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THE EFFECT OF THERMOCOUPLE ATTACHMENT BY SPOTWELDING AND BY ADHESIVE BONDING ON FATIGUE BEHAVIOR OF Ti-13V-11Cr-3Al AND Ti-6Al-4V

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16. Abstract

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SUMMARY

An experimental investigation was conducted to evaluate the effect of spotwelded or adhesively bonded thermocouples on the fatigue behavior of two titanium alloys suitable for use in high-speed airplanes: Ti-13V-11Cr-3Al in sheet form and Ti-6Al-4V in plate form. The effects of the thermocouple attachments were evaluated by comparing the results of constant-amplitude fatigue tests of specimens with thermocouples with those for plain specimens. The fatigue strengths at 10^7 cycles of specimens with spotwelded thermocouples were between one-fifth and one-third of the fatigue strengths of plain specimens for all test conditions. Specimens with thermocouples attached by adhesive bonding had fatigue strength equal to that of plain specimens.

INTRODUCTION

Very small spotwelds to attach instrumentation were shown in reference 1 to be more detrimental to the fatigue strength of Ti-6Al-4V than the spotwelded joints of reference 2. That result was somewhat unexpected because the instrumentation spotwelds were very small, produced welding only on the surface of the specimens, and were not load-carrying welds, whereas the spotwelds in the joints of reference 2 were larger, extended through three thicknesses of sheet metal, and transferred load from one sheet to another. Because of the large effect of the instrumentation spotwelds on fatigue strength and because instruments of various types are frequently installed on airplane structures, the present investigation was initiated to obtain more experimental information on the subject. The present study which is similar to that of reference 1 investigated the effects of thermocouple attachments by spotwelding and adhesive bonding on the fatigue strength of two additional titanium materials: Ti-13V-11Cr-3Al sheet and Ti-6Al-4V plate. The effect of the thermocouple attachments was determined in a limited experimental investigation by comparing the results of constant-amplitude fatigue tests of specimens with and without thermocouples. All tests were conducted at room temperature.

The units for physical quantities used in this paper are given in both the International System of Units (SI) and in U.S. Customary Units. The SI units are followed parenthetically by U.S. Customary Units throughout the paper; computations during the investigation were made by using U.S. Customary Units. Factors relating these two systems of units are given in reference 3 and those pertinent to the present investigation are presented in the appendix.

MATERIALS AND PROCEDURES

Materials

The fatigue behavior of Ti-6Al-4V plate and Ti-13V-11Cr-3Al sheet was studied in this investigation. Both materials were annealed. The Ti-6Al-4V plate was 9.5 mm thick (0.375 inch) and was produced according to the specifications in reference 4. The Ti-13V-11Cr-3Al sheet was 1.27 mm thick (0.050 inch) and was procured commercially, but the particular specifications for this material were not determined.

Specimen Preparation

Tensile and fatigue specimens were machined from the alloys to the configurations shown in figure 1. The long dimension of all specimens was parallel to the rolling direction of the material. The radii for the Ti-13V-11Cr-3Al fatigue specimens were machined in stacks of at least six specimen blanks in a lathe. The radii for the Ti-6Al-4V specimens were machined individually in a boring mill. After machining, the edges of each specimen were sanded lightly in the longitudinal direction with No. 600 silicon-carbide paper to remove burrs.

Thermocouple Attachment

Two sizes of chromel-alumel thermocouples were used in the investigation: 30 AWG (American wire gage) having a wire diameter of 0.254 mm (0.0100 in.) and 22 AWG having a wire diameter of 0.642 mm (0.0253 in.). Thermocouples were attached to the Ti-13V-11Cr-3Al specimens either by spotwelding or by adhesive bonding; only spotwelding was used on the Ti-6Al-4V specimens. Typical thermocouple installations are shown in figure 2; the procedures for attaching the thermocouples are described in the following paragraphs.

Spotwelding.- Specimen surfaces were sanded lightly in the longitudinal direction with No. 280 silicon-carbide paper that had been wetted with a commercial dilute-acid preparation. The specimens were then wiped clean with a commercial ammonia-based neutralizer.

All spotwelds were made with an electrode force of 22 N (5 lbf) using a portable commercial spotwelder. For Ti-13V-11Cr-3Al specimens, the large (22 AWG) thermocouples were welded with an energy setting of 30 J (30 W-s); the 30 AWG thermocouples were welded with an energy setting of 6 J (6 W-s). For Ti-6Al-4V specimens the 22 AWG thermocouples were welded with an energy setting of 40 J (40 W-s); the 30 AWG thermocouples were welded with an energy setting of 8 J (8 W-s). As shown in figure 2, the conductors of the thermocouples were separated by about $1\frac{1}{2}$ mm $\left(\frac{1}{16}\text{ inch}\right)$ and each conductor had three welds. The weld at the end of each conductor was made first; the next two welds were made at intervals of about 3 mm (1/8 inch) and the final weld coincided with the transverse center line of the specimen.

For Ti-13V-11Cr-3Al specimens, a short length of the insulated thermocouple was held firmly to the specimen by three small metal foil straps which were also spotwelded to the specimens. The straps were Ti-65A, a commercially pure titanium material, and were 0.127 mm thick (0.005 inch). Three spotwelds were made on each end of the straps with an energy setting of 12 J (12 W-s) and an electrode force of 22 N (5 lbf).

Adhesive bonding.- Specimens to which thermocouples were attached by adhesive bonding were cleaned in the same way as the specimens used for spotwelding. Thermocouples to be adhesively bonded were first spotwelded to tabs of Ti-65A which were approximately 6 mm (1/4 inch) square. The combination of thermocouple and tab was then attached to the specimen with a commercially available epoxy cement.

Test Equipment

Tensile tests.- Two standard tensile tests of each alloy were conducted in a 534-kN (120 000-lbf) capacity universal hydraulic testing machine. Stress-strain curves were obtained autographically with an x-y plotter. The stress and strain axes of the plotter, respectively, were activated by the electronic signal from a load cell in mechanical series with the specimen, and from an extensometer attached to the reduced section of the specimen.

Fatigue tests.- Fatigue tests were conducted with constant-amplitude axial stresses in the ratio of minimum stress to maximum stress R of 0.05. The stresses were based on the minimum cross-sectional area of each specimen. All tests were conducted at room temperature. The Ti-13V-11Cr-3Al specimens were tested in the subresonant machines that are described in reference 5. Those machines were equipped to count thousands of cycles. The tests of the plate specimens of Ti-6Al-4V were conducted in a 1780-kN (400 000-lbf) capacity axial-load fatigue-testing machine. Loading in this machine is controlled by a servo-hydraulic system capable of a wide range of loading ranges and frequencies. The present tests were conducted in the 445-kN (100 000-lbf) load range at a frequency of 10 Hz (10 cps). This machine counted each cycle of load.

Metallographic Examination

Photomicrographs of cross sections through spotwelds were made from failed fatigue specimens of each alloy to aid in interpreting the effects of the spotwelds.

RESULTS AND DISCUSSION

Tests

The tensile properties of the alloys (table I), obtained from two tests of each alloy, were within the specifications frequently quoted in procurements of these alloys; for example, see references 4 and 6 for Ti-6Al-4V and Ti-13V-11Cr-3Al. Fatigue data from tests of Ti-13V-11Cr-3Al and Ti-6Al-4V are given in tables II and III and are plotted in figures 3 and 4, respectively. Each symbol in the figures represents the fatigue life of an individual specimen. All curves in the figures were faired through the plotted symbols.

