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EFFECT OF SERVICE USAGE ON TENSILE, FATIGUE, AND FRACTURE PROPERTIES OF 7075-T6 AND 7178-T6 ALUMINUM ALLOYS

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16. Abstract

A study has been made to determine the effects of extensive service usage on some basic material properties of 7075-T6 and 7178-T6 aluminum alloy materials. The effects of service usage were determined by comparing material properties for new material (generally obtained from the literature) with those for material cut from the center wing box of a C-130B transport airplane with 6385 flight-hours of service. The properties investigated were notched and unnotched fatigue strengths, fatigue-crack-growth rate, fracture toughness, and tensile properties. For the properties investigated and the parameter ranges considered (crack length, stress ratio, etc.), the results obtained in this study showed no significant difference between service and new materials.

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SUMMARY

A study has been made to determine the effects of extensive service usage on some basic material properties of 7075-T6 and 7178-T6 aluminum alloy materials. The effects of service usage were determined by comparing material properties for new material (generally obtained from the literature) with those for material cut from the center wing box of a C-130B transport airplane with 6385 flight-hours of service. The properties investigated were notched and unnotched fatigue strengths, fatigue-crack-growth rate, fracture toughness, and tensile properties. For the properties investigated and the parameter ranges considered (crack length, stress ratio, etc.), the results obtained in this study showed no significant difference between service and new materials.

INTRODUCTION

After an aircraft has been in service, fatigue cracks usually develop because of repeated loads. To assess the consequence of these cracks, the damage tolerance of the structure is calculated in terms of crack-growth rates and residual strength. These calculations are based on fatigue and fracture properties obtained from new material and on the assumption that these properties do not change during the service life of the aircraft. However, no experimental investigation validating this assumption has been reported in the literature. The purpose of this investigation was to assess the validity of the assumption.

The service materials used in these tests were machined 7178-T6 extrusion and machined 7075-T6 plate which had accumulated 6385 flight-hours in the upper and lower wing surfaces, respectively, of the center wing box from a C-130B transport airplane. Cracks at eight locations on the upper wing surface and seven on the lower surface had been repaired. The properties of the service materials were compared with the properties of new materials to evaluate the effect of service usage. The material properties investigated include fatigue strength, fatigue-crack-growth rate, fracture toughness, and the static tensile properties of ultimate strength, yield strength, Young's modulus, and elongation.

SYMBOLS

The units for physical quantities used in this paper are given both in the International System of Units (SI) and in U.S. Customary Units. The measurements and calculations were made in U.S. Customary Units. Conversion factors relating the two systems are given in reference 1 and those used in the present investigation are presented in appendix A.

a	half-length of a central symmetrical crack, m (in.)
a_i	half-length of crack at start of a fracture-toughness test, m (in.)
da/dN	rate of fatigue-crack growth, m/cycle (in./cycle)
E	Young's modulus of elasticity, N/m^2 (psi)
e	elongation in 51-mm (2-in.) gage length, percent
K_{cn}	critical stress-intensity factor based on a_i, $N/m^{3/2}$ (ksi-in$^{1/2}$)
K_{max}	maximum stress-intensity factor, $N/m^{3/2}$ (ksi-in$^{1/2}$)
K_{min}	minimum stress-intensity factor, $N/m^{3/2}$ (ksi-in$^{1/2}$)
K_T	theoretical elastic stress-concentration factor
ΔK	stress-intensity-factor range, $N/m^{3/2}$ (ksi-in$^{1/2}$)
N	number of load cycles to failure
R	ratio of minimum stress to maximum stress
S_a	alternating gross stress, N/m^2 (ksi)
S_f	maximum gross stress applied to specimen during fracture-toughness test, N/m^2 (ksi)
S_m	mean gross stress, N/m^2 (ksi)

S_{max} maximum gross stress, N/m^2 (ksi)

S_{min} minimum gross stress, N/m^2 (ksi)

t specimen thickness, m (in.)

w specimen width, m (in.)

α secant correction factor for stress intensity in a finite-width panel

σ_u ultimate tensile strength, N/m^2 (ksi)

σ_y yield strength (0.2-percent offset), N/m^2 (ksi)

MATERIALS, SPECIMENS, TESTS, AND PROCEDURES

Materials and Specimens

The service material used for these tests was taken from a C-130B transport airplane which was manufactured in the late 1950's or early 1960's and which had accumulated 6385 flight-hours by April 1969 when the center wing box was removed. The longitudinal axis of each specimen cut from this material was parallel to the wing spanwise direction. (See fig. 1.) All service specimens were machined from the upper and lower surfaces of the center wing box. The upper surface was 7178-T6 extruded panel with a nominal surface thickness of 2.5 mm (0.10 in.) and with integral stiffeners spaced on 84-mm (3.3-in.) centers. The lower surface was made from 7075-T6 plate with a range of nominal thickness from 2.5 mm to 4.1 mm (0.10 in. to 0.16 in.).

Because only limited data were available in the literature, S-N curves had to be established for new 7178-T6 material. Although the 7178-T6 service material was extruded, the material used to establish the fatigue-life curves for the new 7178-T6 was rolled sheet. Unless otherwise stated, all new-material data from the literature were for sheet material.

The fatigue, fatigue-crack-growth, and fracture-toughness specimen configurations used in this investigation are shown in figure 2. The machining processes for the different specimen configurations are given in references 2, 3, and 4. The tensile specimens were made according to the American Society for Testing and Materials (ASTM) standard specifications. The specimens were cut from the upper surface material so that the integral stiffeners were not included in the test section of the unnotched specimens and were not near the notch in the $K_T = 4$ and the fatigue-crack-growth specimens. The integral stiffeners were removed from the material using machining tolerances of 0.00 to 0.08 mm (0.003 in.) to prevent undercutting.

For the most part, material properties for the new material were obtained from tests on specimens of identical configuration and dimensions as those used for the service-material test. (See fig. 2.) An exception was the dimensions of the specimens used for the fatigue-crack-growth and fracture-toughness tests for the 7178-T6 alloy. (See ref. 5.)

Testing Machines and Procedures

Two types of axial-load fatigue testing machines were used: a subresonant machine with a fixed operating frequency of 30 Hz (30 cps) for fatigue-life tests, and two closed-loop servohydraulic machines operated at 2 or 5 Hz (2 or 5 cps) for a few high-load fatigue-life tests and for all the crack-growth and fracture-toughness tests. All testing machines had a load capacity of 89 kN (20 kips). The following table shows which tests were conducted in each testing machine:

Type machine	Materials used in test type –			
	Unnotched	Notched	Crack growth	Fracture
Subresonant, 30 Hz (ref. 6)	7075 7178	7075 7178		
Closed-loop servohydraulic (ref. 3)	7075 7178	7075 7178	7178	
Closed-loop servohydraulic[a]			7075	7075 7178

[a]Like the machine described in reference 5 except the load capacity was 89 kN (20 kips).

The S-N curves for the service materials and the new 7178-T6 sheet material were established from constant-amplitude fatigue tests. Each curve contained data from six or more levels of maximum net stress. Several specimens were tested at each level. All tests were at a stress ratio R of 0.02. All specimens were axially loaded. The configurations of the unnotched and the notched $\left(K_T = 4\right)$ specimens are shown in figures 2(a) and 2(b).

Fatigue-crack-growth data were obtained from constant-amplitude axial-load tests of the specimen shown in figure 2(c). The tests of 7075-T6 service material (R = 0.02) were conducted at maximum gross stresses of 138 or 207 MN/m^2 (20 or 30 ksi). For the

7178-T6 service material, the maximum gross stresses were between 69 and 207 MN/m^2 (10 and 30 ksi) at values of R equal to 0.02 and 0.5.

To record the crack-growth data, crack-propagation gages were bonded to the specimens with an AE-10 epoxy adhesive which was cured at 340 K (150° F) for 1 hour. The gages consisted of constantan elements spaced at 1.3-mm (0.05-in.) intervals on a polyimide backing. An automatic monitoring system recorded the number of cycles at which each succeeding constantan element of the gage failed as the fatigue crack progressed across the specimen. The crack-growth tests were terminated before the specimens failed so that the specimens could be used for fracture-toughness tests.

The fracture toughness of the service materials was determined from fracture tests of unbroken fatigue-crack-growth specimens. Monotonically increasing test loads were applied at a constant rate of about 160 kN/min (36 kips/min) until each specimen failed. The maximum load sustained by each specimen was recorded for later use in the fracture-toughness analysis.

RESULTS AND DISCUSSION

Tensile Properties

The tensile properties for the two service materials are presented in table I. Since the service-material tensile properties shown in table I are greater than the appropriate B values for both materials in MIL-HDBK-5B (ref. 7), no degradation in tensile properties due to service usage was indicated.

