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TECHNICAL NOTE

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TENSILE PROPERTIES AND SHEET-BENDING FATIGUE PROPERTIES OF SOME REFRACTORY METALS AT ROOM TEMPERATURE

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SUMMARY

Results of tensile stress-strain tests and completely reversed sheet-bending fatigue tests conducted at room temperature on unnotched sheet specimens of Ta-10W tantalum alloy, D-31 niobium alloy, pure tungsten, and Mo-0.5Ti molybdenum alloy are presented. Fatigue data from tests on similar specimens of 2024-T3 aluminum alloy and 17-7 PH stainless steel are compared with previous data from axial-load tests on larger specimens of these materials to determine whether the small size of the specimens used in this investigation produces representative results. Comparisons of the various materials on the basis of applied-stress—ultimate-strength and strength-density ratio also are presented.

INTRODUCTION

Refractory metals have been considered for structural applications in vehicles that experience temperatures in excess of 2,000° F during high-speed flight. The performance of the refractory metals in flight structures must be satisfactory not only at the high service temperatures but also at lower temperatures. One area of concern is the behavior of refractory metals under fatigue loading. Molybdenum and tungsten, in particular, display brittle behavior at room temperature and consequently there is reason to question their performance under fatigue loading conditions. Though some fatigue data have been reported (refs. 1, 2, and 3) for unalloyed refractory metals, data for specific alloys are scarce.

The Langley Research Center has initiated an experimental investigation to determine the room-temperature tensile and fatigue properties of several refractory-metal alloys. The present study, of a preliminary nature, consisted of a number of room-temperature sheet-bending fatigue tests on four refractory metals: D-31 niobium alloy, Mo-0.5Ti molybdenum alloy, Ta-10W tantalum alloy, and pure tungsten. The available supply of these metals was very limited at the start of the test program and, therefore, small test specimens were used. Sheet-bending fatigue tests were conducted on 2024-T3 aluminum alloy and 17-7 PH stainless steel machined to the same test-specimen configuration to determine whether the small specimen size used in this investigation would produce representative results. Tensile stress-strain test results were utilized to estimate the loads to be applied in the fatigue tests. The tensile stress-strain data and the sheet-bending fatigue data are compared on the basis of a strength-density ratio because of the large range of densities represented by the materials under investigation.

SPECIMENS

Specimens were made from 0.020- or 0.025-inch-thick sheet material of the following metals: D-31 niobium alloy, Ta-10W tantalum alloy, pure tungsten, Mo-0.5Ti molybdenum alloy, 2024-T3 aluminum alloy, and 17-7 PH stainless steel. A description of the materials is given in table I. The nominal chemical composition of each material is given in table II.

Tensile specimens were cut from each sheet of material and machined to the configuration shown in figure 1(a). Unnotched cantilever bending specimens for fatigue tests were machined to the configuration shown in figure 1(b). The test section had a nominal width of 0.20 inch. All edges were carefully machined and all burrs removed prior to testing.

Specimens of each of the refractory-metal sheet materials, except tungsten, were machined and tested in both the longitudinal and transverse grain directions. Efficient utilization of the small quantity of tungsten sheet material available for this investigation required the fabrication of tensile specimens in the longitudinal grain direction and fatigue specimens in the transverse direction only.

EQUIPMENT AND PROCEDURE

Tensile Tests

Tensile stress-strain tests were performed in a 120,000-pound-capacity universal hydraulic testing machine at the Langley Research Center at a nominal strain rate of 0.005 per minute to yield and 0.050 per minute from yield to failure. Strain rates were controlled by continuously monitoring head motion during the test. Strains were measured by Tuckerman optical strain gages attached on both sides of the specimen; strains were read while the strain rate was maintained. Elongation measurements were made by using finely scribed pencil lines at 1/4-inch intervals along the specimen.

Fatigue Tests

Specimens were tested in the Sonntag SF-2 sheet-bending fatigue testing machine at the Langley Research Center. A schematic diagram of this machine is shown in figure 2. Dynamic force is produced by the rotation of an eccentric mass at a constant speed of 1,800 rpm. Static loads are applied by means of the handwheel and compensator spring and are measured on the loading-dial gage. The machine incorporates an automatic shutoff device to terminate operation upon specimen failure.

The stress levels for the fatigue tests were determined from the tensile stress-strain data. The flexure formula was used to determine the applied load required to produce the desired stress at the critical cross section. This computed load was applied statically and the tip deflection was measured. The specimen was then returned to the zero-load position and an eccentric-mass setting was determined which would produce the same tip deflection. A reset-type revolution counter recorded the number of load cycles applied.

RESULTS AND DISCUSSION

Tensile Tests

Room-temperature tensile properties for all sheet materials tested are presented in table III. Typical stress-strain curves are presented in figure 3 for all materials in the longitudinal grain direction. Stress-strain curves for each material in the transverse grain direction generally had the same shape as those presented for the longitudinal grain direction.

The materials reported herein possess wide variations, not only in strength, but also in density. (See table I.) For example, the density of tungsten is seven times that of the aluminum alloy. Therefore, several of the mechanical properties are compared on a strength-density basis. In figures 4(a), 4(b), and 4(c), the ultimate tensile strength, 0.2-percent-offset yield stress, and Young's modulus, respectively, have been divided by the density of the specific material and have been plotted in decreasing order of the ratio. On this basis the refractory metals tested have lower values than the aluminum alloy and the stainless steel for ultimate and yield stresses. For the modulus-density ratio, the molybdenum alloy has a slightly higher value than the aluminum alloy and the stainless steel. The modulus-density ratios for the tungsten and for the niobium and tantalum alloys are considerably lower than those for the aluminum alloy and the stainless steel.

