimen blanks to the headstock of a lathe for machining. After machining, the edges of each specimen were deburred by sanding lightly in the longitudinal direction with No. 600 emery paper.

Some specimens were alined with and some were oriented at 90° to the sheet rolling direction. No effect of specimen orientation was apparent from the test data.

Strain Gages

The dimensions of the metal backings of the weldable gages were approximately 0.2 by 1.1 inches (5 by 28 mm). The backing thicknesses were approximately 0.0025 inch (0.064 mm) for the stainless steel and gold alloy and about 0.003 inch (0.076 mm) for the titanium alloy. A tubular housing for the resistance element was attached to the backing by a continuous weld. The tubing was approximately semicircular in cross section with a "diameter" of about 0.04 inch (1 mm). The bonded gages with resin backs were about 0.56 by 1.02 inches (14 by 26 mm) and the bonded gages with fiber-glass backs were about 0.26 by 0.56 inch (6.6 by 14 mm).

Before the gages were attached, all specimen surfaces were sanded lightly in the longitudinal direction with silicon carbide paper that had been dipped in methyl ethyl ketone (MEK). Metal foils and strain gages were also cleaned with MEK before they were spotwelded to the specimens. Spotwelding was done with a portable commercial resistance spotwelder. An electrode force of 5 lbf (22 N) and an energy setting of 12 W-s (12 J) were used to weld the gages with stainless steel and titanium alloy backings to the titanium specimens. Gages with gold-alloy backs were welded to the titanium specimens with 5 lbf (22 N) and 30 W-s (30 J). The gages were welded to the specimens by a row of about 30 spotwelds per inch (about 12 spotwelds per cm) along each side of the resistance-element housing. (See fig. 1.)

Simulated gages (metal foils) were welded to the superalloys with an electrode force of 5 lbf (22 N) and an energy setting of 10 W-s (10 J). The René 41 foils measured 0.25 by 0.8 by 0.003 inch (6.4 by 20 by 0.076 mm) and the Inconel X foils measured 0.25 by 0.75 by 0.005 inch (6.4 by 19 by 0.127 mm). The foils were attached by two rows of spotwelds, each containing about 20 to 25 welds per inch (8 to 10 welds per cm).

The gages with resin or fiber-glass backs were attached with a commercial epoxy adhesive. The curing treatment for this adhesive was 1 hour at 300° F (420 K).

Test Equipment

Tensile tests.- Standard tensile tests were conducted in a 120 000-pound-capacity (534-kN) universal hydraulic testing machine at the Langley Research Center. Stress-strain curves were obtained autographically by means of an x-y plotter. The electronic signal from a load cell in series with the specimen actuated the recorder drive for the stress axis. The strain axis was actuated by the output of an extensometer that incorporated a linear variable differential transformer. The extensometer was attached to the specimen in the reduced section and had a gage length of 1.00 inch (25.4 mm). The elongation in 2.00 inches (50.8 mm) was determined by measuring the distance, after fracture, between grid lines placed on each specimen prior to the test.

Fatigue tests.- Two types of testing machines were used to conduct the fatigue tests. Specimens with an expected life of more than 10 000 stress cycles were tested in subresonant machines that operated at a frequency of 30 cps (30 Hz) and are described in reference 5. Specimens with an expected life of less than 10 000 stress cycles were tested in a hydraulically actuated testing machine that operated at about 15 cps (15 Hz) and are described in reference 6.

Fatigue tests at 1500° F (1090 K) were conducted in subresonant machines equipped with the heating device represented in figure 6. Specimens were heated from one side with radiation from quartz-envelope lamps using commercial water-cooled, parabolic reflectors. The specimen and the reflector assembly were enclosed in an insulated housing. The temperature in the heater was sensed by a thermocouple on a metal strip of the same material as the test specimen positioned in the plane of the specimen near the test section. The signal provided by the thermocouple was used as the input for a commercial temperature controller. This method of heating provided a temperature distribution on the specimen within 10° F (5.5 K) of the desired temperature over the middle 3 inches (8 cm) of the specimen, as determined by a temperature survey on a specimen blank with an array of thermocouples attached.

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7. Anon.: Alloy Sheet and Strip, Corrosion and Heat Resistant: Nickel Base – 19Cr – 11Co – 10Mo – 3Ti – 1.5Al, Vacuum Melted – Solution Heat Treated. AMS 5545, Soc. Automot. Eng., Jan. 15, 1961.