Fatigue Properties

The fatigue-life data for unnotched specimens of new 7178-T6 sheet material are presented in table II and plotted in figure 3. Data for unnotched specimens of new 7075-T6 sheet material were taken from reference 8. The fatigue-life data for unnotched specimens of both service materials are presented in table III. For comparison, the fatigue lives of service and new materials are plotted in figures 4(a) and 4(b) for 7075-T6 and 7178-T6, respectively. No significant differences between the fatigue lives of service and new materials were found for either 7075-T6 or 7178-T6.

The fatigue-life data for notched specimens $\left(K_T = 4\right)$ of new 7178-T6 sheet material are presented in table II and plotted in figure 5. Data for notched specimens of new 7075-T6 sheet material were taken from reference 8. The fatigue-life data for notched specimens of both service materials are presented in table III. For comparison, the fatigue lives of service and new materials are plotted in figures 6(a) and 6(b) for 7075-T6 and 7178-T6, respectively. As for the unnotched specimens, no significant difference between the fatigue lives of service and new materials was found for the notched specimens.

Fatigue-Crack-Growth and Fracture-Toughness Properties

The fatigue-crack-growth data of new 7075-T6 and 7178-T6 sheet materials were taken from references 8 and 5, respectively. As previously stated, the data for the fatigue-crack-growth rates and the fracture-toughness values for new 7178-T6 sheet material (ref. 5) were obtained from specimens which had different dimensions from the service-material specimens. The difference in specimen thicknesses was of no consequence because the data in reference 5 showed that for the thickness range of interest, thickness had no significant effect on fatigue-crack-growth rates or fracture-toughness values for 7178-T6 sheet. The difference in specimen widths, 57 mm (2.25 in.) for the service-material specimen and 292 mm (11.5 in.) for the new-material specimen, was taken into account by comparing fatigue-crack-growth rates (ref. 9) and fracture-toughness values (ref. 10) at small values of crack aspect ratio $2a/w$.

The results of the fatigue-crack-growth tests for both service materials are presented in table IV. Fatigue-crack-growth rates and stress-intensity factor ranges ΔK were calculated from the data presented in table IV. The method used for calculating ΔK is given in appendix B.

Fatigue-crack-growth rates of service and new materials are compared in figures 7(a) and 7(b) for 7075-T6 and 7178-T6, respectively. Figure 7(a) shows good agreement between service and new materials for the 7075-T6 alloy. For the 7178-T6 alloy (fig. 7(b)), the crack-growth rates for the service and new materials were about the same except at the higher ΔK values. For high ΔK values, the crack-growth rate for new material was approximately twice the rate for service material. This difference is not significant, since the results of reference 4 show that scatter of this magnitude exists for aluminum alloys at the higher ΔK values.

The fracture-toughness test results for the service material are presented in table V in terms of the critical stress-intensity factor K_{cn}. The equation used for calculating K_{cn} is

$$K_{cn} = \alpha S_f \sqrt{a_i \pi}$$

The half-crack length used in this equation a_i was the half-crack length at the end of the fatigue-crack-growth tests.

Fracture-toughness data for new 7178-T6 sheet material were taken from reference 5. Data for new 7075-T6 material were taken from reference 8, where the half-crack length at the onset of unstable crack growth was used to calculate the fracture-toughness values. To compare these results with those for service material, the fracture-toughness values in reference 8 were recalculated by using the half-crack length at the end of the fatigue-crack-growth tests. Critical stress-intensity factors for service and new materials are shown in figures 8(a) and 8(b) for 7075-T6 and 7178-T6, respectively. No significant difference between service and new materials was found for either material for the range of aspect ratios investigated.

CONCLUSIONS

A study has been made to determine the effects of extensive service usage on some basic material properties of 7075-T6 and 7178-T6 aluminum alloy materials. The effects of service usage were determined by comparing material properties for new material (generally obtained from the literature) with those for material cut from the center wing box of a C-130B transport airplane with 6385 flight-hours of service. The properties investigated were notched and unnotched fatigue strengths, fatigue-crack-growth rate, fracture toughness, and tensile properties. For the properties investigated and the parameter ranges considered (crack length, stress ratio, etc.), the results obtained in this study showed no significant difference between service and new materials.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., December 16, 1974.

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 in 1960 (ref. 1). Conversion factors required for the units used herein are given in the following table:

Physical quantity	U.S. Customary Unit	Conversion factor (a)	SI Unit (b)
Force	lbf	4.448	newton (N)
Frequency	cps	1.0	hertz (Hz)
Length	in.	0.0254	meter (m)
Stress	ksi	6.895×10^6	newtons per meter^2 (N/m^2)
Stress intensity	ksi-in$^{1/2}$	1.0989×10^6	newtons per meter$^{3/2}$ (N/m$^{3/2}$)
Temperature	$^{\circ}$F	$\frac{^{\circ}F + 459.7}{1.8}$	kelvin (K)

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

[b]Prefixes to indicate multiples of SI Units are as follows:

Prefix	Multiple
nano (n)	10^{-9}
milli (m)	10^{-3}
kilo (k)	10^3
mega (M)	10^6
giga (G)	10^9

APPENDIX B

CALCULATION OF STRESS-INTENSITY-FACTOR RANGE

Paris (ref. 11) showed that the rate of fatigue-crack growth was a function of the stress-intensity-factor range; that is,

$$\frac{da}{dN} = f(\Delta K) \tag{B1}$$

where

$$\Delta K = K_{max} - K_{min} \tag{B2}$$

For centrally cracked specimens subjected to a uniformly distributed axial load

$$K_{max} = \alpha S_{max}\sqrt{a\pi} \tag{B3}$$

and

$$K_{min} = \alpha S_{min}\sqrt{a\pi} \tag{B4}$$

where S_{max} and S_{min} are the maximum and minimum gross stresses in the cycle. The term α is a finite-width correction given by (ref. 12)

$$\alpha = \sqrt{\sec \frac{\pi a}{w}} \tag{B5}$$

For small crack-growth increments from a half-crack length a_1 to a_2,

$$\Delta K = \alpha\left(S_{max} - S_{min}\right)\sqrt{\frac{a_1 + a_2}{2}\pi} \tag{B6}$$

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TABLE I.- TENSILE PROPERTIES OF SERVICE ALUMINUM ALLOYS

Material	σ_u		σ_y		E		e, percent
	MN/m^2	ksi	MN/m^2	ksi	GN/m^2	ksi	
7075-T6 (Plate)	574	83.2	538	78.1	66.9	9.7×10^3	11
7178-T6 (Extrusion)	657	95.3	605	87.8	69.0	10.0×10^3	8.9

TABLE II.- RESULTS OF AXIAL-LOAD FATIGUE TESTS ON NEW 7178-T6 ALUMINUM ALLOY SHEET (R = 0.02)

Maximum net stress, MN/m^2	Maximum net stress, ksi	Number of load cycles to failure N, kilocycles						
$K_T = 1$								
552	80	4	5	6	7	8	----	------
414	60	11	12	17	17	18	----	------
276	40	37	66	134	173	235	----	------
241	35	60	189	306	699	>10 000	----	------
228	33	77	184	280	621	>10 000	----	------
207	30	>10 000	>10 000	>10 000	>10 000	------	----	------
$K_T = 4$								
345	50	0.3	------	------	------	------	----	------
276	40	1	------	------	------	------	----	------
241	35	1	2	2	2	4	----	------
207	30	4	5	5	6	6	----	------
138	20	45	65	66	75	75	86	------
103	15	56	891	1 985	2 595	4 971	7942	>10 000
70	10	>10 000	>10 000	>10 000	>10 000	>10 000	----	------

TABLE III.- RESULTS OF AXIAL-LOAD FATIGUE TESTS ON SERVICE MATERIALS (R = 0.02)

(a) 7075-T6 aluminum alloy plate

Maximum net stress		Number of load cycles to failure N, kilocycles								
MN/m^2	ksi									
$K_T = 1$										
414	60	13	14	19	20	20	23	24	----	------
345	50	25	39	41	43	44	48	52	----	------
276	40	68	87	90	109	143	156	168	492	------
241	35	91	149	168	212	392	>10 000	>10 000	----	------
228	33	376	513	528	1 272	1 353	8 717	>10 000	----	------
214	31	927	------	------	------	------	------	------	----	------
207	30	>10 000	>10 000	>10 000	>10 000	>10 000	>10 000	>10 000	----	------
$K_T = 4$										
207	30	5	6	6	6	8	8	9	----	------
138	20	45	47	48	52	54	79	129	----	------
117	17	75	118	145	161	163	------	------	----	------
110	16	68	1 840	------	------	------	------	------	----	------
105	15.2	144	------	------	------	------	------	------	----	------
103	15	200	213	242	300	429	2 498	2 966	3667	>10 000
85	12.3	>10 000	------	------	------	------	------	------	----	------
83	12	10 857	>10 000	>10 000	>10 000	>10 000	>10 000	>10 000	----	------
70	10.2	>10 000	------	------	------	------	------	------	----	------