The tensile elongation data also show a wide variation, not only from material to material, but also between the longitudinal and transverse grain directions of a given material. The elongation data of table III are shown in figure 5 in order of decreasing ductility in the longitudinal grain direction. Consideration of the longitudinal elongation measured over the standard 2-inch gage length (fig. 5(a)) shows that the values for tantalum alloy, stainless steel, and molybdenum and niobium alloys ranged from 4 to 11 percent. The transverse elongations measured over the 2-inch gage length varied from only 3 percent for the tantalum and niobium alloys to 8 percent for the stainless steel. Over the 1/2-inch gage length (fig. 5(b)), however, the elongation for the refractory-metal alloys varied from 10 to 16 percent in the longitudinal direction and from 8 to 12 percent in the transverse direction. These values are considerably higher than those measured over the 2-inch gage length and are indicative of localized necking occurring in these materials, which is not apparent from the measurements of elongation in 2 inches. Therefore, in working with the refractory-metal alloys of this investigation, the elongation measurement over the standard 2-inch gage length may not present an adequate evaluation of the relative ductility of these materials. Elongations measured over shorter gage lengths, such as the 1/2-inch gage length, may supply useful additional information. For example, limited fabrication experience indicates that the tantalum alloy is easier to fabricate at room temperature than the molybdenum alloy. This is contrary to the elongation data shown in figure 5(a) for the transverse-grain 2-inch gage length. However, this fabrication experience would substantiate the data shown in figure 5(b) for the 1/2-inch gage length.

The pure tungsten, tested in the longitudinal direction only, exhibited brittle behavior in that no measurable elongation was obtained.

Fatigue Tests

Aluminum and steel alloys.- In order to establish the validity of the technique and procedures used in the sheet-bending tests of small specimens, specimens of 2024-T3 aluminum alloy and 17-7 PH stainless steel were tested for comparison with axial-load fatigue-test data for larger specimens. Results of the sheet-bending tests are tabulated in tables IV and V and plotted in figures 6 and 7. The dashed lines in the figures represent results of axial-load fatigue tests under completely reversed loading. (See refs. 4 and 5.) Bending tests are expected to produce longer life than axial-load tests at the same ratio of minimum stress to maximum stress, because a smaller percentage of the material is highly stressed in the bending tests as compared with the axial-load tests. The test results in figures 6 and 7 indicate that the bending fatigue tests exhibited longer lifetimes for a given stress level than did the axial-load fatigue tests. Thus, the testing procedure used for the small specimens of this investigation may be regarded as producing results similar to those which might be expected from tests of larger, more conventional specimens. Transverse-grain specimens of aluminum alloy had slightly shorter fatigue lives at a given stress level than did longitudinal-grain specimens.

Tantalum alloy.- Results of sheet-bending fatigue tests on Ta-10W tantalum alloy are shown in table VI and figure 8. The transverse-grain specimens had shorter lives at a given stress level than did the longitudinal-grain specimens. The fatigue limit for longitudinal-grain specimens must be estimated because of limited data. Two tests at 70 ksi for transverse-grain specimens produced an average life of 3.4 million cycles. Based on the effect of grain direction on fatigue life at the higher stress levels, it is estimated that longitudinal-grain specimens tested at 70 ksi would have lifetimes approaching 10 million cycles. Two tests at 60 ksi, however, did not produce failure in 17 million cycles. Thus, a fatigue limit slightly below 70 ksi for longitudinal-grain specimens would seem reasonable.

Niobium alloy.- Results of sheet-bending fatigue tests on D-31 niobium-alloy specimens are presented in table VII and figure 9. The effect of grain direction on life of specimens of this metal was negligible. The fatigue limit was approximately 65 ksi. A stress of 110 ksi is indicated as having been used for two fatigue tests on D-31 niobium alloy whereas the tensile test data of table III showed 108 ksi as the average yield stress for this material. The static load applied to these specimens was that which was required to produce 110-ksi stress on the outer fiber of the specimen according to elastic analysis. The dynamic deflection was then maintained in the value obtained in the static calibration.

Pure tungsten.- Results of sheet-bending tests on specimens of pure tungsten are listed in table VIII and are plotted on figure 10. The fatigue limit for this metal was not defined because the S-N curve (maximum stress plotted against life in cycles) through the test data retained a significant slope at 10 million cycles. In a test at 100 ksi no evidence of fatigue was present in 40 million cycles. Fatigue limits for the other metals in this report were adequately defined at 10 million cycles. Therefore, to permit a comparison of tungsten with the other metals, the fatigue strength at 10 million cycles, approximately 112 ksi, is used.

Molybdenum alloy.- Results of sheet-bending fatigue tests on Mo-0.5Ti molybdenum-alloy specimens are presented in table IX and figure 11. The fatigue limit is approximately 98 ksi. The transverse-grain specimens had shorter lives than the longitudinal-grain specimens.