8. Anon.: Alloy Sheet, Strip, and Plate, Corrosion and Heat Resistant: Nickel Base – 15.5Cr – 2.5Ti – 1(Cb + Ta) – 0.7Al – 7Fe. AMS 5542G, Soc. Automot. Eng., Sept. 1, 1949 (Rev. Jan. 15, 1962.)

TABLE I.- CHEMICAL COMPOSITIONS AND TENSILE PROPERTIES OF SHEET MATERIALS

(a) Chemical compositions determined by manufacturers

Alloy	Percentage of constituent by weight –																	
	Al	Nb and Ta	Co	Cr	Cu	Fe	Mn	Mo	V	B	C	S	Si	H	N	O	Ni	Ti
Ti-6Al-4V	5.8	---	----	----	---	0.12	---	---	4.1	-----	0.023	----	---	0.011	0.009	0.10	-----	Bal.
René 41	1.40	---	11.11	18.41	---	.58	Nil	9.68	---	0.0035	.04	0.006	0.10	----	----	---	Bal.	3.10
Inconel X	.66	0.94	----	15.14	0.03	6.52	0.27	---	---	-----	.02	.007	.25	----	----	---	[a]73.68	2.46

[a]Includes a small amount of cobalt.

(b) Tensile properties at room temperature (based on one test of each alloy)

Alloy	Condition	Thickness		Tensile ultimate strength		Tensile yield strength at 0.2-percent offset		Elongation in 2 in. (51 mm), percent
		in.	mm	ksi	MN/m^2	ksi	MN/m^2	
Ti-6Al-4V	Duplex annealed[a]	0.063	1.60	148	1020	139	958	15
René 41	Solution treated[b]	.070	1.78	142	980	81	558	50
Inconel X	Annealed[c]	.062	1.57	109	752	49	338	55

[a]Annealed by heating to 1750° F (1230 K) for 10 minutes, air cooling, heating to 1250° F (950 K) for 4 hours, and air cooling.

[b]Solution heat treated according to Aerospace Material Specification 5545 (ref. 7).

[c]Annealed according to Aerospace Material Specification 5542G (ref. 8).

TABLE II.- CONDITIONS FOR FATIGUE TESTS

(a) Plain specimens

Alloy	Test temperature	
	°F	K
Ti-6Al-4V	70	294
René 41	70 and 1500	294 and 1090
Inconel X	70 and 1500	294 and 1090

(b) Specimens with strain gages[a]

Alloy	Gage backing material	Method of attaching gage	Test temperature	
			°F	K
Ti-6Al-4V	Fiber glass	Adhesive bonding	70	294
	Resin			
	Titanium alloy	Resistance spotwelding		
	Stainless steel			
	Gold alloy			
René 41	René 41 (simulated gages)		70 and 1500	294 and 1090
Inconel X	Inconel X (simulated gages)		70 and 1500	294 and 1090

[a]Dimensions of strain gages and simulated gages are given in appendix B.

TABLE III.- FATIGUE DATA FOR Ti-6Al-4V SPECIMENS TESTED AT ROOM TEMPERATURE

[R = 0.05]

Gage backing material	Method of attaching gage	Maximum stress, ksi	Maximum stress, MN/m2	Fatigue life of specimen, cycles	Fatigue life of strain gage, cycles (a)
Titanium alloy	Resistance spotwelding	130	900	[b]6 040	80
		130	900	[b]6 060	60
		110	760	10 000	3 000
		50	340	76 000	[c]76 000
		24	170	1 029 000	90 000
		[d]80	550	35 000	Not available
Stainless steel		[e]130	900	[b]7 370	6 690
		[e]130	900	[b]8 040	5 380
		90	620	20 000	[c]20 000
		30	210	445 000	[c]445 000
		20	140	1 330 000	Not available
		[f]80	550	52 000	Not available
Gold alloy		[e]130	900	[b]5 950	Lead wires failed
		130	900	[b]6 960	[c]6 960
		70	480	26 000	[c]26 000
		[e]24	170	216 000	[c]216 000
		16	110	3 158 000	Not available
		12	80	>10 000 000	[c]10 000 000
Fiber glass	Adhesive bonding	130	900	22 000	3 000
		130	900	111 000	15 000
		70	480	>10 000 000	3 400 000
		60	410	>10 000 000	[c]10 000 000
Resin		130	900	427 000	[g]2 000
		100	690	119 000	[g]1 000
		100	690	>20 000	20 000
		[h]70	480	115 000	Not available
		50	340	>10 000 000	[c]10 000 000
		40	280	>10 000 000	[c]10 000 000
No gages		130	900	30 000	
		130	900	86 000	
		125	860	1 723 000	
		120	830	5 239 000	
		116	800	3 908 000	

[a]Complete electrical failure unless otherwise noted.