TABLE III.- RESULTS OF AXIAL-LOAD FATIGUE TESTS ON SERVICE MATERIALS (R = 0.02) – Concluded

(b) 7178-T6 aluminum alloy extrusion

Maximum net stress		Number of load cycles to failure N, kilocycles						
MN/m^2	ksi							
$K_T = 1$								
552	80	5	6	7	7	8	------	------
483	70	8	10	11	12	13	17	------
414	60	14	15	16	17	18	18	------
345	50	25	35	38	40	42	44	------
276	40	46	47	67	87	109	------	------
241	35	83	115	125	142	158	265	2 915
228	33	180	303	859	2 747	9 601	>10 000	>10 000
207	30	1484	1 984	>10 000	>10 000	>10 000	>10 000	>10 000
$K_T = 4$								
345	50	0.3	------	------	------	------	------	------
276	40	1	------	------	------	------	------	------
241	35	2	2	2	3	3	------	------
207	30	3	3	3	3	5	------	------
138	20	14	17	20	21	22	23	29
117	17	26	38	40	46	54	------	------
103	15	39	53	56	100	815	2 876	>10 000
83	12	127	3 355	4 492	5 910	6 404	>10 000	------
70	10	3471	>10 000	>10 000	>10 000	>10 000	>10 000	------

TABLE IV.- RESULTS OF FATIGUE-CRACK-GROWTH TESTS ON SERVICE MATERIALS

Material	t		S_m		S_a		Loading frequency		R	Average number of cycles required to propagate a crack from a half-length of 1.8 mm (0.07 in.) to a half-length of –								
	mm	in.	$\frac{MN}{m^2}$	ksi	$\frac{MN}{m^2}$	ksi	Hz	cps		3.0 mm (0.12 in.)	4.3 mm (0.17 in.)	5.6 mm (0.22 in.)	6.9 mm (0.27 in.)	8.1 mm (0.32 in.)	9.4 mm (0.37 in.)	10.7 mm (0.42 in.)	11.9 mm (0.47 in.)	13.2 mm (0.52 in.)
7075-T6 (Plate)	2.8	0.11	70.3	10.2	67.6	9.8	5	5	0.02	4 545	6 847	8 309	9 390	10 224	10 813	11 218	-----	-----
			70.3	10.2	67.6	9.8	5	5		4 721	6 929	8 469	9 453	10 293	-----	-----	-----	-----
			70.3	10.2	67.6	9.8	5	5		4 223	6 504	7 916	9 005	9 768	10 362	-----	-----	-----
			105.5	15.3	101.4	14.7	2	2		1 633	2 509	2 871	3 095	3 249	-----	-----	-----	-----
			105.5	15.3	101.4	14.7	2	2		1 982	2 802	3 336	3 636	3 840	-----	-----	-----	-----
7178-T6 (Extrusion)	2.8	0.11	35.2	5.1	33.8	4.9	5	5	0.02	20 305	32 515	38 090	41 805	44 620	46 805	48 510	49 875	-----
			35.2	5.1	33.8	4.9	5	5	↓	23 565	39 525	49 210	55 710	60 474	63 989	-----	-----	-----
			70.3	10.2	67.6	9.8	5	5	↓	1 935	3 170	4 005	4 580	4 995	5 350	5 505	-----	-----
			70.3	10.2	67.6	9.8	5	5	↓	2 640	4 113	5 143	5 814	-----	-----	-----	-----	-----
			105.5	15.3	101.4	14.7	2	2	↓	1 089	1 633	1 937	2 096	2 192	2 249	2 275	-----	-----
			105.5	15.3	101.4	14.7	2	2	↓	590	839	-----	-----	-----	-----	-----	-----	-----
			105.5	15.3	101.4	14.7	2	2	↓	751	1 129	1 328	1 477	1 571	1 610	-----	-----	-----
			103.4	15.0	34.5	5.0	5	5	.50	7 945	-----	-----	-----	-----	-----	-----	-----	-----
			103.4	15.0	34.5	5.0	5	5	↓	7 400	11 680	14 350	16 260	17 785	18 925	19 710	20 395	20 700
			103.4	15.0	34.5	5.0	5	5	↓	5 695	9 130	11 350	12 890	14 075	14 795	15 435	-----	-----
			155.1	22.5	51.7	7.5	2	2	↓	2 281	3 414	4 195	4 715	5 033	5 201	-----	-----	-----
			155.1	22.5	51.7	7.5	2	2	↓	2 456	3 675	4 277	-----	-----	-----	-----	-----	-----

TABLE V.- RESULTS OF FRACTURE-TOUGHNESS TESTS

ON SERVICE MATERIALS

Material	t		a_i		$\frac{2a_i}{w}$	S_f		K_{cn}	
	mm	in.	mm	in.		MN/m^2	ksi	MN/m$^{3/2}$	ksi-in$^{1/2}$
7075-T6 (Plate)	2.8	0.11	8.13	0.320	0.28	305	44.3	50.5	46.0
			8.26	.325	.29	294	42.6	49.0	44.6
			8.59	.338	.30	285	41.3	48.6	44.2
			9.78	.385	.34	268	38.8	49.5	45.0
			11.05	.435	.39	247	35.8	47.6	43.3
7178-T6 (Extrusion)	2.5	0.10	3.68	0.145	0.13	321	46.5	37.9	31.4
			6.05	.238	.21	303	43.9	42.1	38.3
			7.49	.295	.26	243	35.2	38.2	34.8
			9.14	.360	.32	221	32.1	39.2	35.7
			11.93	.470	.42	192	27.9	40.2	36.6
			13.34	.525	.47	170	24.7	38.3	34.9
			19.30	.760	.68	137	19.8	43.0	39.2