Fatigue tests of Ti-13V-11Cr-3Al sheet specimens.- The fatigue strengths at 10^7 cycles for both the plain specimens and specimens with adhesively bonded thermocouples were about 400 MN/m^2 (58 ksi) as indicated by the upper curve in figure 3. Thus, as expected, the bonding had no effect on the fatigue strength of the specimens. However, the fatigue strengths for specimens with spotwelded thermocouples were much lower than those for the plain specimens throughout the range of lives investigated. For specimens with small (30 AWG) thermocouples the fatigue strength at 10^7 cycles was about 140 MN/m^2 (20 ksi), and for specimens with the 22 AWG thermocouples the fatigue strength at 10^7 cycles was about 83 MN/m^2 (12 ksi). Although specimens with the two sizes of thermocouples had different fatigue strengths, the effect of the spotwelds was very detrimental in both cases. Potential contributions to the large effect of spotwelding are from the following: stress concentration due to the local increase in cross-sectional area at the weld, residual tensile stress due to the welding, and metallurgical weakening of the material in the weld. These factors were not examined further to learn the importance of each. The difference in fatigue strengths for specimens with the two wire sizes and different welding parameters also suggests that optimizing the welds for a given wire size might provide improved fatigue behavior.

Fatigue cracks in the plain specimens and specimens with adhesively bonded thermocouples originated at the machined edges of specimens in tests at the lower stress levels and along the original rolled surface in tests at higher stress levels. Figure 5 shows that many fatigue cracks developed in the surface of a plain specimen tested at a maximum stress of 690 MN/m^2 (100 ksi). In specimens with spotwelded thermocouples, fatigue cracks originated near the spotweld at the end of the thermocouple, as shown in figure 6, and propagated until failure of the specimen. As is usually the case, the most severe stress concentration occurred at the first in a series of closely spaced discontinuities.

None of the welds at the holddown straps produced fatigue cracks. That result was somewhat suprising in view of the closeness of one of the holddown straps to the minimum section of the specimens. Pulling the thermocouple wires off the specimen produced depressions in the specimen, but when the holddown straps were pulled off, small plugs of material remained on the specimen. This behavior indicates that the stronger materials, chromel and alumel, caused more severe stress discontinuities than did the weaker pure titanium tabs. Detailed analyses of these conditions and the other factors potentially contributing to the overall effect of the welding discussed earlier would probably be required to explain the loss of fatigue strength that was observed.

Fatigue tests of Ti-6Al-4V plate specimens.- The fatigue strengths of the plain specimens of Ti-6Al-4V are shown by the upper curve in figure 4. At 10^7 cycles the fatigue strength was about 480 MN/m^2 (70 ksi); this fatigue strength was somewhat lower than the fatigue strength for the Ti-6Al-4V sheet material discussed in reference 1 for which the fatigue strength at 10^7 cycles was above 690 MN/m^2 (100 ksi). For the present tests, the fatigue strength at 10^7 cycles of specimens with spotwelded thermocouples was about 170 MN/m^2 (25 ksi). Thus, for the plate material, as for the sheet material of reference 1, the spotwelds caused a very great loss of fatigue strength.

Fatigue cracks in the plain specimens originated at a corner of the critical cross section, as shown in figure 7, and propagated across the specimen. In specimens with spotwelded thermocouples, fatigue cracks originated at the spotwelds and produced the fracture surfaces shown in figure 8.

Metallographic Examination

The photomicrographs in figures 9 and 10 show partial cross sections through spotwelds for specimens of Ti-13V-11Cr-3Al and Ti-6Al-4V, respectively. These figures illustrate the surface roughening associated with the spotwelds, the local increase in cross-sectional area due to the presence of the thermocouple, and reveal that in some instances material was ejected from the welds.

The grain structure of the Ti-13V-11Cr-3Al material adjacent to the weld was very similar to that remote from the weld, insofar as could be determined by optical inspection. (See fig. 9.) That observation leads to the tentative conclusion that metallurgical phenomena were not responsible for the large reduction in fatigue strength that was observed. In contrast, the photomicrographs in figure 10 show evidence of heat-affected zones near the welds in the Ti-6Al-4V specimens. The needle-like structure shown in figure 10(c) indicates that a partial metallurgical transformation occurred in the weld-affected material. The effect of the transformed material on the fatigue strength of the specimens was not determined but might have contributed to the reduction in fatigue strength of the Ti-6Al-4V specimens.

CONCLUDING REMARKS

The effect of thermocouple attachment by spotwelding and adhesive bonding on the fatigue behavior of Ti-13V-11Cr-3Al sheet and Ti-6Al-4V plate was investigated experimentally. The effect of the attachments was determined by comparing the fatigue strengths of specimens with and without thermocouples. Thermocouples attached by adhesive bonding had no effect on fatigue strength. On the other hand, thermocouples attached by spotwelding caused reductions in the fatigue strength at 10^7 cycles to one-third or less of the fatigue strength of specimens without thermocouples. In tests of the Ti-13V-11Cr-3Al, the fatigue behavior of the specimens was affected by the size of the thermocouple wire that was used. The results of the investigation show that the fatigue strength of critical structure can be severely reduced by the application of spotwelded instrumentation; thus, the possibilities for, and consequences of, structural failure should be carefully considered before using instruments that must be attached by spotwelding.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., April 29, 1971.

APPENDIX

CONVERSION OF THE INTERNATIONAL SYSTEM OF UNITS TO U.S. CUSTOMARY 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 from reference 3 and are presented in the following table.

Physical quantity	SI Unit (*)	Conversion factor (**)	U.S. Customary Unit
Energy	joule (J)	1.0	W-s
Force	newton (N)	0.2248	lbf
Frequency	hertz (Hz)	1.0	cps
Length	meter (m)	39.37	in.
Stress	newton/meter^2 (N/m^2)	1.45×10^{-7}	ksi = 1000 lbf/in^2
Temperature	kelvin (K)	$^{o}F = \frac{9}{5}K - 459.7$	degree Fahrenheit (^{o}F)

*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}

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

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3. Committee on Metric Pract.: ASTM Metric Practice Guide. NBS Handbook 102, U.S. Dep. Com., Mar. 10, 1967.

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5. Grover, H. J.; Hyler, W. S.; Kuhn, Paul; Landers, Charles B.; and Howell, F. M.: Axial-Load Fatigue Properties of 24S-T and 75S-T Aluminum Alloy as Determined in Several Laboratories. NACA Rep. 1190, 1954. (Supersedes NACA TN 2928.)

6. Anon: Military Specification. Titanium and Titanium Alloy, Sheet, Strip and Plate. Mil-T-9046F, Apr. 3, 1967. (Amended Mar. 15, 1968.)

TABLE I.- ROOM-TEMPERATURE TENSILE PROPERTIES

FOR ANNEALED TITANIUM ALLOYS

Material	Ti-6Al-4V	Ti-13V-11Cr-3Al
Tensile strength, MN/m^2	924	938
(ksi)	(134)	(136)
Tensile yield,[a] MN/m^2	896	917
(ksi)	(130)	(133)
Elongation in 51 mm (2 in.), percent	17	28

[a] Determined at 0.2-percent offset.