The fracture surface of longitudinal-grain molybdenum-alloy specimens tested at the lower stress levels showed evidence of delamination, whereas specimens tested at 120 ksi or higher did not. This type of failure was not evident in specimens of other metals tested. A photograph of the fracture surfaces appears as figure 12. In general, as the stress level decreased, delamination became more noticeable for the molybdenum alloy.

Evaluation of data.- A comparison of data from sheet-bending fatigue tests for all the metals of this investigation is made in figure 13 by presenting the S-N curves in terms of the ratio of applied stress to ultimate stress. The fatigue limit for the molybdenum alloy occurs at the highest percentage of the ultimate stress with tungsten, niobium, and tantalum alloys following in that order. All the refractory metals tested had fatigue limits at higher percentages of ultimate tensile stress than the stainless steel or the aluminum alloy.

The fatigue data are compared on a stress-density basis in figure 14. In this plot the refractory metals appear less efficient than the stainless steel because of their higher densities. On the basis of stress-density ratio, the fatigue limit of the molybdenum alloy was higher than that of the other refractory metals investigated. The fatigue limits of the niobium alloy, tungsten, and tantalum alloy followed in that order.

It should be repeated that these data were obtained on unnotched specimens at room temperature. Before refractory metals can be used in structural design, however, other factors such as notch effects, elevated temperatures, and the effect of surface coatings also must be studied.

CONCLUSIONS

The results of tensile stress-strain tests and sheet-bending fatigue tests at room temperature on unnotched specimens of Ta-10W tantalum alloy, D-31 niobium alloy, pure tungsten, Mo-0.5Ti molybdenum alloy, 2024-T3 aluminum alloy, and 17-7 PH stainless steel are presented.

The following conclusions are made from the data for the tensile tests:

1. The refractory metals tested had lower ultimate-strength—density and yield-stress—density ratios than the aluminum alloy and the stainless steel.

2. The molybdenum alloy had a modulus-density ratio slightly higher than that for the aluminum alloy or the stainless steel; the other refractory metals had lower values of this ratio.

3. Elongation measurements on the standard 2-inch gage length may not present an adequate evaluation of the relative ductility when refractory metals are compared. Elongation measured over shorter gage lengths may supply useful additional information.

and from the data for the fatigue tests:

1. Transverse-grain specimens of tantalum alloy and molybdenum alloy had shorter fatigue life at a given stress level than did longitudinal-grain specimens. No effect of grain direction on the life of the niobium alloy specimens was observed.

2. The refractory metals - molybdenum alloy, niobium alloy, tungsten, and tantalum alloy - had fatigue limits at a higher percentage of ultimate tensile strength than the 17-7 PH stainless steel or the 2024-T3 aluminum alloy.

3. On the basis of the stress-density ratio, the fatigue limit of the molybdenum alloy was higher than that for the other refractory metals investigated. The niobium alloy, tungsten, and tantalum alloy had lower fatigue limits, in that order.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., October 5, 1962.

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2. Houck, J. A.: Physical and Mechanical Properties of Commercial Molydbenum-Base Alloys. DMIC Rep. 140, Battelle Memorial Inst., Nov. 30, 1960.

3. Anon.: Molybdenum Metal. Climax Molybdenum Co., 1960.

4. Illg, Walter: Fatigue Tests on Notched and Unnotched Sheet Specimens of 2024-T3 and 7075-T6 Aluminum Alloys and of SAE 4130 Steel With Special Consideration of the Life Range From 2 to 10,000 Cycles. NACA TN 3866, 1956.

5. Leybold, Herbert A.: Axial-Load Fatigue Tests on 17-7 PH Stainless Steel Under Constant-Amplitude Loading. NASA TN D-439, 1960.

TABLE I.- DESCRIPTION OF MATERIALS

Material	Nominal sheet thickness, in.	Condition	Density, lb/cu in.
2024-T3 aluminum alloy	0.025	Heat treated by manufacturer	0.100
17-7 PH stainless steel	0.025	TH 1050	0.276
D-31 niobium alloy	0.020	Stress relieved	0.292
Mo-0.5Ti molybdenum alloy	0.020	Stress relieved	0.369
Ta-10W tantalum alloy	0.025	Cold rolled	0.608
Pure tungsten	0.020	Rolled	0.700

TABLE II.- NOMINAL CHEMICAL COMPOSITION OF MATERIALS

Material	Element, percent by weight													
	Al	C	Cr	Cu	Fe	Mg	Mn	Mo	Ni	Nb	Si	Ta	Ti	W
2024-T3 aluminum alloy	93.6			4.3		1.5	0.6							
17-7 PH stainless steel	1		17		73		1		7		1			
D-31 niobium alloy								10		80			10	
Mo-0.5Ti molybdenum alloy		0.02						99.52					0.46	
Ta-10W tantalum alloy												90		10
Pure tungsten														100

TABLE III.- RESULTS OF ROOM-TEMPERATURE TENSILE TESTS

OF VARIOUS SHEET MATERIALS

[Nominal strain rate: 0.005 per minute to yield, 0.050 per minute to failure]