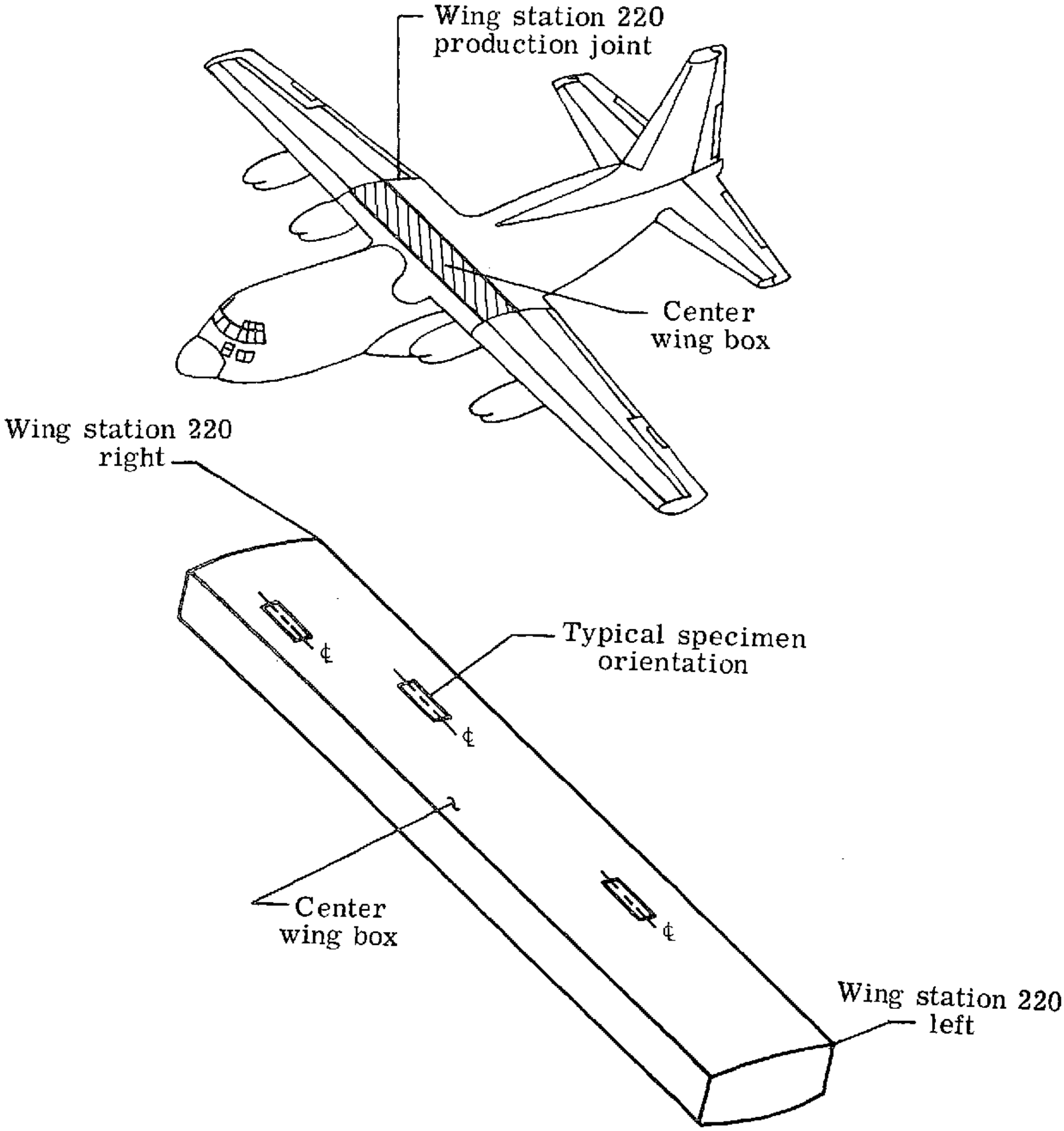
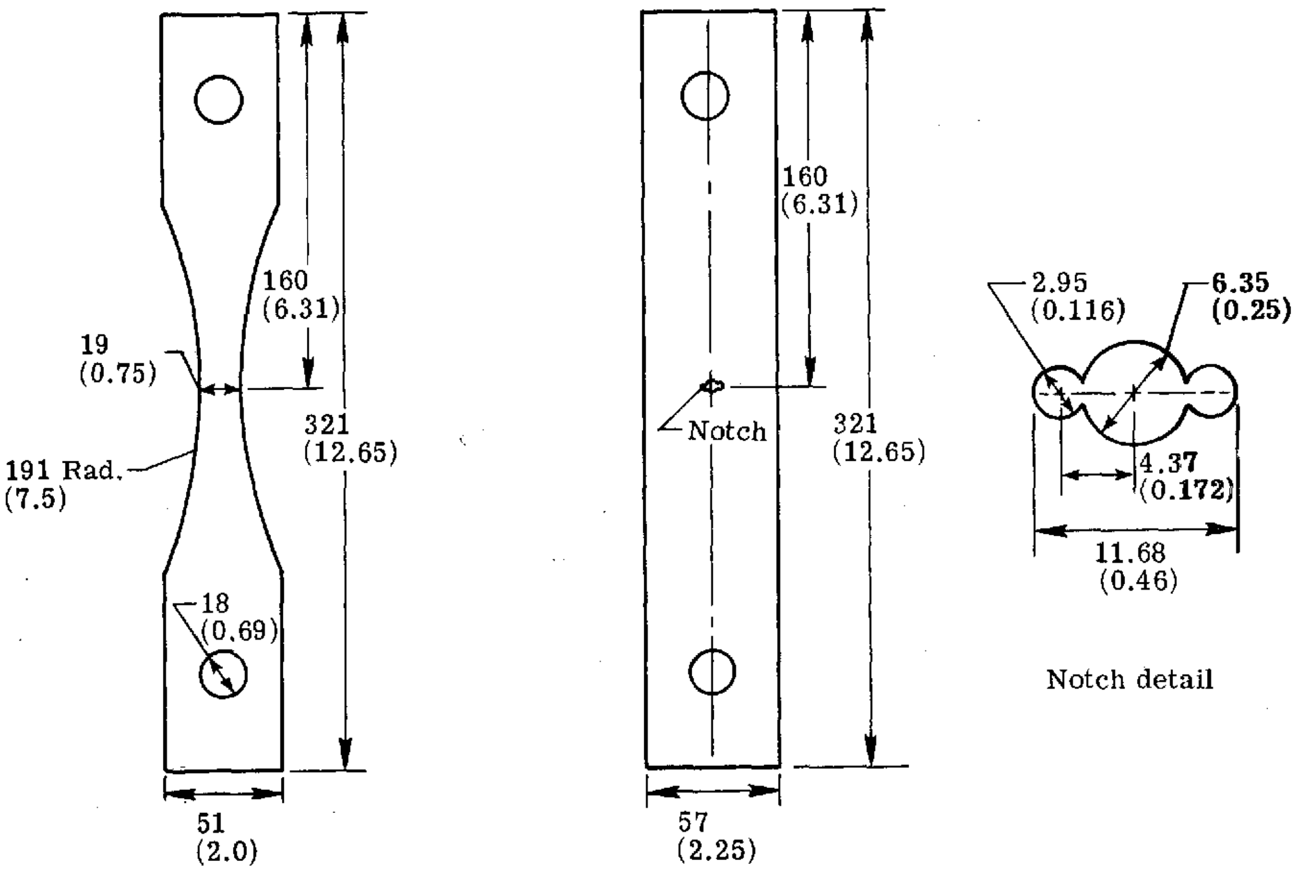


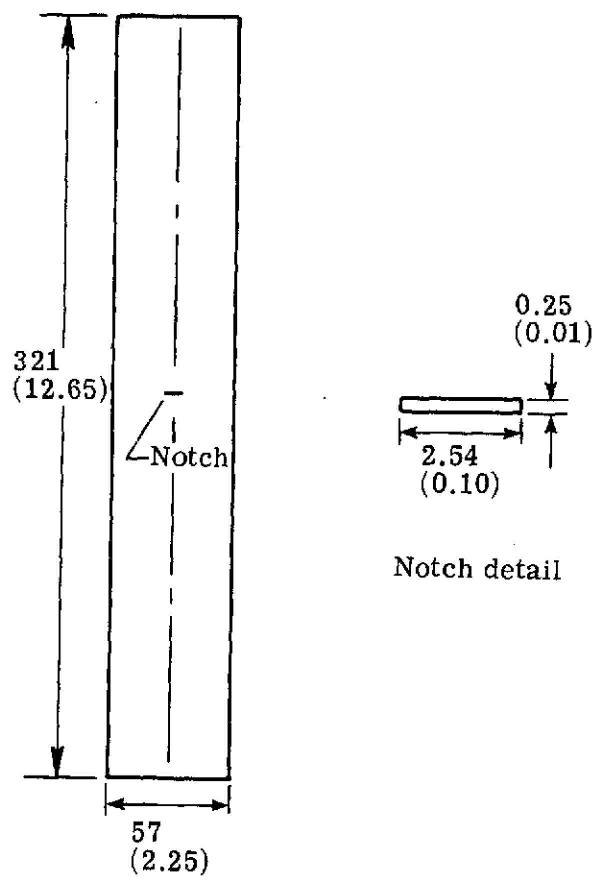
Figure 1.- Orientation of the service material specimens taken from the center wing box of a C-130B transport airplane.



(a) Unnotched, $K_T = 1$.

(b) Notched, $K_T = 4$.

Figure 2.- Specimen configurations. All dimensions are in millimeters (inches).



(c) Crack-propagation and fracture-toughness specimen.

Figure 2.- Concluded.