TABLE II.- FATIGUE DATA FOR 1.27-mm (0.050-in) THICK SPECIMENS OF Ti-13V-11Cr-3Al TESTED AT ROOM TEMPERATURE. R = 0.05

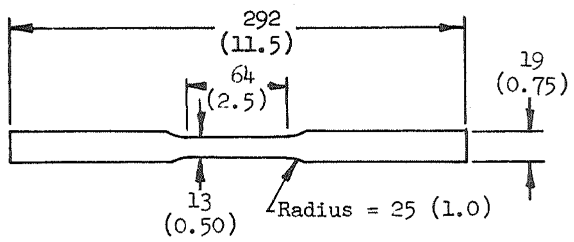
Maximum stress, MN/m^2	Maximum stress, ksi	Fatigue life, cycles
Plain specimens		
827	120	14 000
689	100	23 000
552	80	47 000
483	70	114 000
448	65	167 000
414	60	5 663 000
400	58	>10 150 000
Specimens with adhesively bonded thermocouples		
621	90	29 000
517	75	60 000
517	75	928 000
483	70	64 000
483	70	1 900 000
427	62	2 587 000
414	60	4 079 000
400	58	>12 165 000

Maximum stress, MN/m^2	Maximum stress, ksi	Fatigue life, cycles
Specimens with spotwelded thermocouples (30 AWG)		
517	75	14 000
379	55	25 000
310	45	45 000
241	35	111 000
193	28	248 000
172	25	315 000
153	22.25	706 000
138	20	>10 049 000
Specimens with spotwelded thermocouples (22 AWG)		
552	80	12 000
414	60	18 000
276	40	42 000
207	30	69 000
193	28	81 000
138	20	218 000
103	15	570 000
83	12	>10 086 000
69	10	>11 655 000

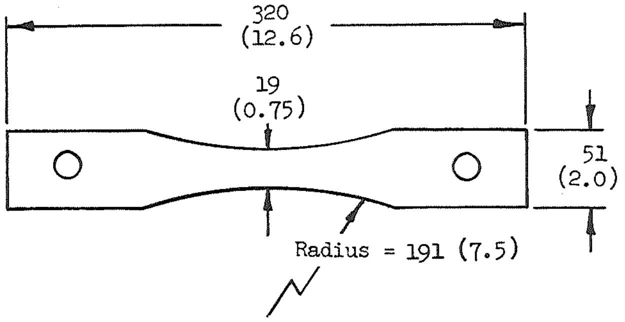
TABLE III.- FATIGUE DATA FOR 9.5-mm (0.375-in) THICK SPECIMENS OF Ti-6Al-4V TESTED AT ROOM TEMPERATURE. R = 0.05.

Maximum stress, MN/m^2	Maximum stress, ksi	Fatigue life, cycles
Plain specimens		
689	100	62 837
621	90	107 587
552	80	314 319
552	80	328 300
517	75	221 768
517	75	253 374
483	70	>10 220 000

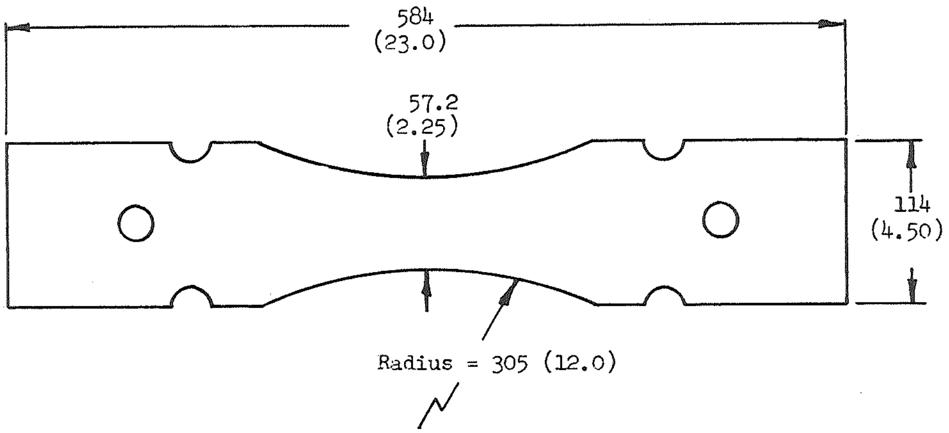
Maximum stress, MN/m^2	Maximum stress, ksi	Fatigue life, cycles
Specimens with spotwelded thermocouples (30 AWG)		
552	80	49 988
414	60	156 272
276	40	583 218
138	20	>6 813 000
Specimens with spotwelded thermocouples (22 AWG)		
483	70	42 699
345	50	357 284
207	30	930 367



(a) Tensile specimen for plate.



(b) Fatigue specimen for Ti-13V-11Cr-3Al sheet.



(c) Fatigue specimen for Ti-6Al-4V plate.

Figure 1.- Specimen configurations. Dimensions are in millimeters (in.).

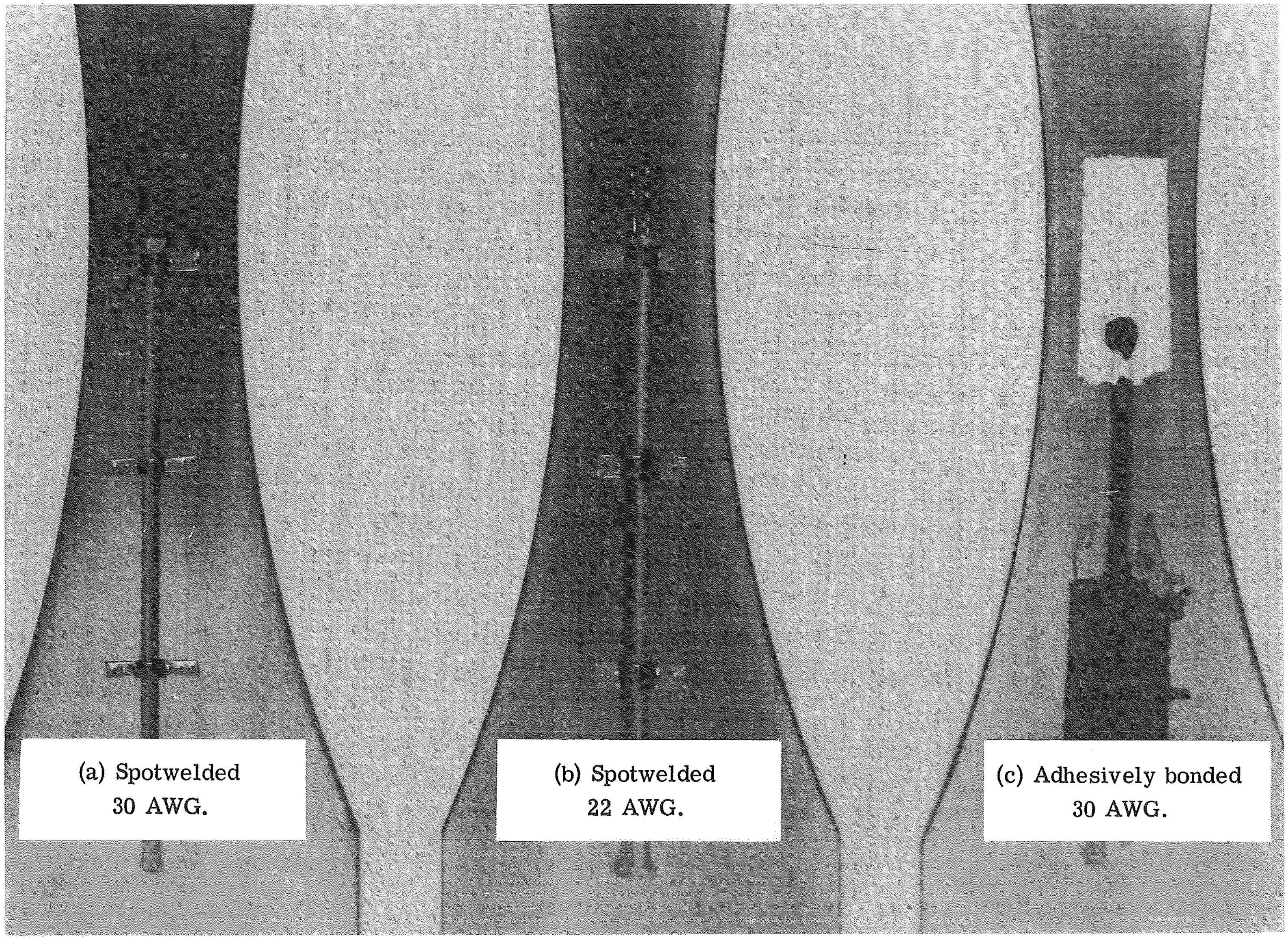


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Figure 2.- Typical thermocouple installations on fatigue specimens of Ti-13V-11Cr-3Al sheet.