Material	Specimen (a)	Ultimate stress, ksi	0.2-percent-offset yield stress, ksi	Young's modulus, psi	Elongation in 2-inch gage length, percent	Elongation in 1/2-inch gage length, percent
2024-T3 aluminum alloy	1L 2T	69.0 67.3	51.7 46.3	10.8×10^6 11.0	20 19	24 24
17-7 PH stainless steel	3L 4T	210.0 211.5	196.4 197.1	30.0×10^6 30.0	7 8	14 12
D-31 niobium alloy	5L 6L 7T 8T	108.3 108.1 107.0 108.7	108.3 108.1 107.0 108.7	15.4×10^6 15.2 14.7 15.1	12 10 3 3	16 16 10 6
Mo-0.5Ti molybdenum alloy	9L 10L 11T 12T	138.8 139.3 148.2 144.5	112.0 109.2 133.5 133.4	41.6×10^6 41.3 41.8 41.7	9 12 5 5	14 18 8 8
Ta-10W tantalum alloy	13L 14L 15T 16T	146.4 136.4 127.2 126.1	134.0 127.0 124.8 124.8	27.2×10^6 26.6 28.0 27.2	3 5 3 3	8 12 10 10
Pure tungsten	17L 18L	155.1 236.5	(b) (b)	49.9×10^6 50.6	0 0	0 0

[a]L and T indicate longitudinal and transverse grain directions, respectively.
[b]Failed before 0.2-percent yield.

TABLE IV.- RESULTS OF COMPLETELY REVERSED SHEET-BENDING FATIGUE TESTS ON UNNOTCHED SPECIMENS OF 2024-T3 ALUMINUM ALLOY AT ROOM TEMPERATURE

Specimen (a)	Maximum stress, ksi	Cycles to failure
1L 2L 3L	50	29,000 31,000 36,000
4L 5L 6L	45	68,000 59,000 61,000
7L 8L 9L	40	89,000 104,000 101,000
10L 11L 12L	35	159,000 156,000 149,000
13L 14L 15L	30	257,000 277,000 294,000
16L 17L 18L	25	1,089,000 852,000 612,000
1T 2T 3T	50	15,000 19,000 17,000
4T 5T 6T	45	42,000 45,000 47,000
7T 8T 9T	40	75,000 58,000 69,000
10T 11T 12T	35	137,000 139,000 108,000
13T 14T 15T	30	241,000 279,000 229,000
16T 17T 18T	25	463,000 539,000 481,000

[a]L and T refer to transverse grain direction.

TABLE V.- RESULTS OF COMPLETELY REVERSED SHEET-BENDING FATIGUE TESTS ON UNNOTCHED SPECIMENS OF 17-7 PH STAINLESS STEEL AT ROOM TEMPERATURE

Specimen (a)	Maximum stress, ksi	Cycles to failure
1L 2L 3L	130	58,000 81,000 72,000
4L 5L 6L	118	123,000 117,000 142,000
7L 8L 9L	106	287,000 241,000 255,000
10L 11L 12L	94	1,284,000 3,215,000 2,408,000
13L	82	>9,565,000

[a] L refers to longitudinal grain direction.

TABLE VI.- RESULTS OF COMPLETELY REVERSED SHEET-BENDING FATIGUE TESTS ON UNNOTCHED SPECIMENS OF Ta-10W TANTALUM ALLOY AT ROOM TEMPERATURE

Specimen (a)	Maximum stress, ksi	Cycles to failure
1L 2L	120	11,000 16,000
3L 4L	110	26,000 38,000
5L 6L	100	78,000 59,000
7L 8L	90	188,000 157,000
9L 10L	85	218,000 242,000
11L 12L	60	>17,801,000 >17,790,000
1T 2T	110	26,000 17,000
3T 4T	100	57,000 50,000
5T 6T	90	102,000 120,000
7T 8T	80	304,000 192,000
9T 10T	70	1,333,000 5,340,000

[a]L and T refer to longitudinal and transverse grain direction, respectively.

TABLE VII.- RESULTS OF COMPLETELY REVERSED SHEET-BENDING FATIGUE TESTS ON UNNOTCHED SPECIMENS OF D-31 NIOBIUM ALLOY AT ROOM TEMPERATURE

Specimen (a)	Maximum stress, ksi	Cycles to failure
1L 2L	110	17,000 14,000
3L 4L	90	57,000 51,000
5L 6L	70	174,000 144,000
7L	60	>10,123,000
8L 9L	50	>10,000,000 >10,008,000
1T 2T	90	56,000 51,000
3T 4T	70	161,000 140,000
5T 6T	65	241,000 337,000
7T	63	>9,986,000
8T	60	>10,357,000

[a] L and T refer to longitudinal and transverse grain direction, respectively.

TABLE VIII.- RESULTS OF COMPLETELY REVERSED SHEET-BENDING FATIGUE TESTS ON UNNOTCHED SPECIMENS OF PURE TUNGSTEN AT ROOM TEMPERATURE