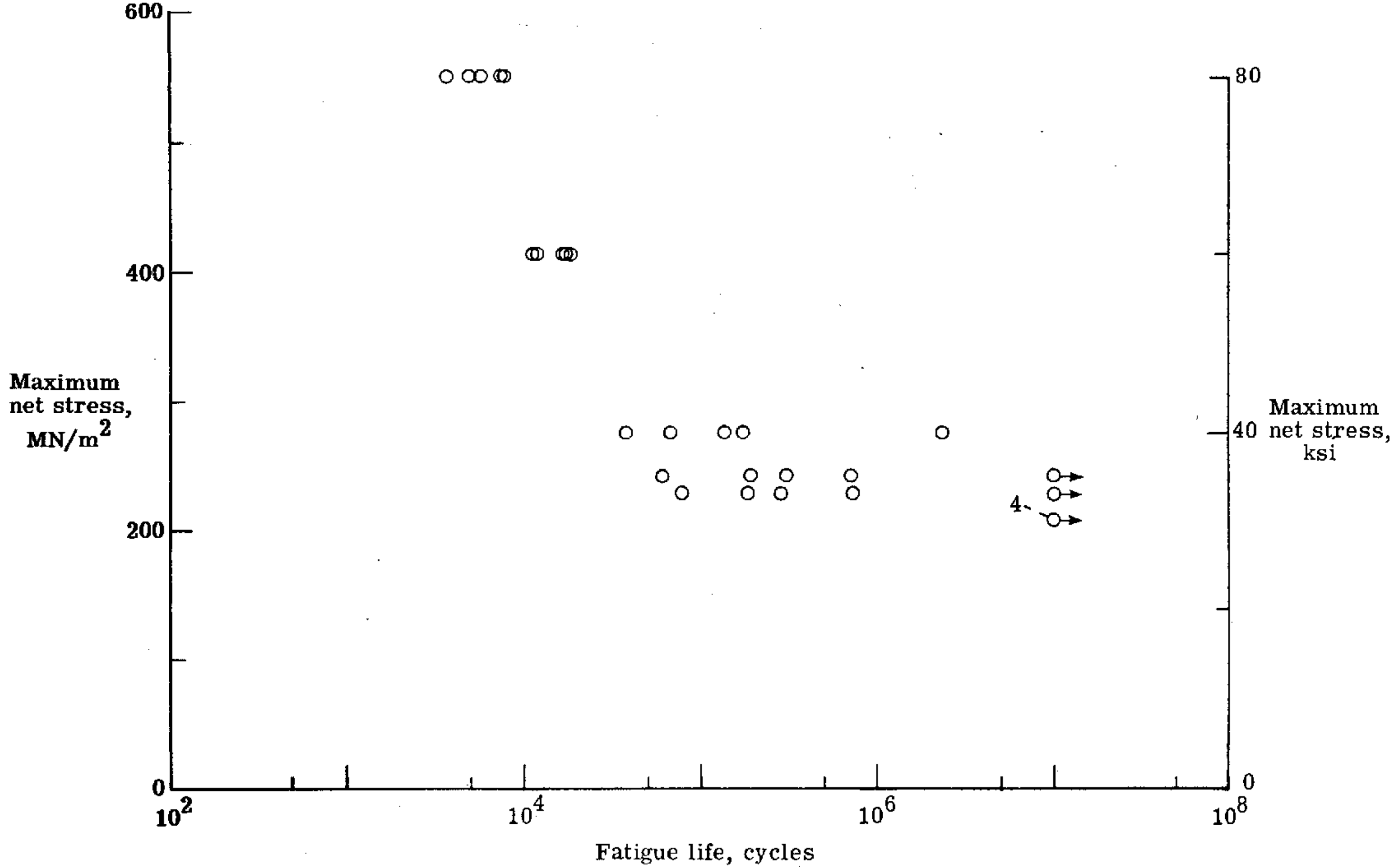
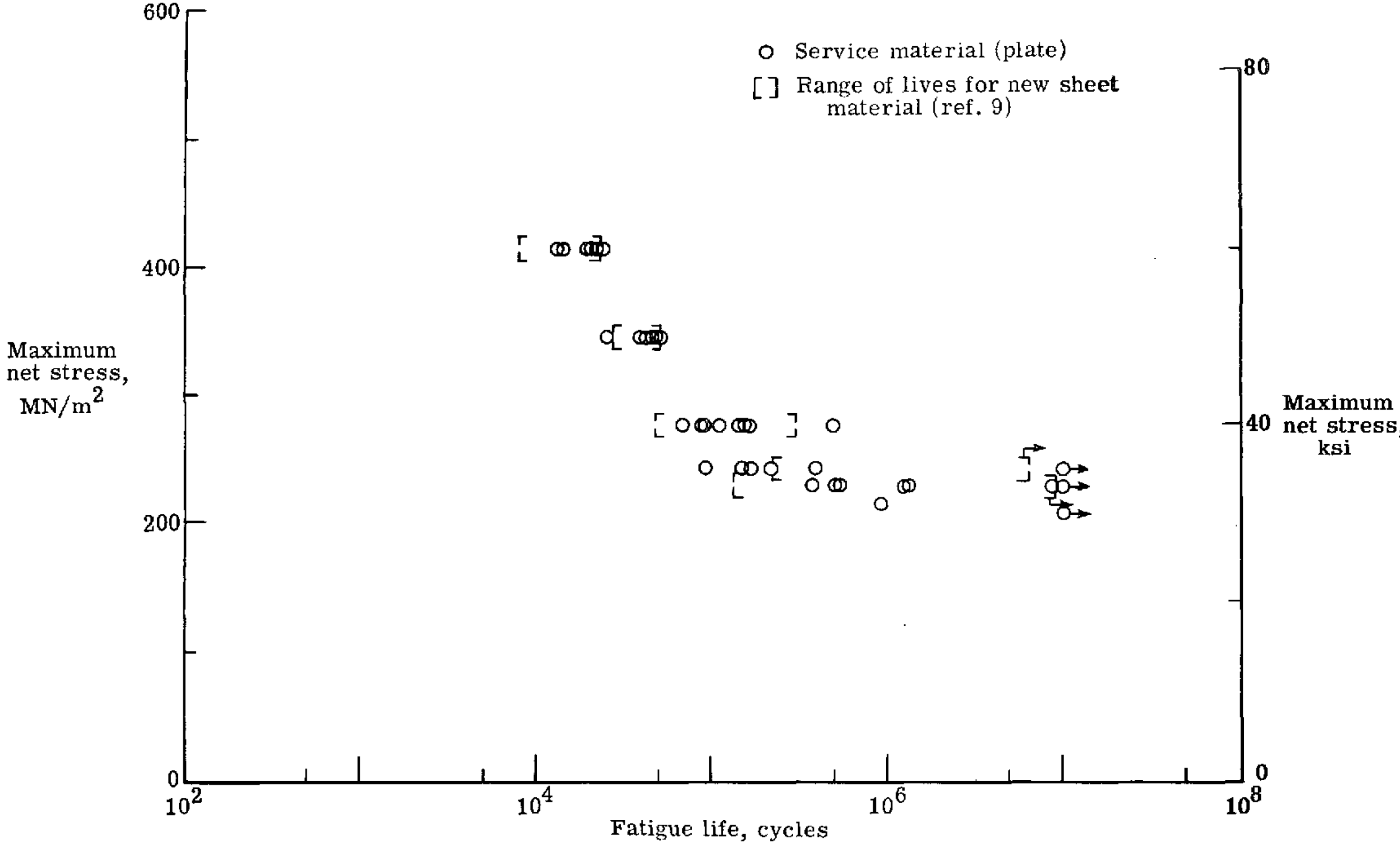
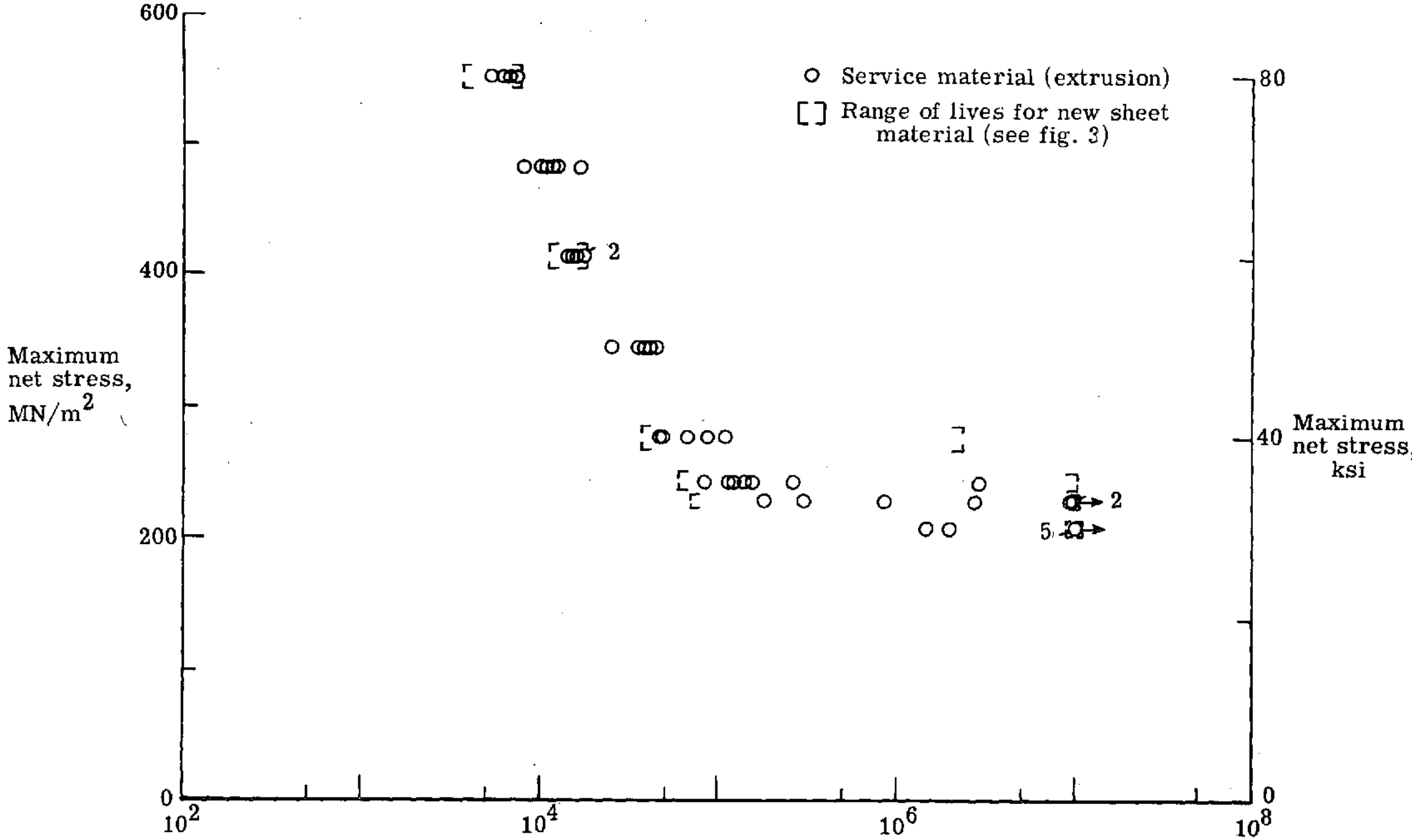