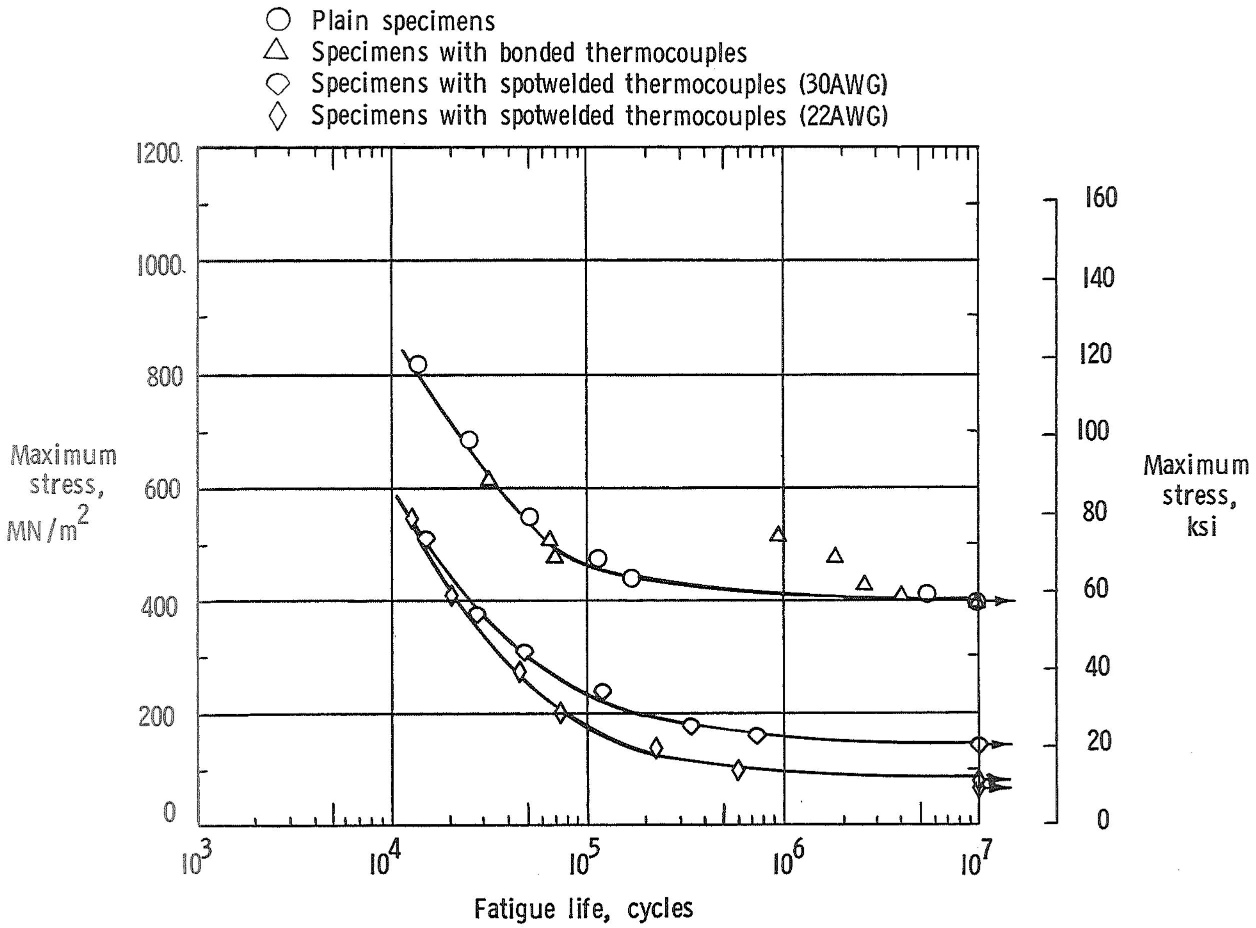

Figure 3.- Results of constant-amplitude fatigue tests of Ti-13V-11Cr-3Al sheet specimens, 1.27 mm thick (0.050 in.). Tests were at room temperature; R = 0.05.

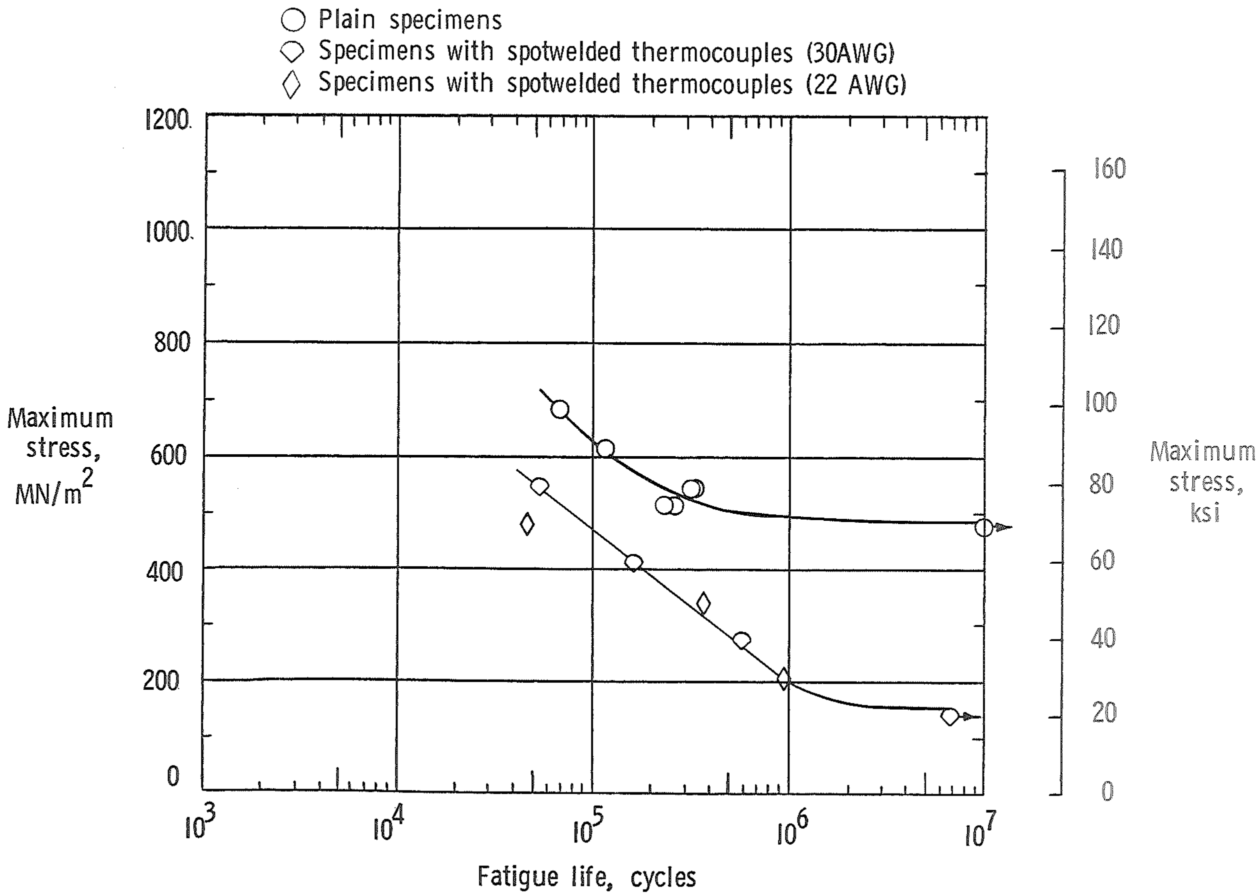

Figure 4.- Results of constant-amplitude fatigue tests of Ti-6Al-4V plate specimens, 9.5 mm thick (0.375 in.) Tests were at room temperature; R = 0.05.