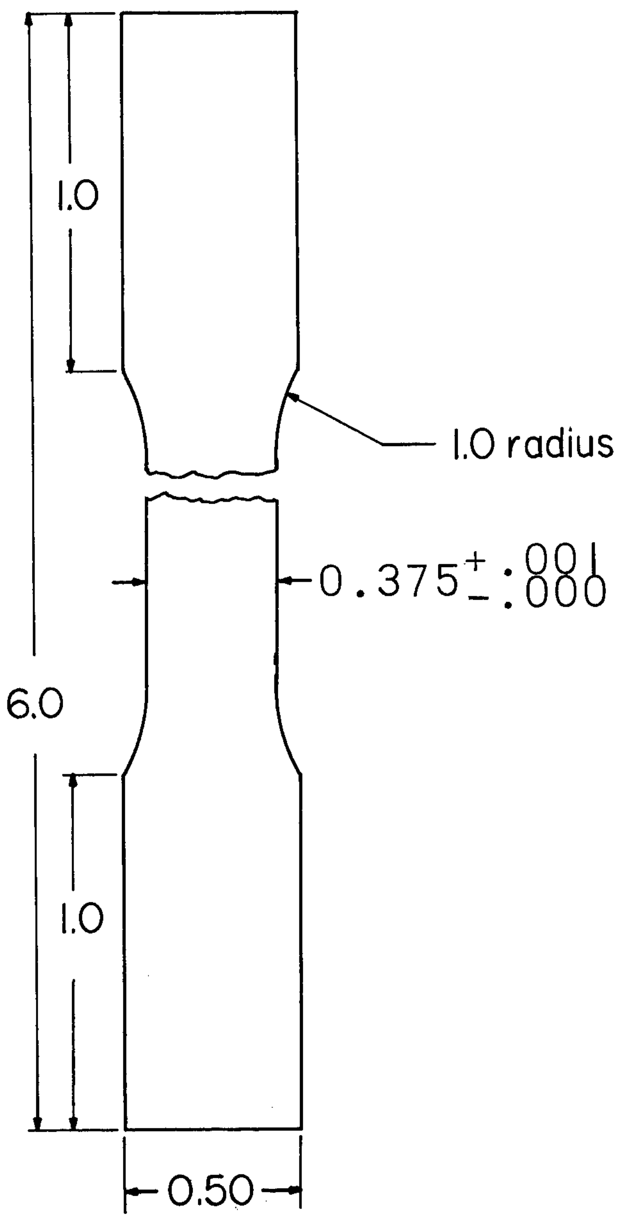
Specimen (a)	Maximum stress, ksi	Cycles to failure
1T 2T	160	24,000 26,000
3T 4T	150	103,000 173,000
5T 6T	130	3,647,000 1,459,000
7T 8T	120	6,658,000 4,564,000
9T 10T	115	8,025,000 10,627,000
11T	100	>40,000,000

[a]T refers to transverse grain direction.

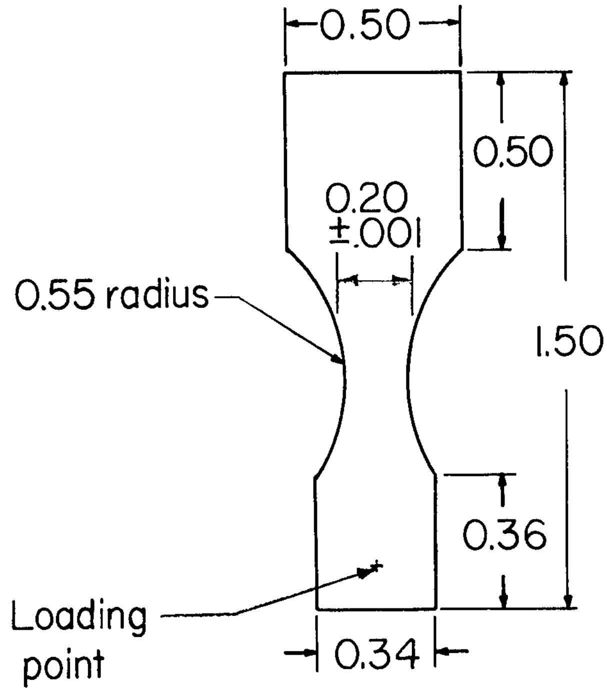
TABLE IX.- RESULTS OF COMPLETELY REVERSED SHEET-BENDING FATIGUE TESTS ON UNNOTCHED SPECIMENS OF Mo-0.5Ti MOLYBDENUM ALLOY AT ROOM TEMPERATURE

Specimen (a)	Maximum stress, ksi	Cycles to failure
1L 2L	125	86,000 67,000
3L 4L	120	143,000 124,000
5L 6L	110	393,000 358,000
7L 8L	105	487,000 580,000
9L 10L	100	6,354,000 2,418,000
11L	95	>10,451,000
1T 2T	120	82,000 77,000
3T 4T	110	181,000 214,000
5T 6T	100	603,000 1,005,000

[a]L and T refer to longitudinal and transverse grain direction, respectively.



(a) Tensile specimen.



(b) Fatigue specimen.

Figure 1.- Specimen configurations. All dimensions are in inches.