Figure 3.- Results of axial-load fatigue tests on unnotched specimens of new 7178-T6 sheet material. R = 0.02.



(a) 7075-T6.

Figure 4.- Results of axial-load fatigue tests on unnotched service and new materials. R = 0.02.



(b) 7178-T6.

Figure 4.- Concluded.

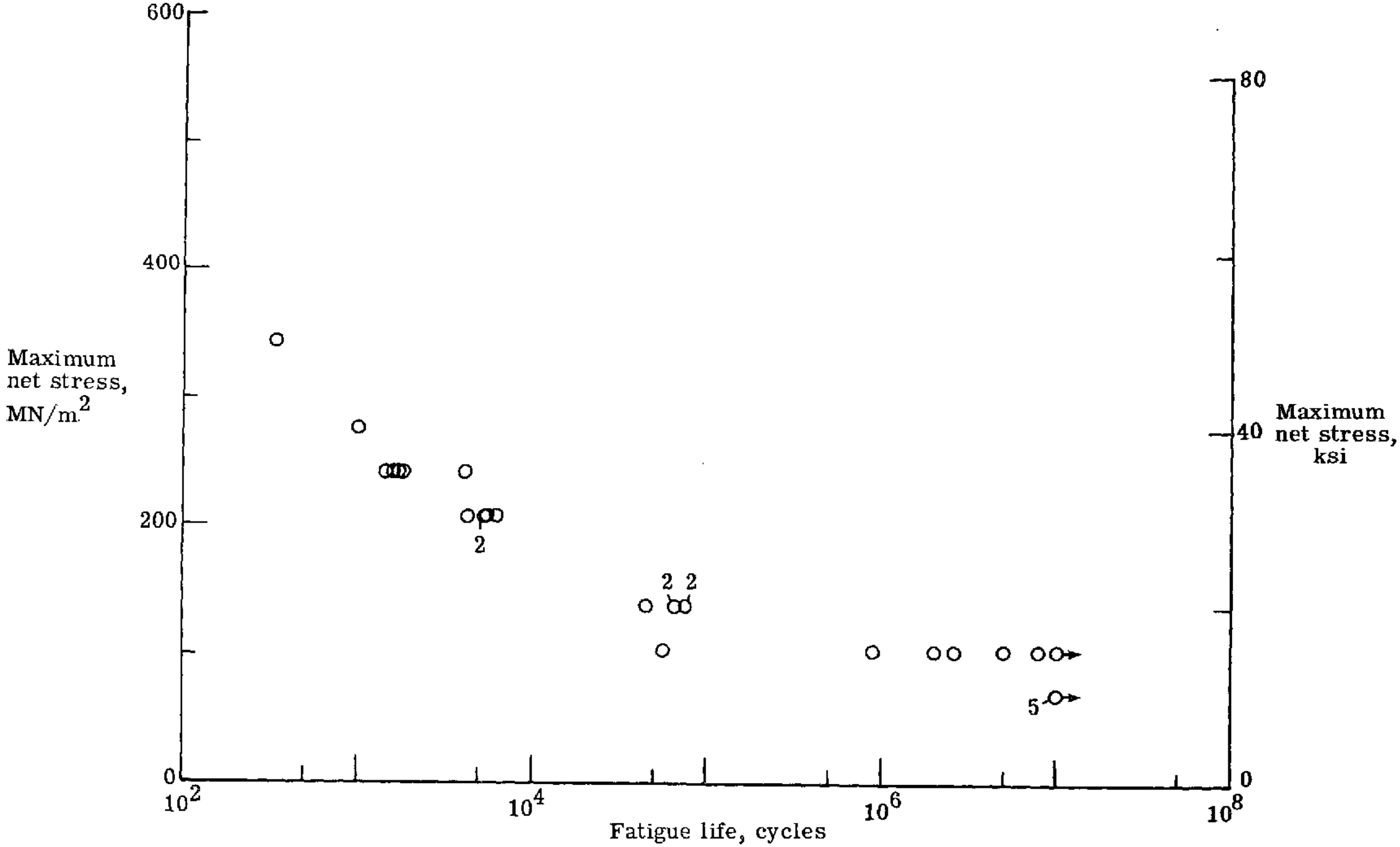
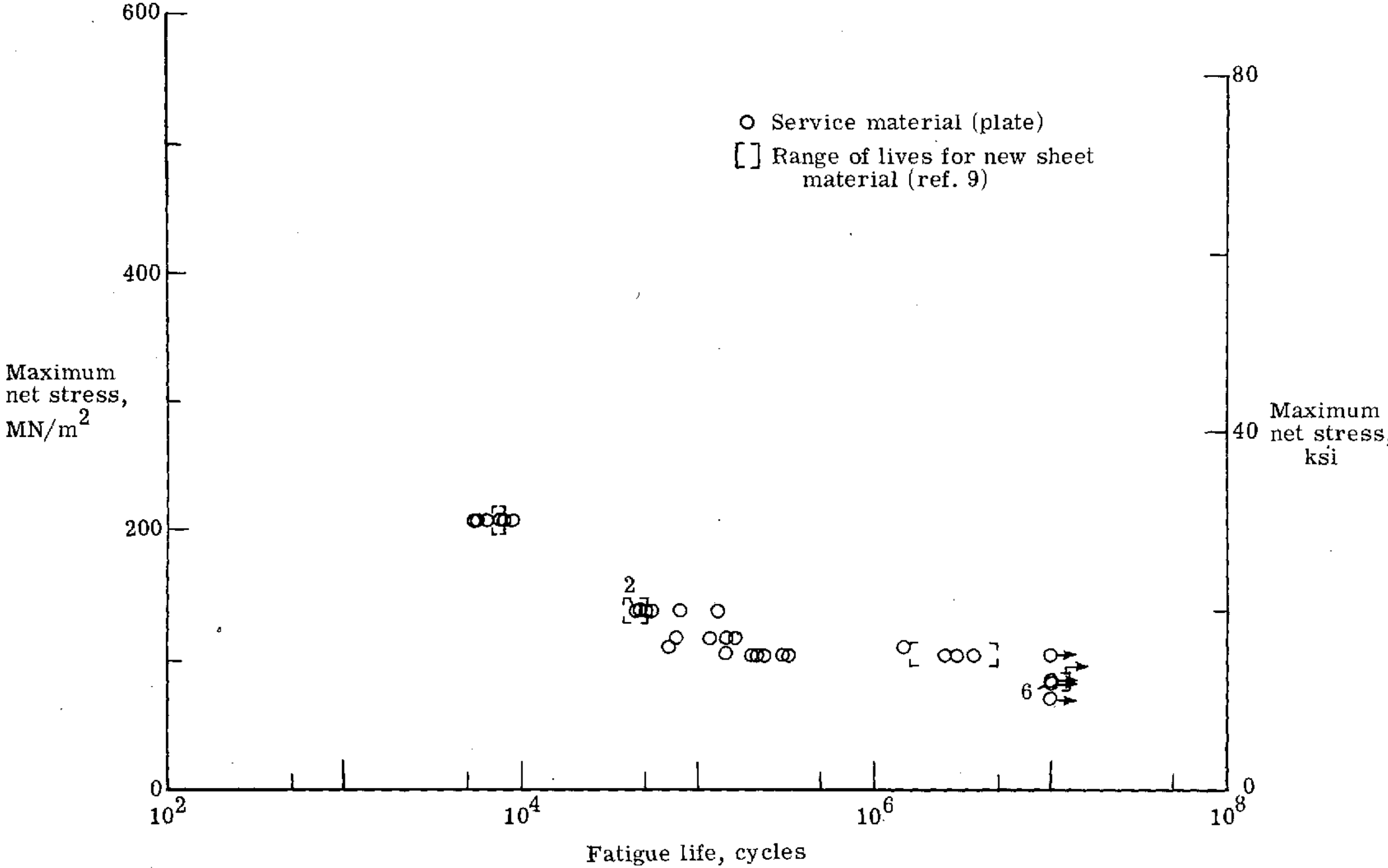
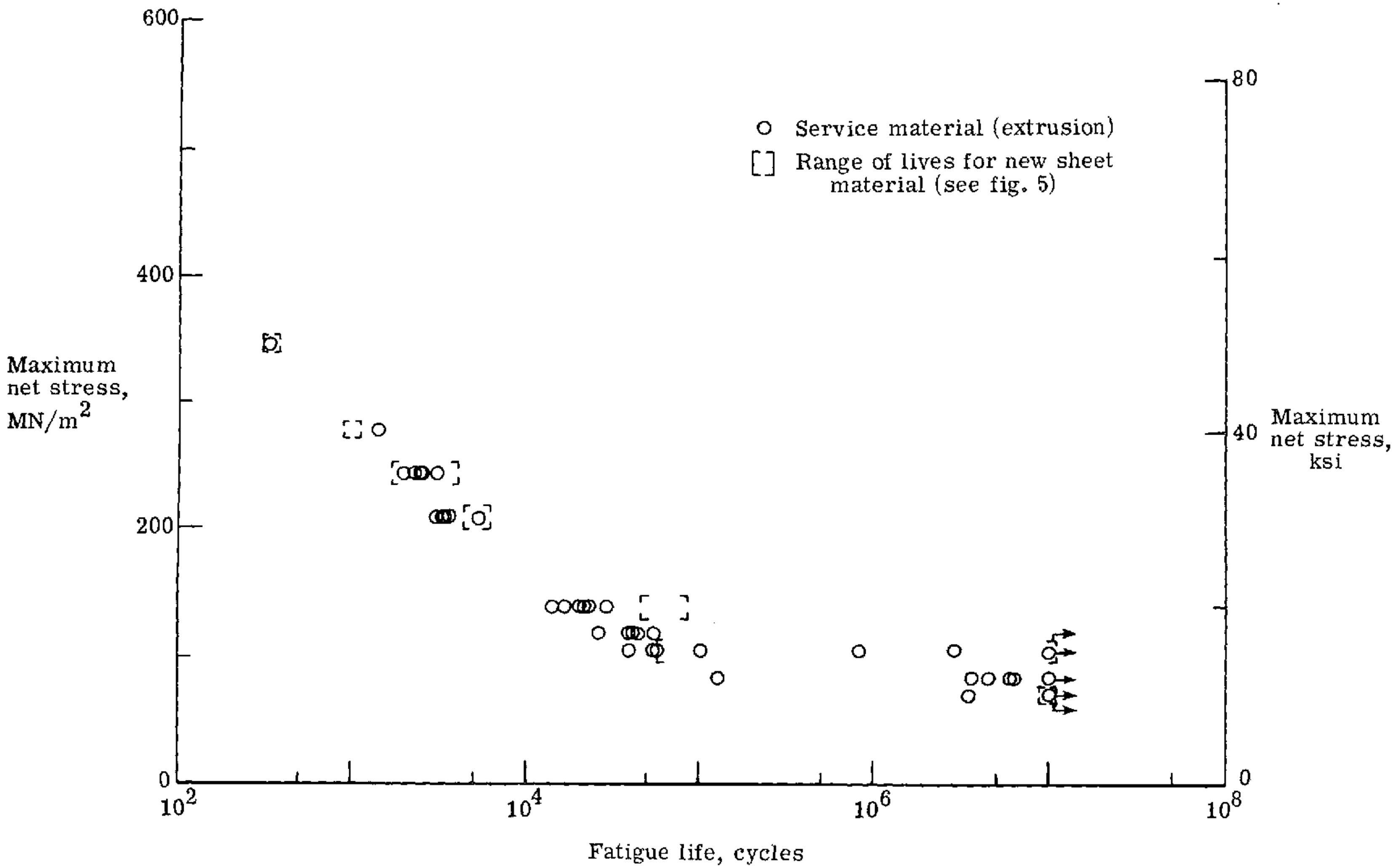