[b]Tested in hydraulically actuated testing machine.

[c]Gage was electrically continuous after specimen failed or at end of test.

[d]Annealed at 1500° F (1090 K) for 6 hours after spotwelding.

[e]Failure initiated at a spotweld interior to the end spotwelds. Failure of all other specimens with spotwelded gages initiated at an end spotweld.

[f]Annealed at 1350° F (1000 K) for 4 hours after spotwelding.

[g]Bond failed.

[h]Specimen failure initiated at surface flaw near minimum section.

TABLE IV.- FATIGUE DATA FOR RENÉ 41 SPECIMENS TESTED AT ROOM TEMPERATURE AND AT 1500° F (1090 K)

[R = 0.05]

(a) Plain specimens

Maximum stress, ksi	Maximum stress, MN/m^2	Fatigue life of specimen, cycles
Tests at room temperature		
68	470	>7 906 000
70	480	3 963 000
75	520	460 000
75	520	3 358 000
85	590	297 000
95	650	77 000
105	720	82 940
115	790	[a]42 700
125	860	[a]31 200
Tests at 1500° F (1090 K)		
60	410	>10 000 000
63	430	9 361 000
66	460	6 226 000
70	480	5 405 000
75	520	2 727 000
80	550	1 691 000
90	620	587 000

(b) Specimens with simulated gages

Maximum stress, ksi	Maximum stress, MN/m^2	Fatigue life of specimen, cycles
Tests at room temperature		
40	280	7 231 000
45	310	2 183 000
50	340	1 197 000
55	380	1 264 000
60	410	716 000
70	480	307 000
80	550	120 000
90	620	[a]71 930
Tests at 1500° F (1090 K)		
30	210	>10 000 000
35	240	>10 000 000
38	260	>10 000 000
40	280	>10 000 000
50	340	39 000
60	410	22 000
70	480	18 000
80	550	15 000

[a]Tested in hydraulically actuated testing machine.

TABLE V.- FATIGUE DATA FOR INCONEL X SPECIMENS TESTED AT ROOM TEMPERATURE AND AT 1500° F (1090 K)

[R = 0.05]

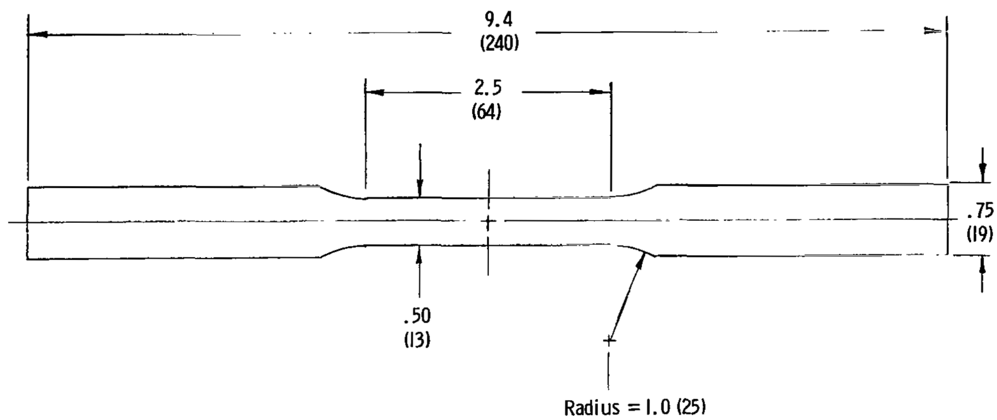
(a) Plain specimens

Maximum stress, ksi	Maximum stress, MN/m²	Fatigue life of specimen, cycles
Tests at room temperature		
55	380	>10 000 000
58	400	5 084 000
60	410	969 000
65	450	446 000
70	480	[a]145 980
80	550	[a]88 700
90	620	[a]63 950
Tests at 1500° F (1090 K)		
24	170	>10 000 000
28	190	4 746 000
32	220	2 786 000
36	250	1 468 000
40	280	831 000
50	340	107 000
60	410	19 000