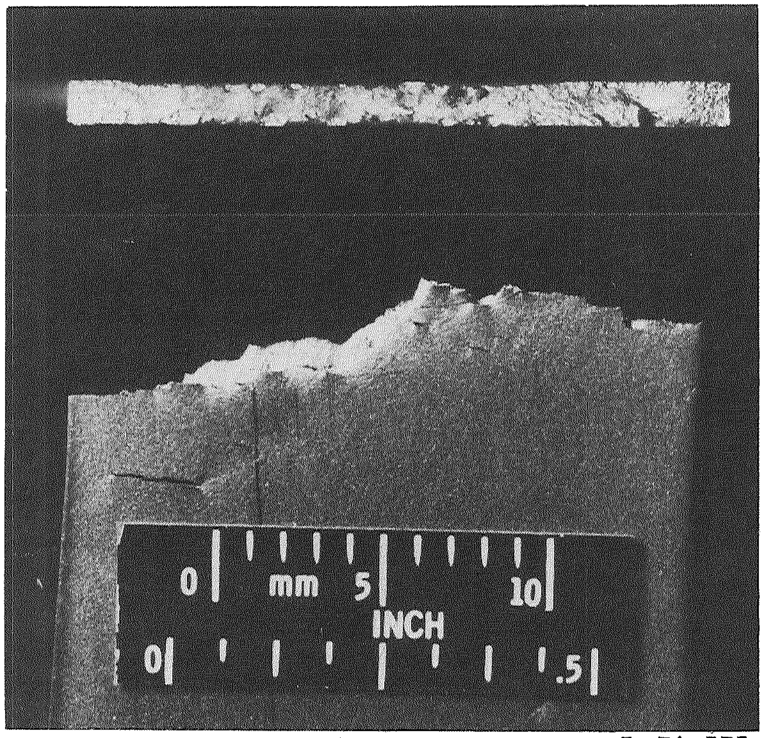

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Figure 5.- Photograph of fatigue cracks in a plain Ti-13V-11Cr-3Al sheet specimen tested at a maximum stress of 690 MN/m^2 (100 ksi). R = 0.05.