Figure 5.- Results of axial-load fatigue tests on notched specimens of new 7178-T6 sheet material. $K_T = 4$; $R = 0.02$.



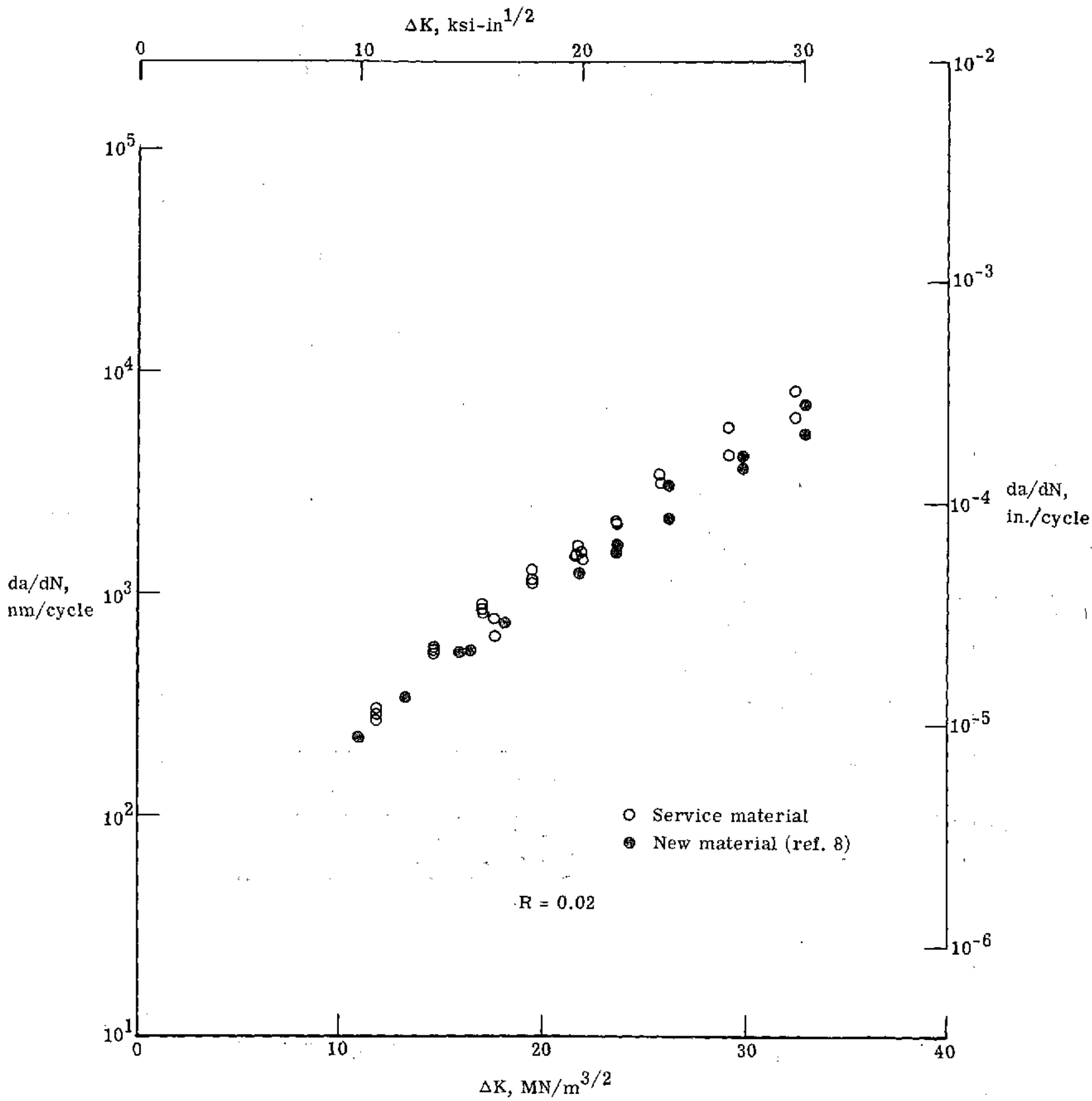
(a) 7075-T6.