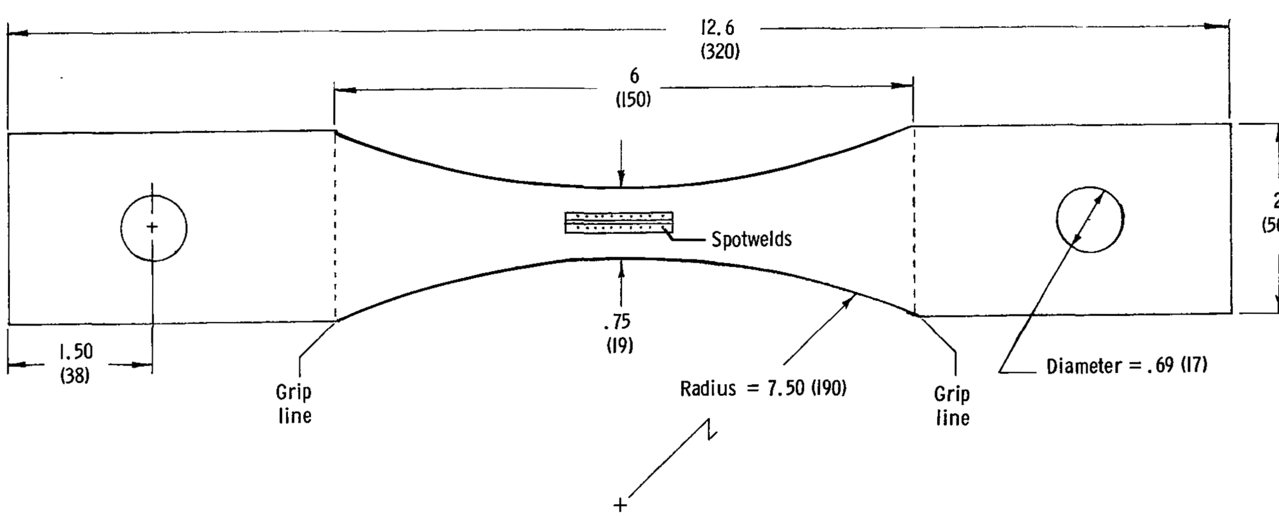
(b) Specimens with simulated gages

Maximum stress, ksi	Maximum stress, MN/m²	Fatigue life of specimen, cycles
Tests at room temperature		
34	230	>10 000 000
36	250	7 389 000
40	280	2 274 000
50	340	1 008 000
60	410	235 000
60	410	396 000
70	480	[a]267 080
70	480	[a]232 110
80	550	[a]148 920
Tests at 1500° F (1090 K)		
23	160	>10 000 000
26	180	6 676 000
30	210	4 709 000
40	280	692 000
50	340	130 000
60	410	17 000

[a]Tested in hydraulically actuated testing machine.



(a) Tensile specimen.



(b) Fatigue specimen with weldable strain gage.

Figure 1.- Tensile and fatigue specimen configurations. Dimensions are in inches (mm).