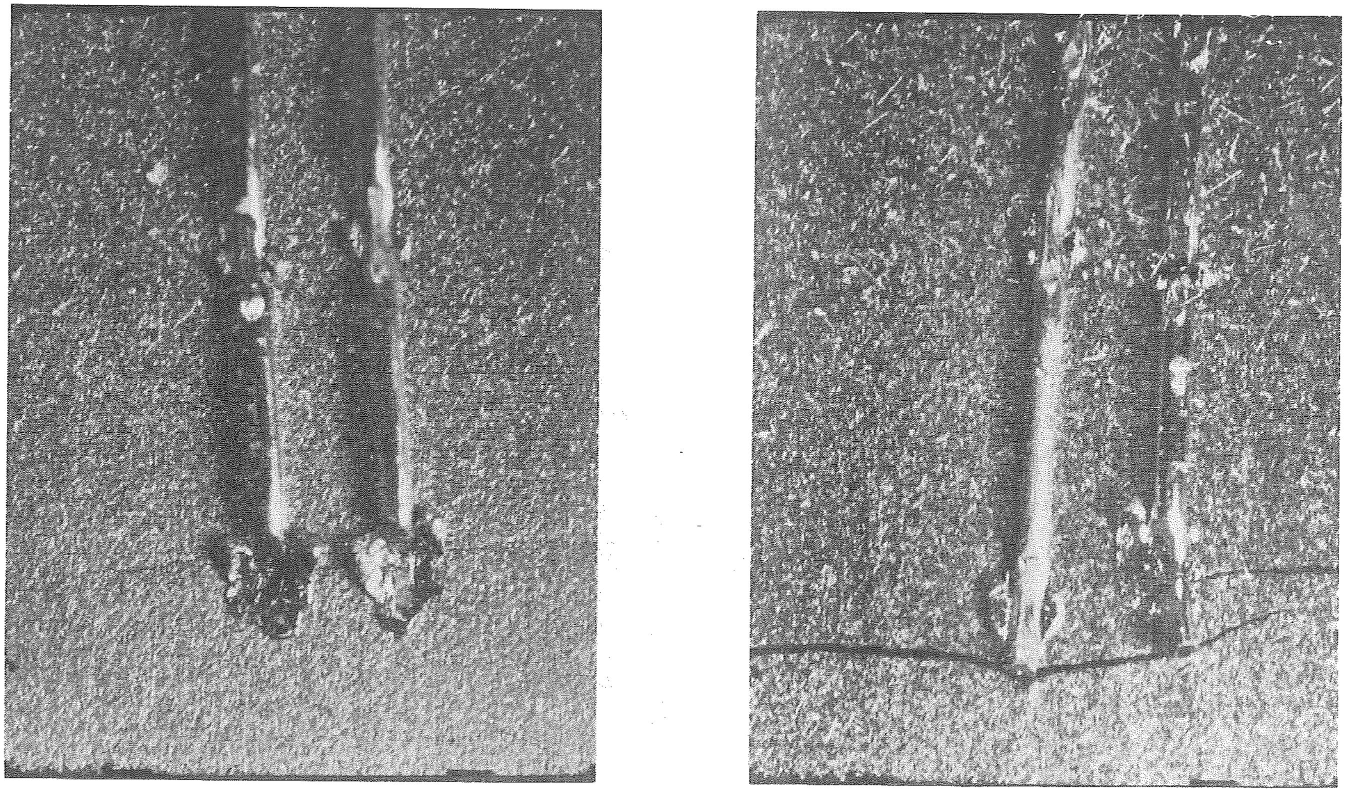

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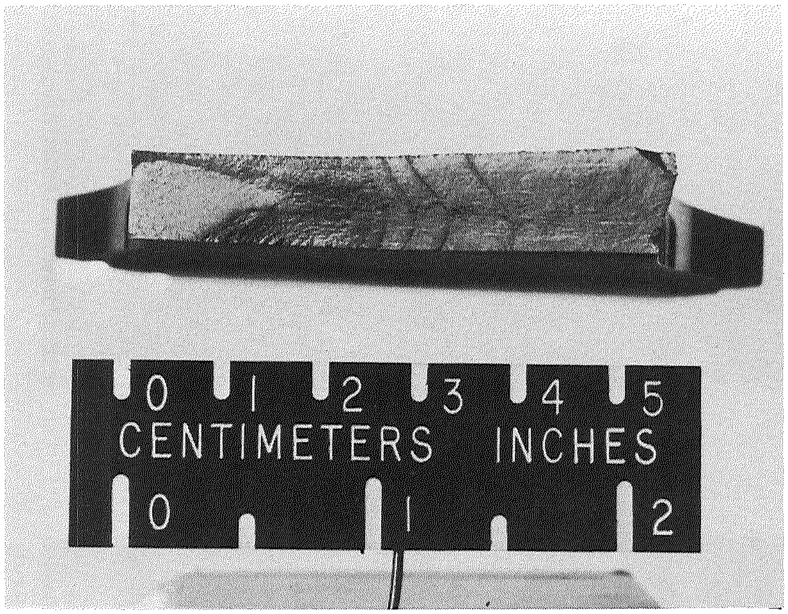
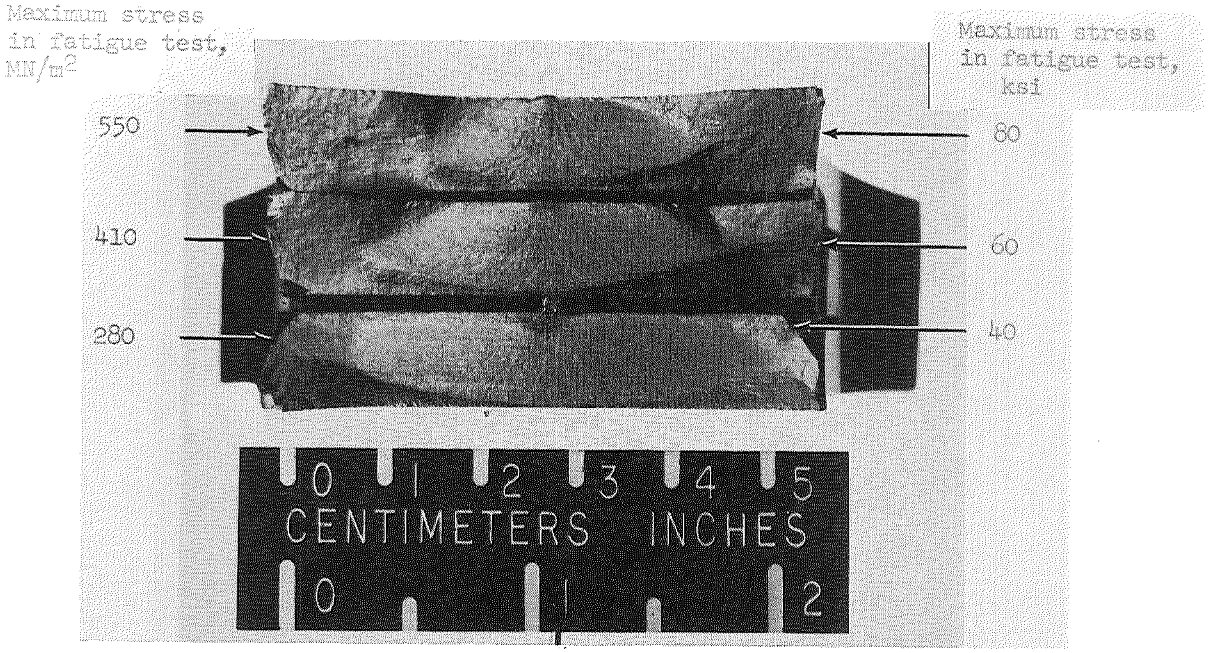
Figure 6.- Photographs of fatigue cracks that originated near the spotwelds in Ti-13V-11Cr-3Al specimens with 30 AWG thermocouples.



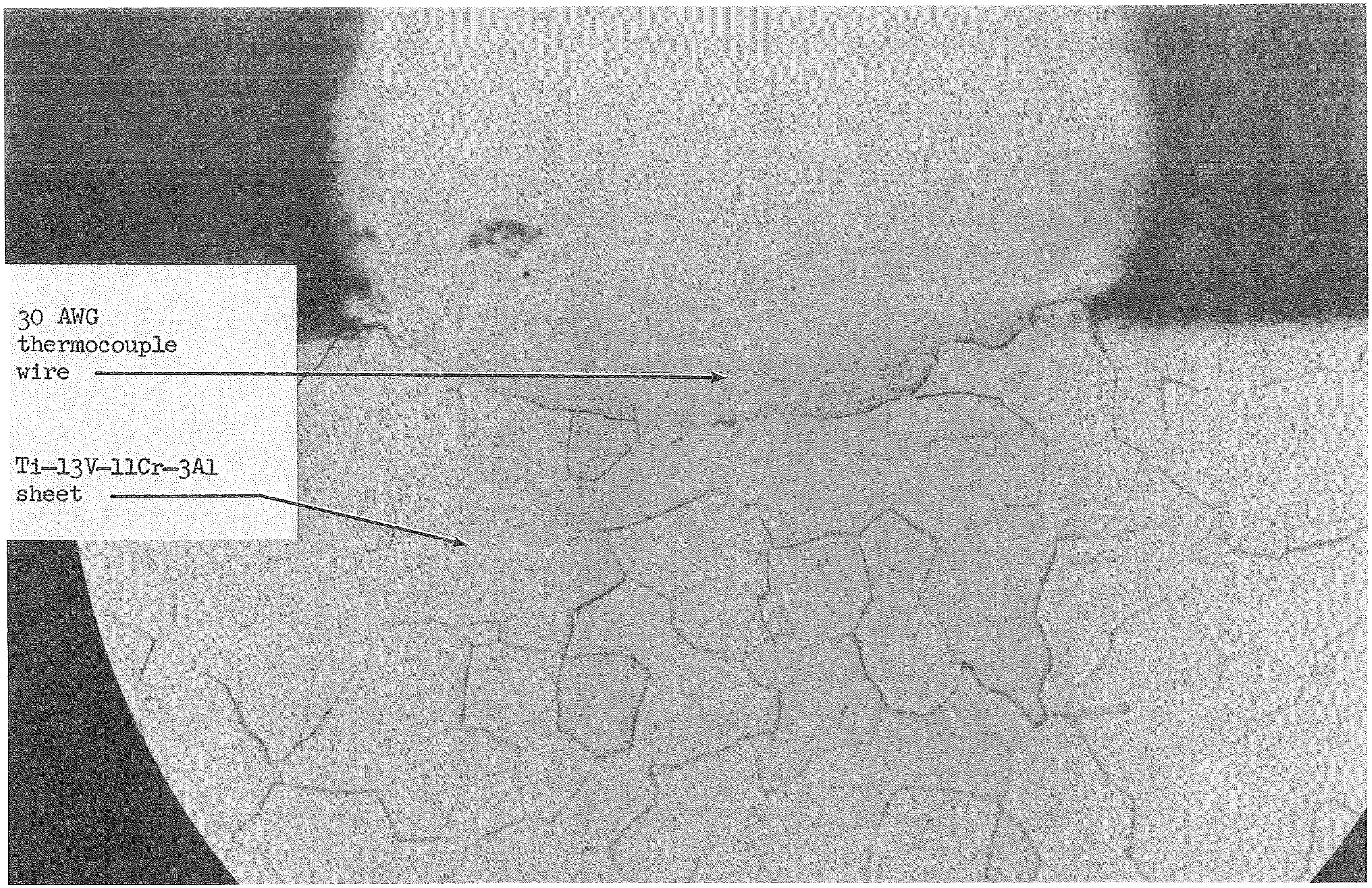
L-70-6419

Figure 7.- Photograph of failure surface of a plain Ti-6Al-4V plate specimen tested at a maximum stress of 520 MN/m^2 (75 ksi). R = 0.05.