Figure 6.- Results of axial-load fatigue tests on notched service and new materials. $K_T = 4$; $R = 0.02$.



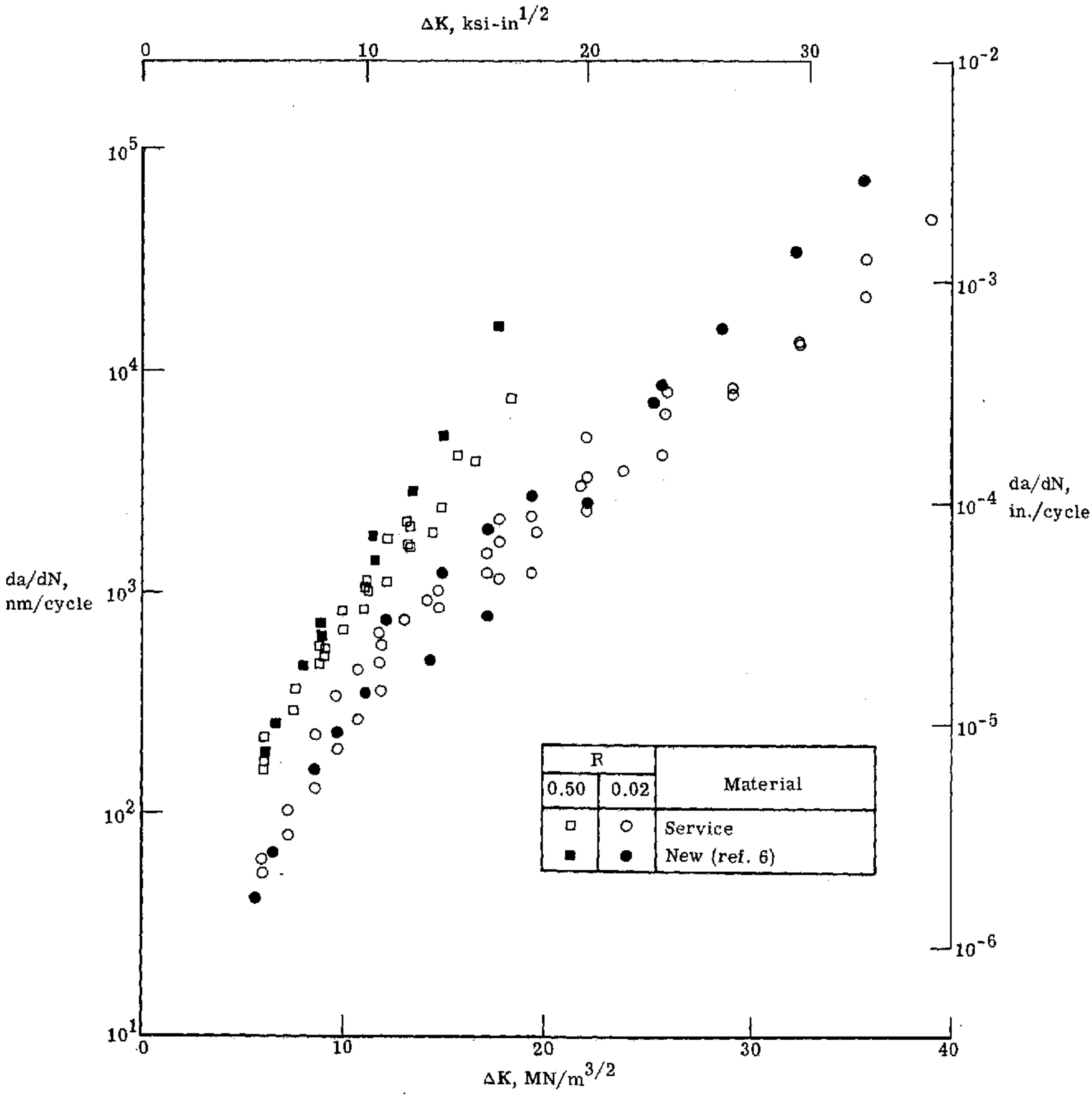
(b) 7178-T6.

Figure 6.- Concluded.



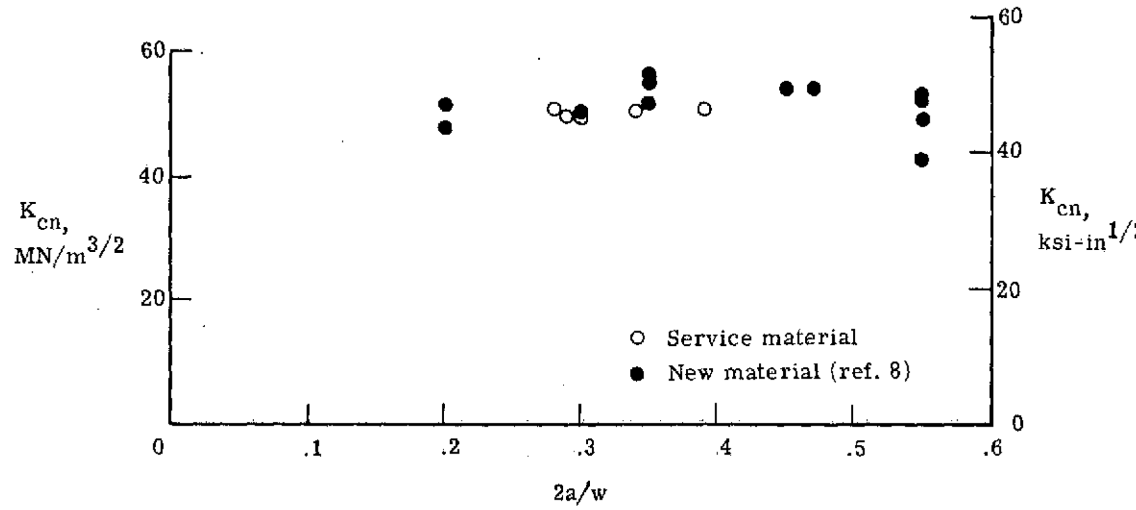
(a) 7075-T6.

Figure 7.- Results of axial-load fatigue-crack-growth tests on service and new sheet materials.

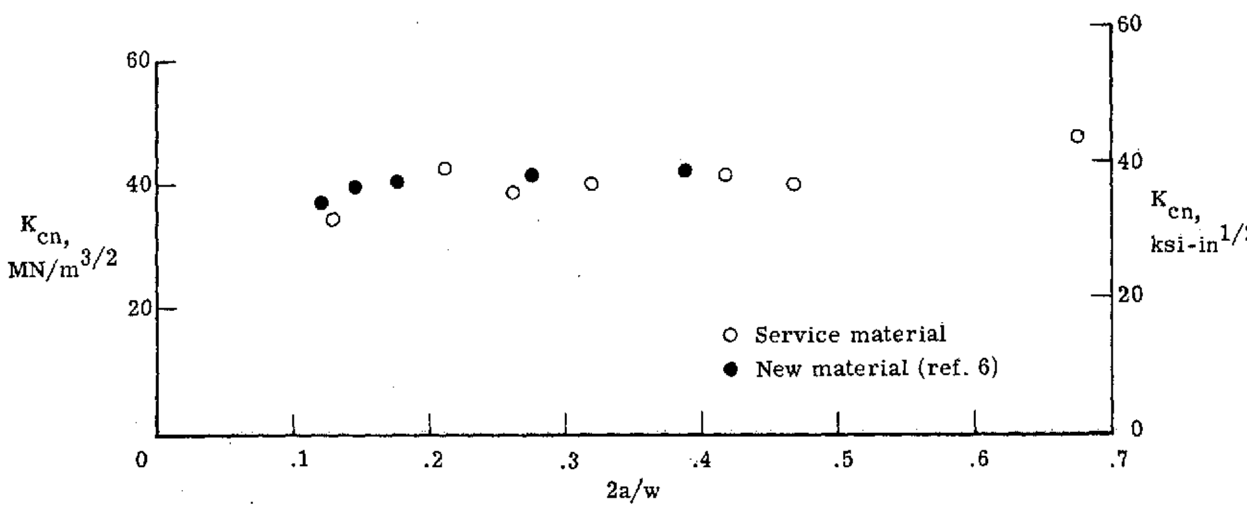


(b) 7178-T6.

Figure 7.- Concluded.



(a) 7075-T6.



(b) 7178-T6.

Figure 8.- Results of fracture-toughness tests on service and new sheet materials