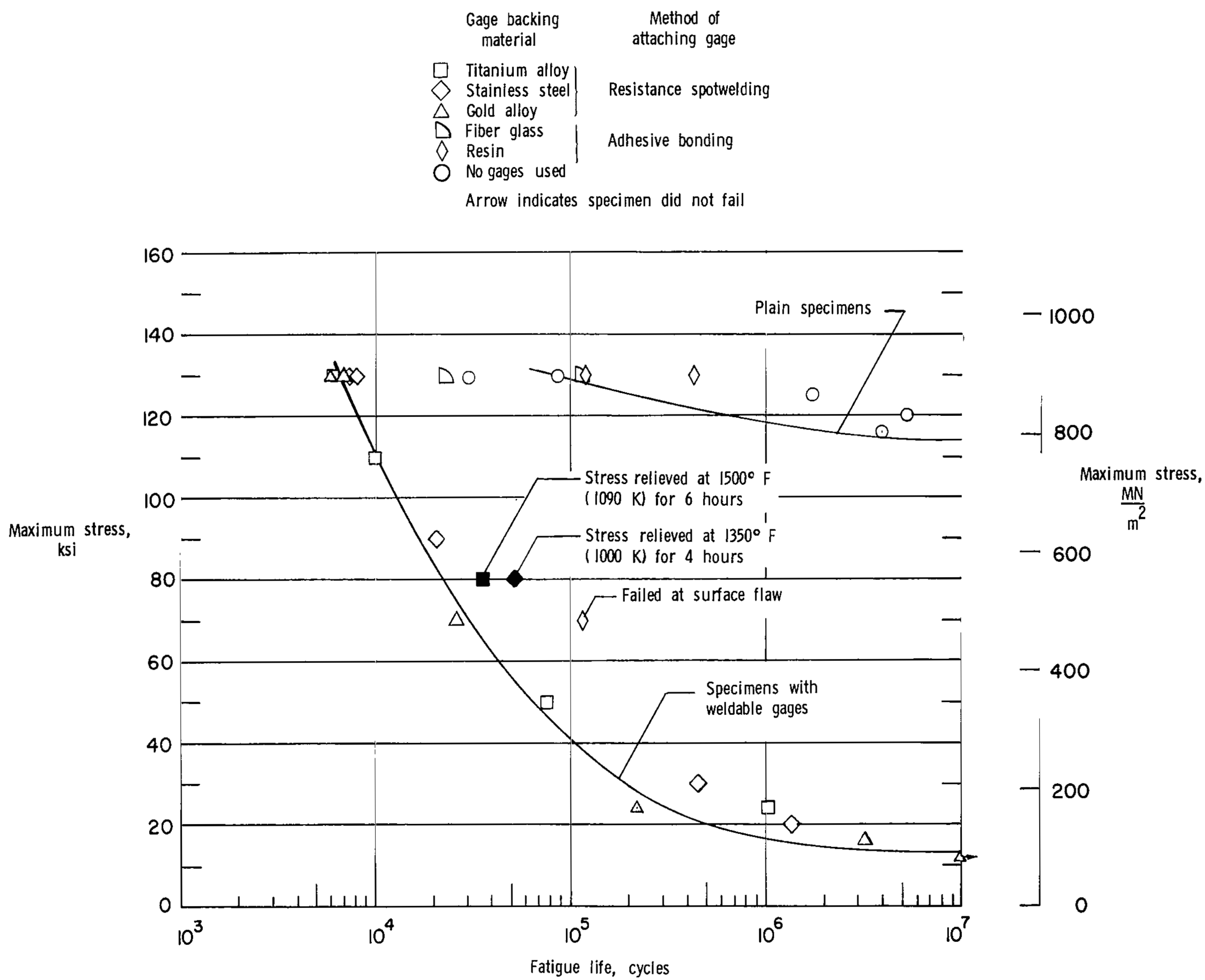


Figure 2.- Constant-amplitude fatigue data for Ti-6Al-4V specimens at room temperature. R = 0.05.