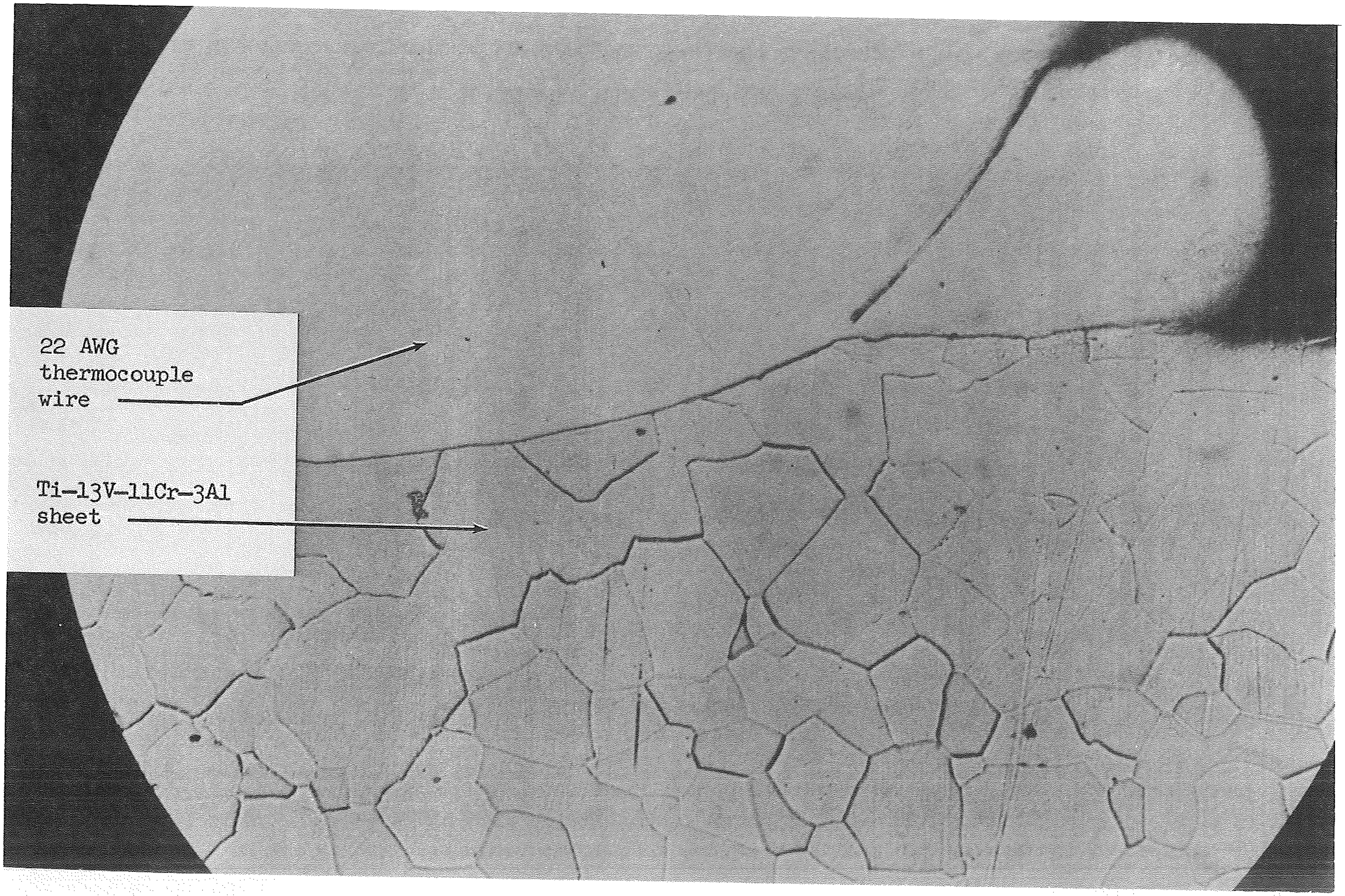
L-70-6416.1

Figure 8.- Photograph of failure surfaces of Ti-6Al-4V plate specimens with 30 AWG thermocouples.



(a) 30 AWG thermocouple wire (×490). L-71-576

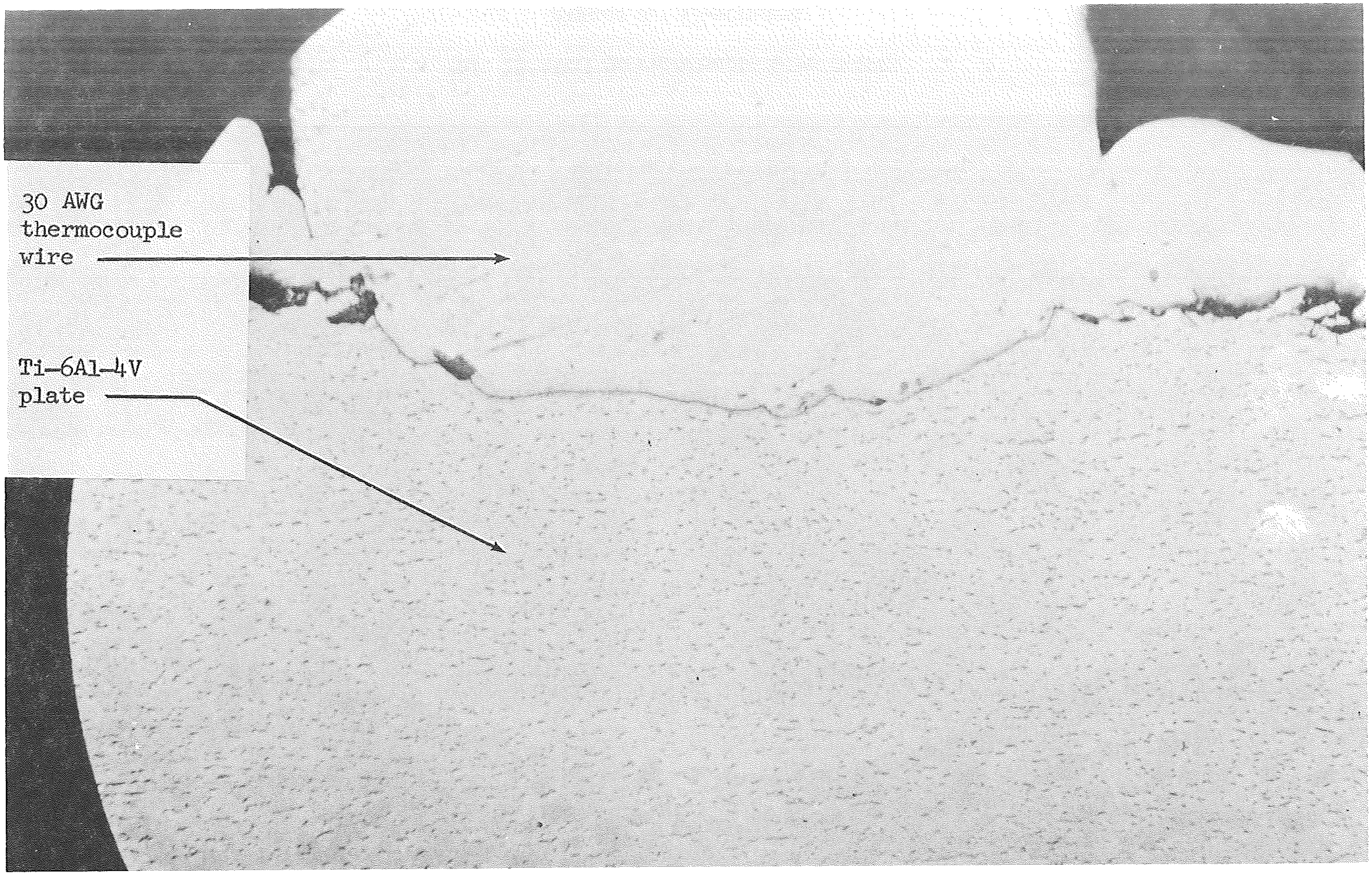
Figure 9.- Photomicrographs through spotwelds between thermocouple wire and Ti-13V-11Cr-3Al sheet.