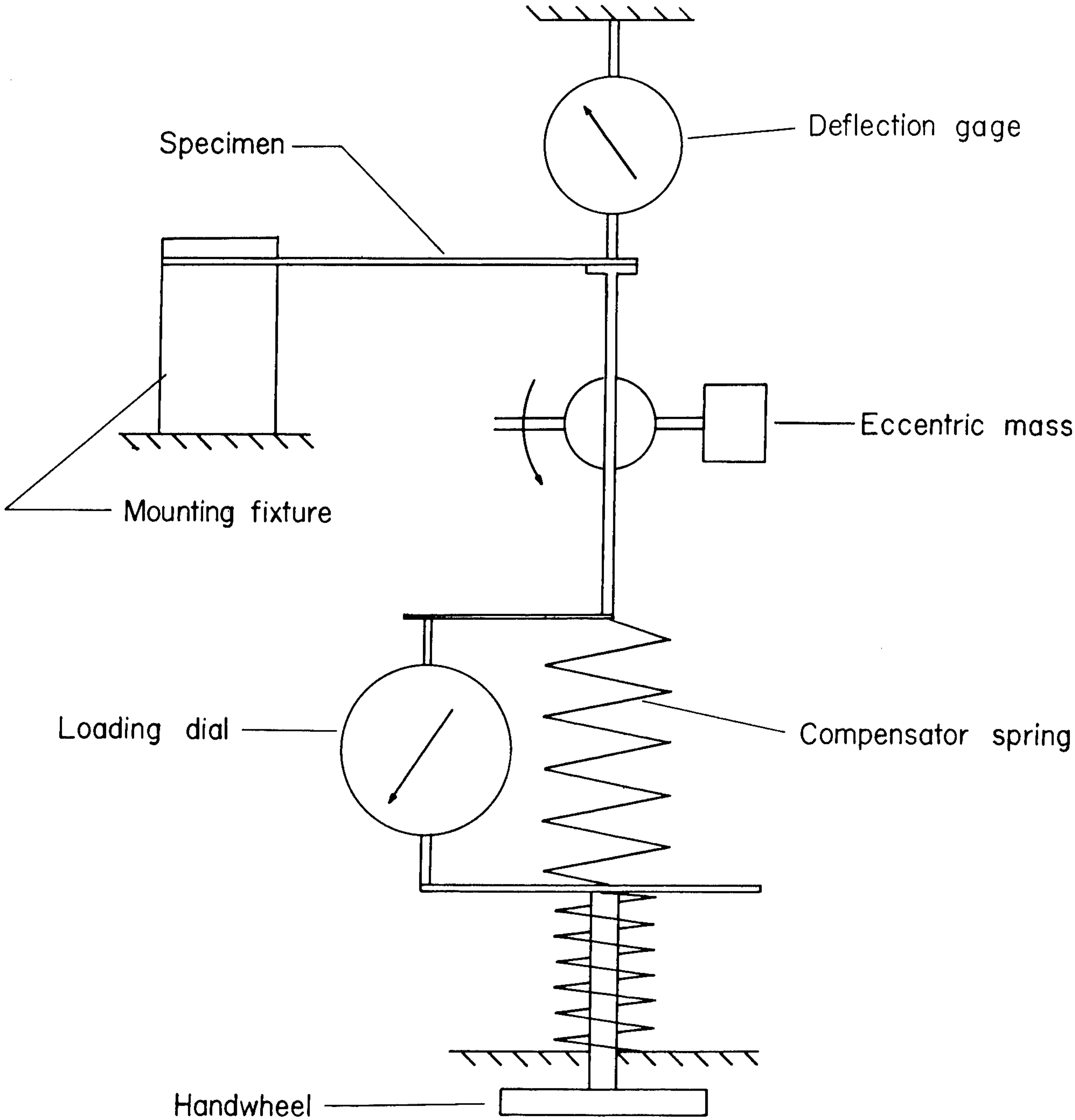


Figure 2.- Schematic diagram of sheet-bending fatigue testing machine.