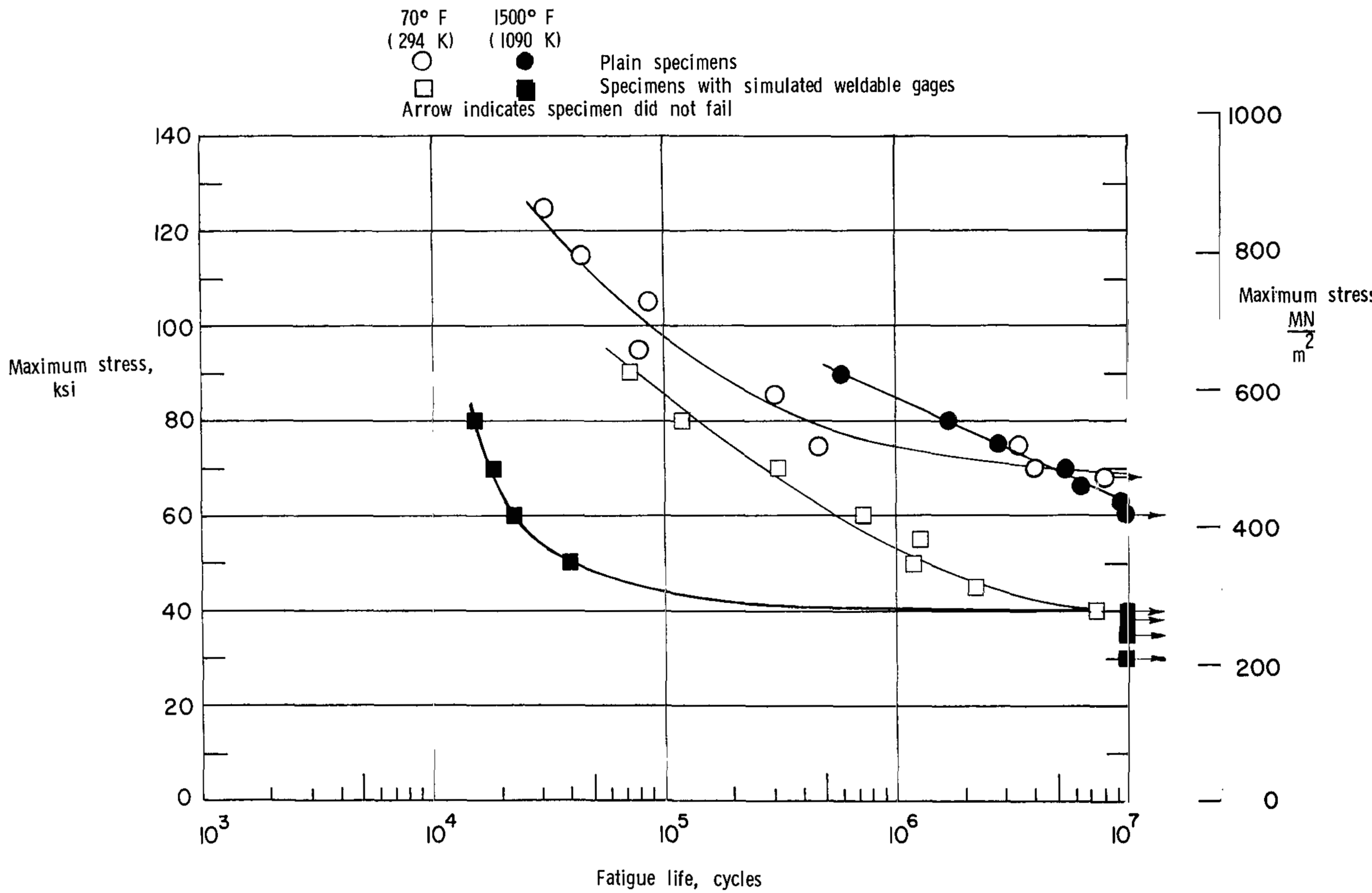


Figure 3.- Constant-amplitude fatigue data for René 41 specimens at room temperature and at 1500° F (1090 K). R = 0.05.