L-71-577

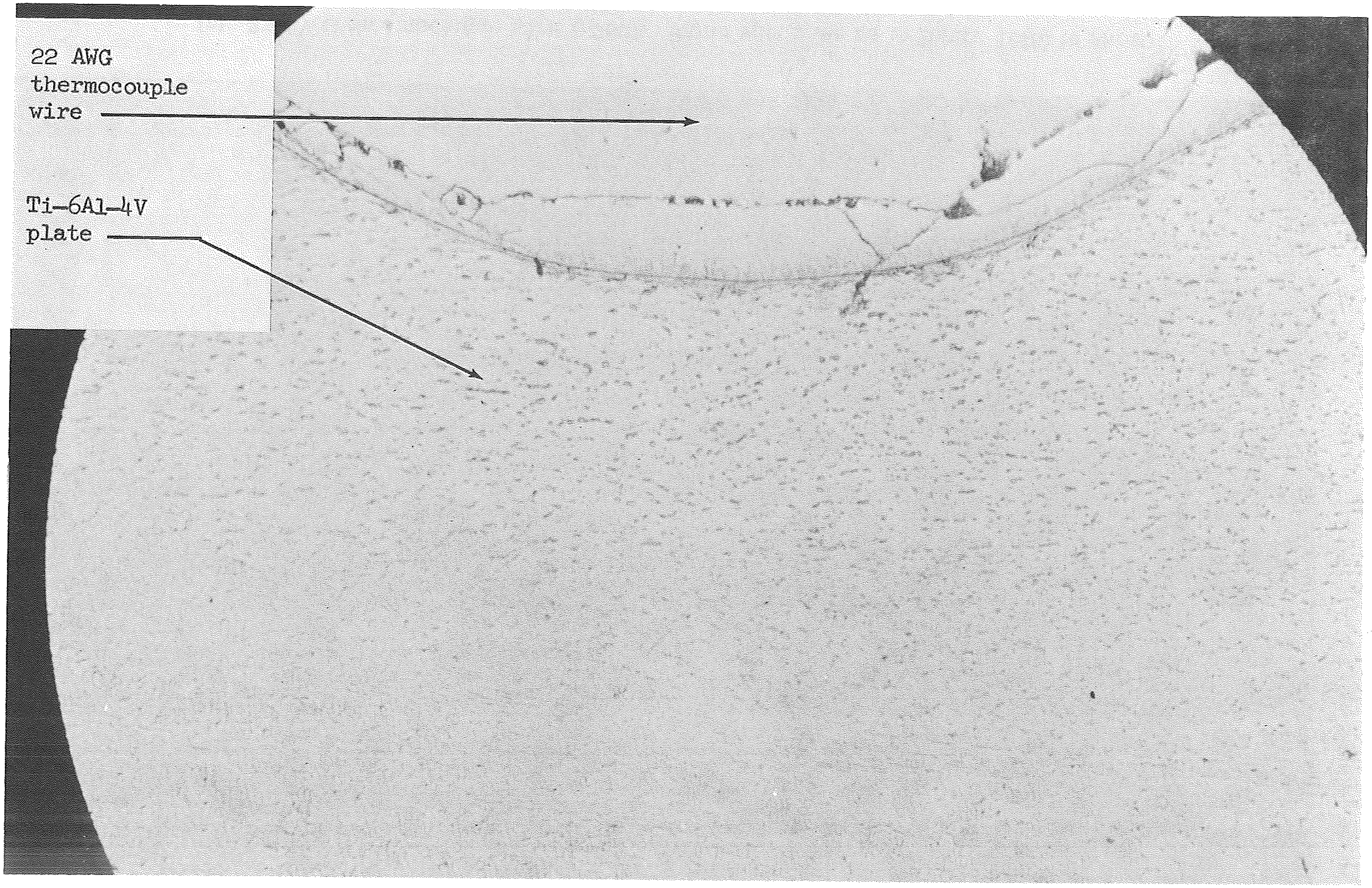
(b) 22 AWG thermocouple wire (×490).

Figure 9.- Concluded.



(a) 30 AWG thermocouple wire (×490). L-71-578

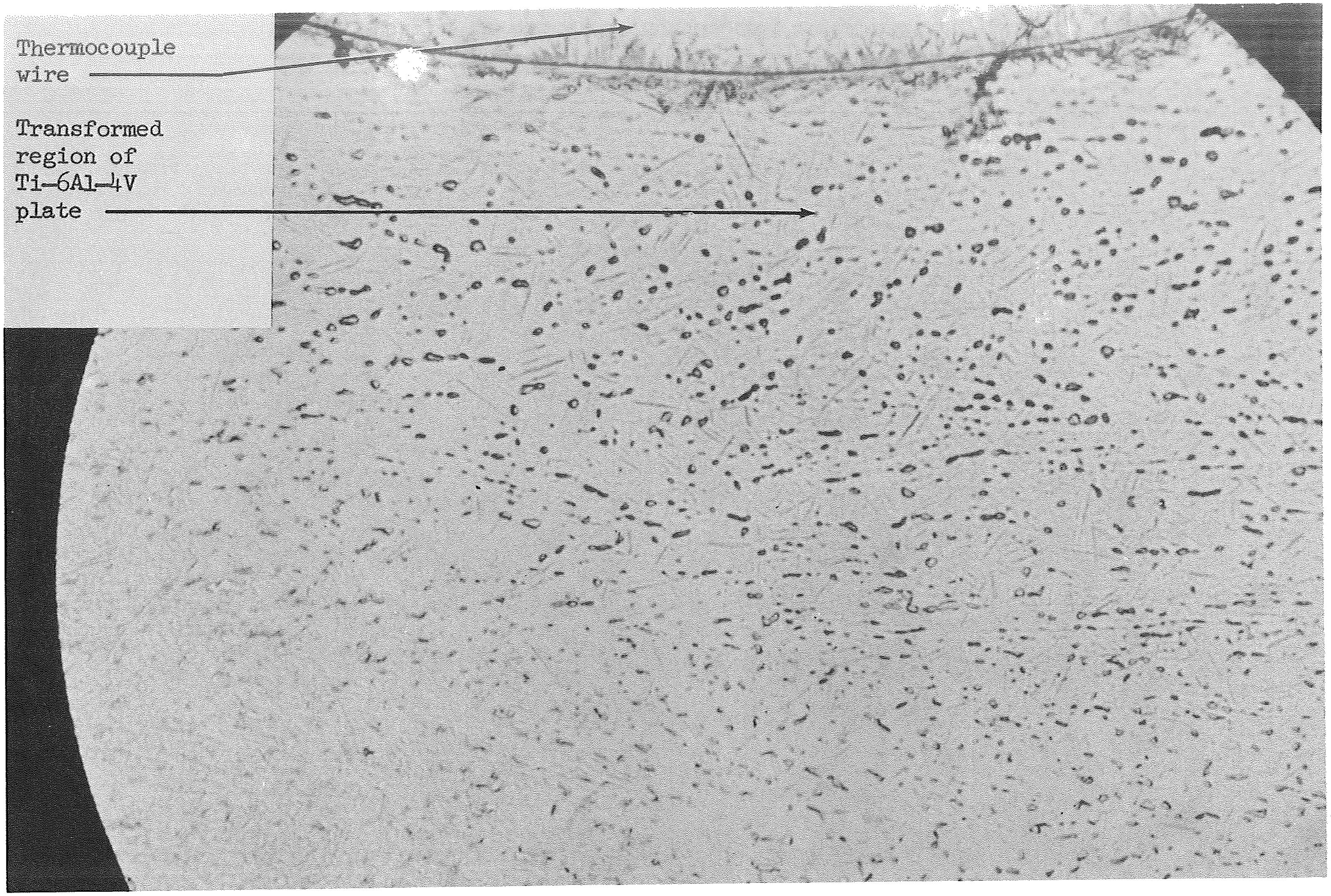
Figure 10.- Photomicrographs through spotwelds between thermocouple wire and Ti-6Al-4V plate.



L-71-579

(b) 22 AWG thermocouple wire (×490).

Figure 10.- Continued.



(c) 22 AWG thermocouple wire (×980). Same specimen as in figure 10(b) to show region of partial metallurgical transformation in Ti-6Al-4V plate. L-71-580

Figure 10.- Concluded.

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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