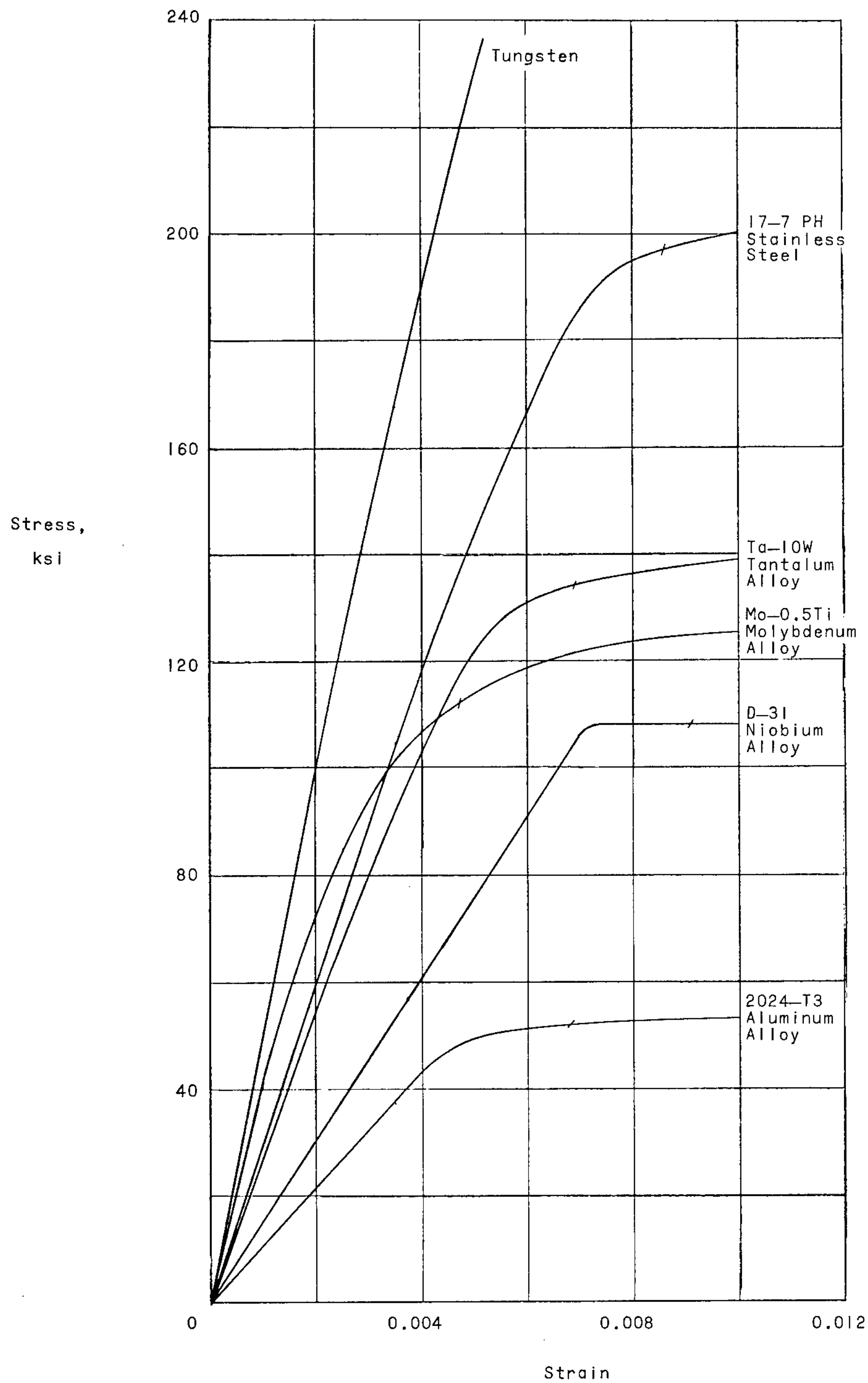
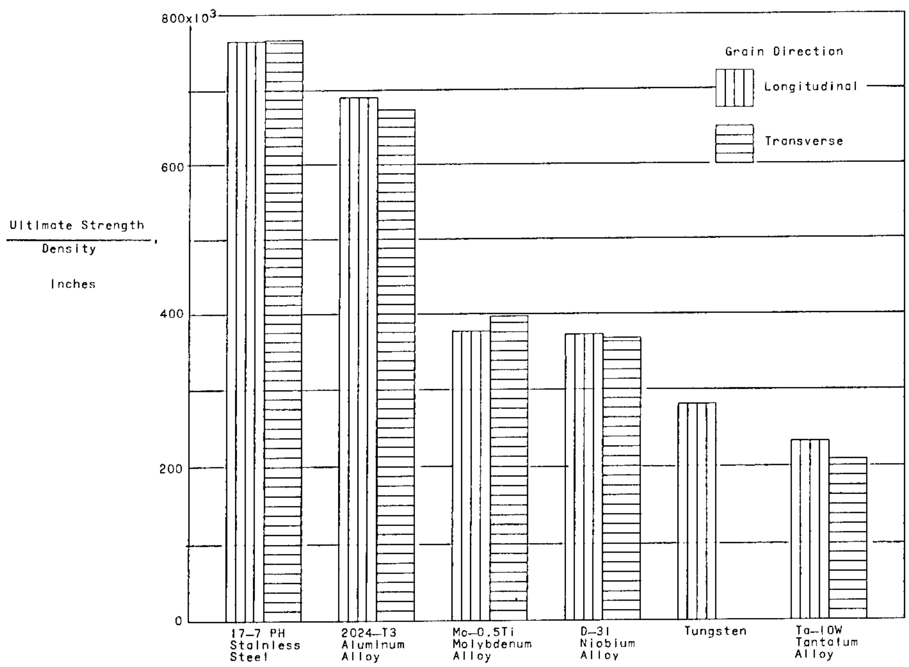
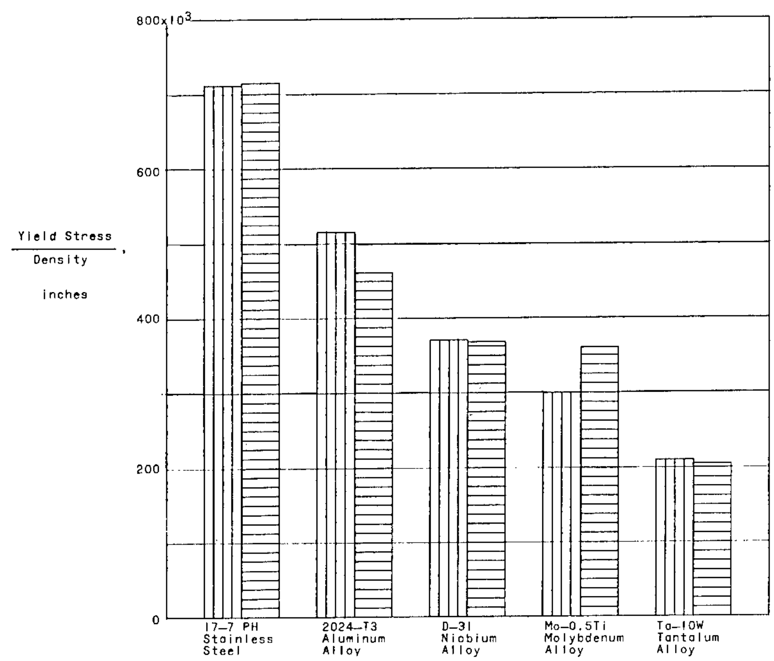


Figure 3.- Room-temperature tensile stress-strain curves for the various materials tested in the longitudinal grain direction. Strain rate: 0.005 per minute to yield, 0.050 per minute to failure.