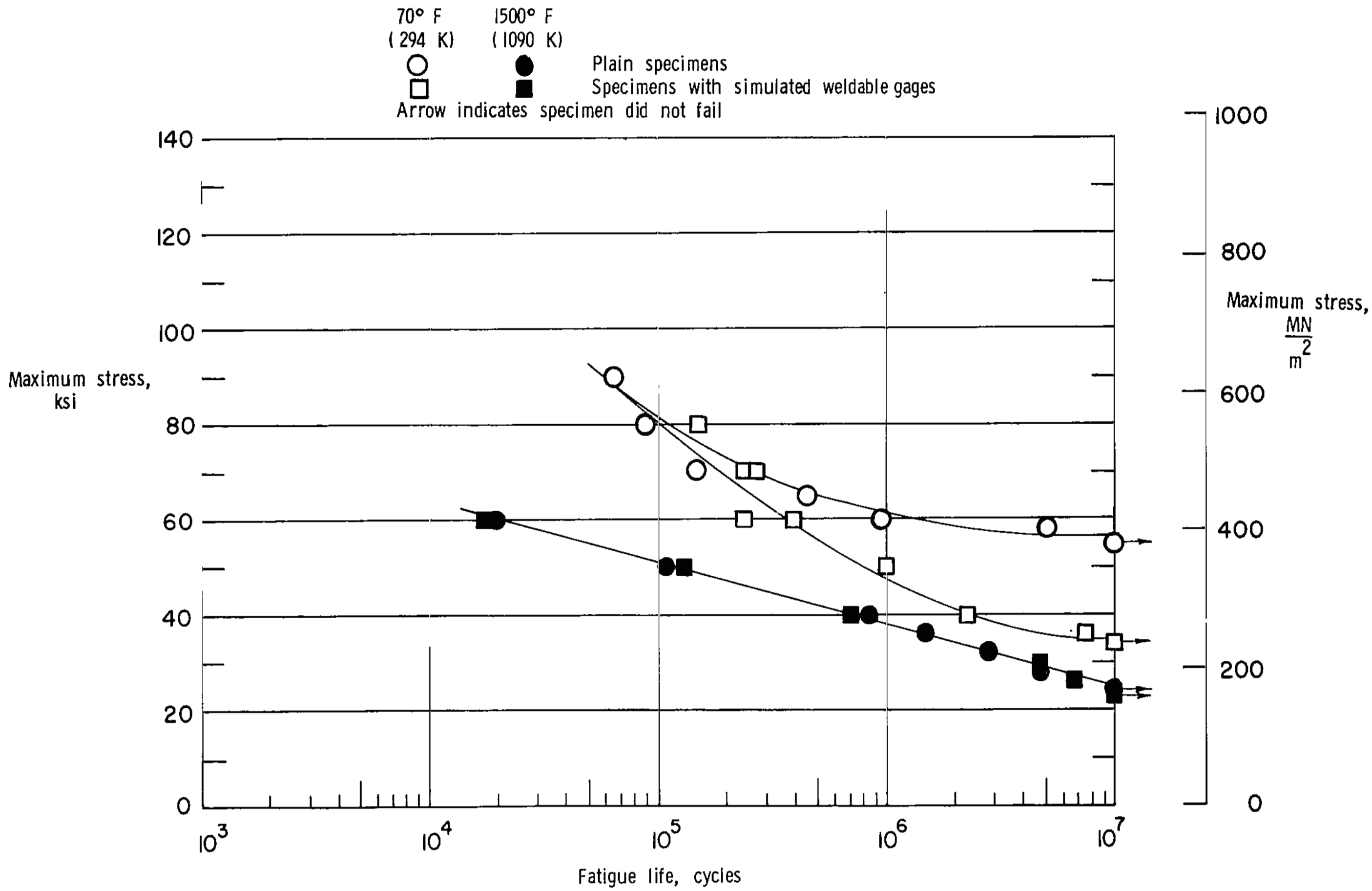
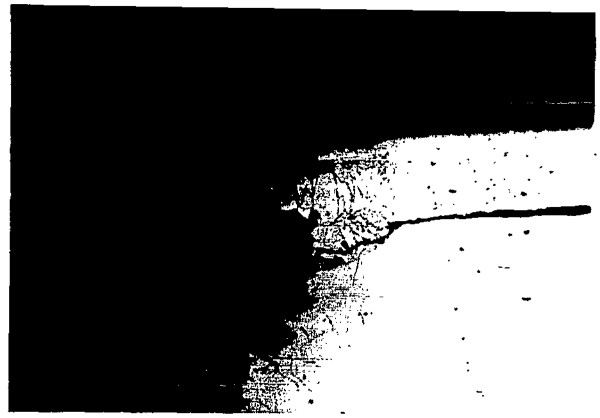


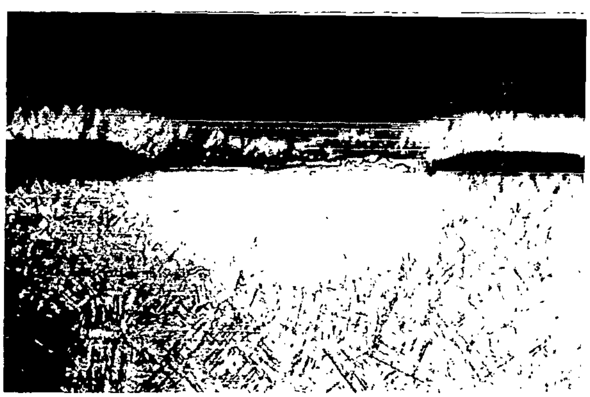
Figure 4.- Constant-amplitude fatigue data for Inconel X specimens at room temperature and at 1500° F (1090 K). R = 0.05.

(a) René 41.



(b) Inconel X.

(c) Ti-6Al-4V as welded, with gold-alloy gage backing.



(d) Ti-6Al-4V as welded, with titanium-alloy gage backing.

L-70-4719

(e) Ti-6Al-4V stress-relieved at 1500°F (1090 K) for 6 hours, with titanium-alloy gage backing.

Figure 5.- Photomicrographs of partial cross sections through spotwelds (× 87).

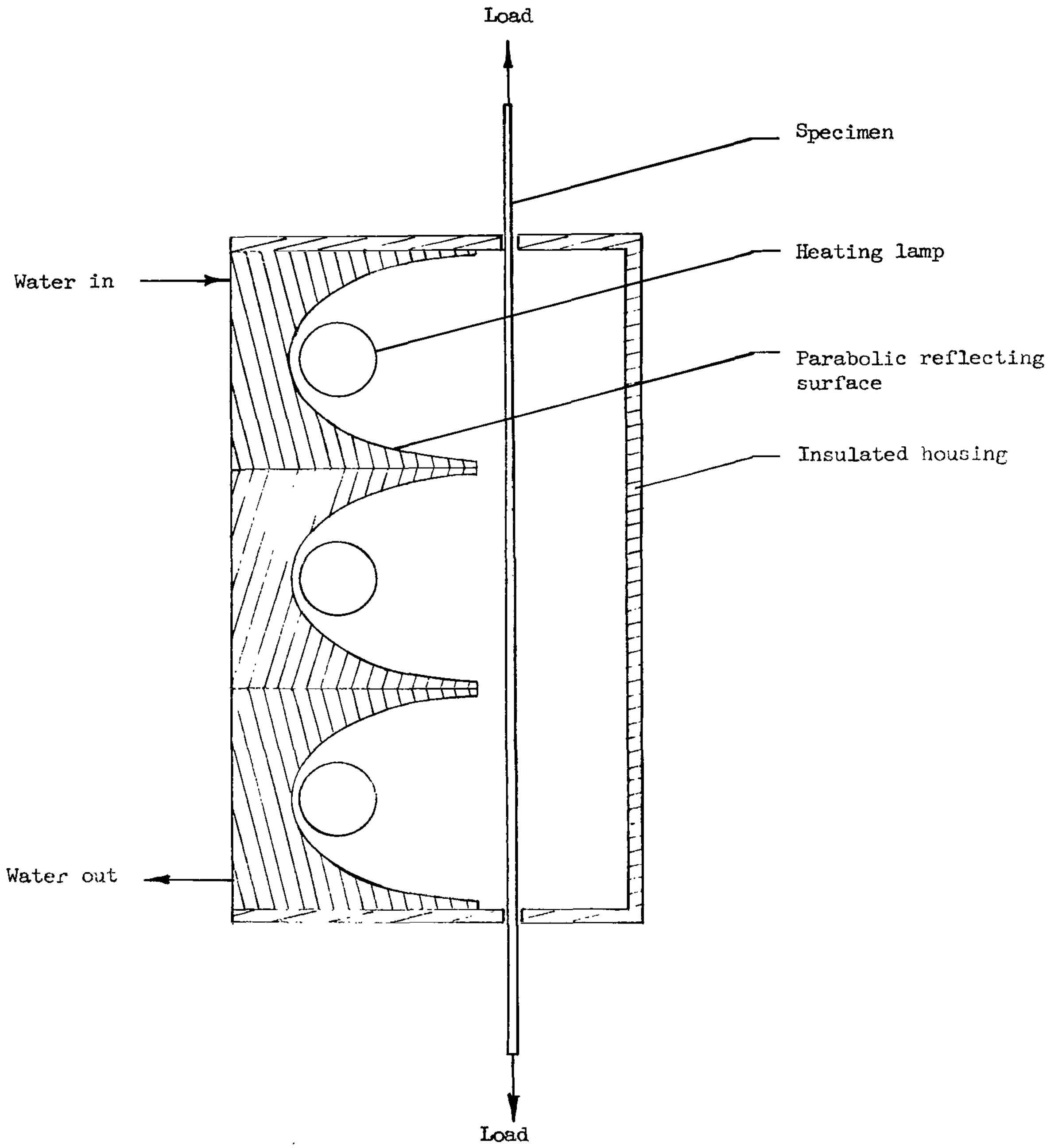


Figure 6.- Schematic cross section of heater for fatigue tests at 1500° F (1090 K).

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