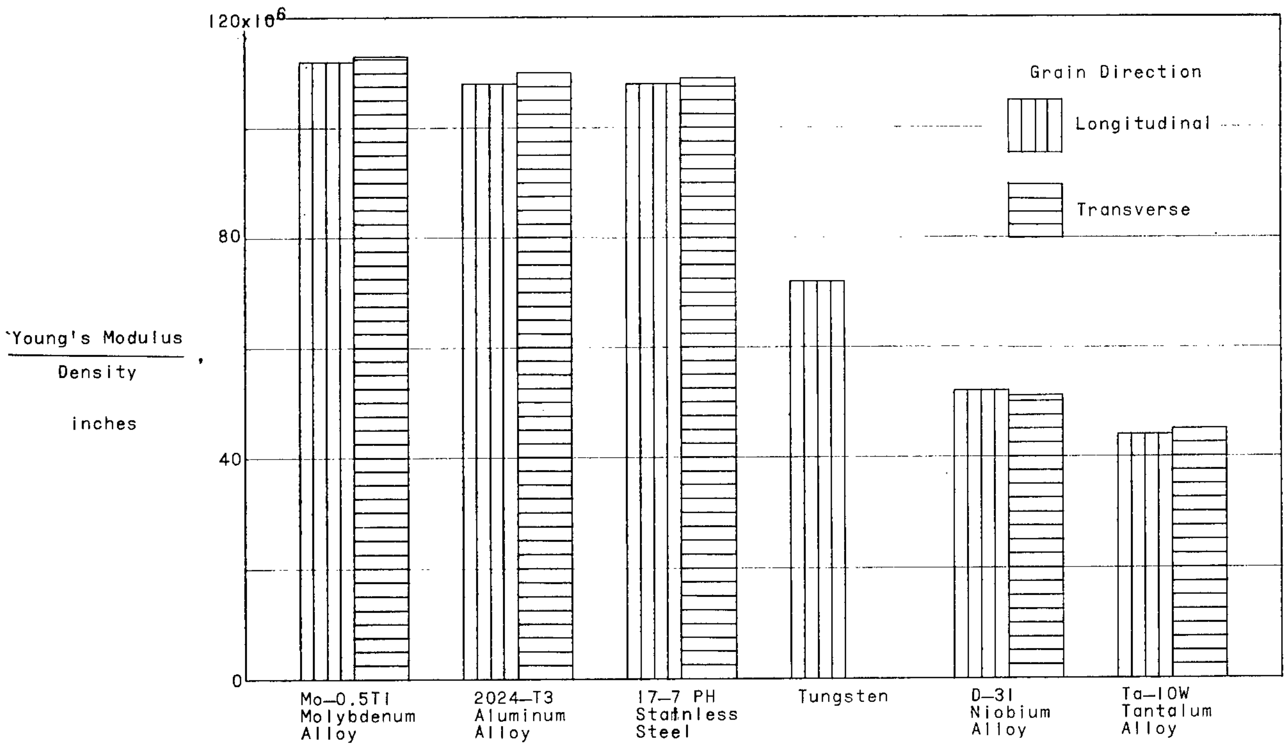


(a) Ultimate strength.



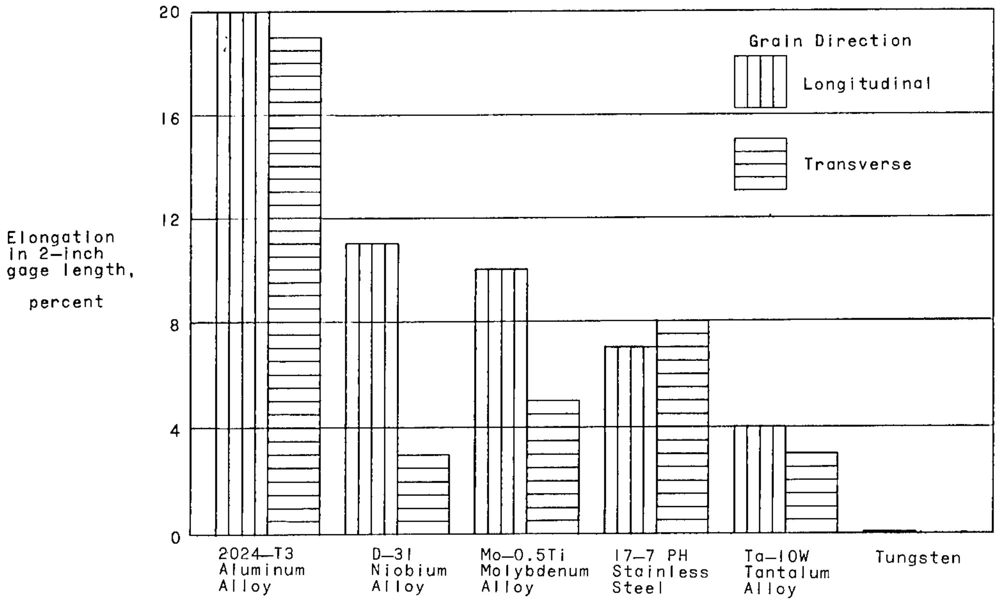
(b) 0.2-percent-offset yield stress.

Figure 4.- Comparison of various materials on a basis of stress-density ratio at room temperature.

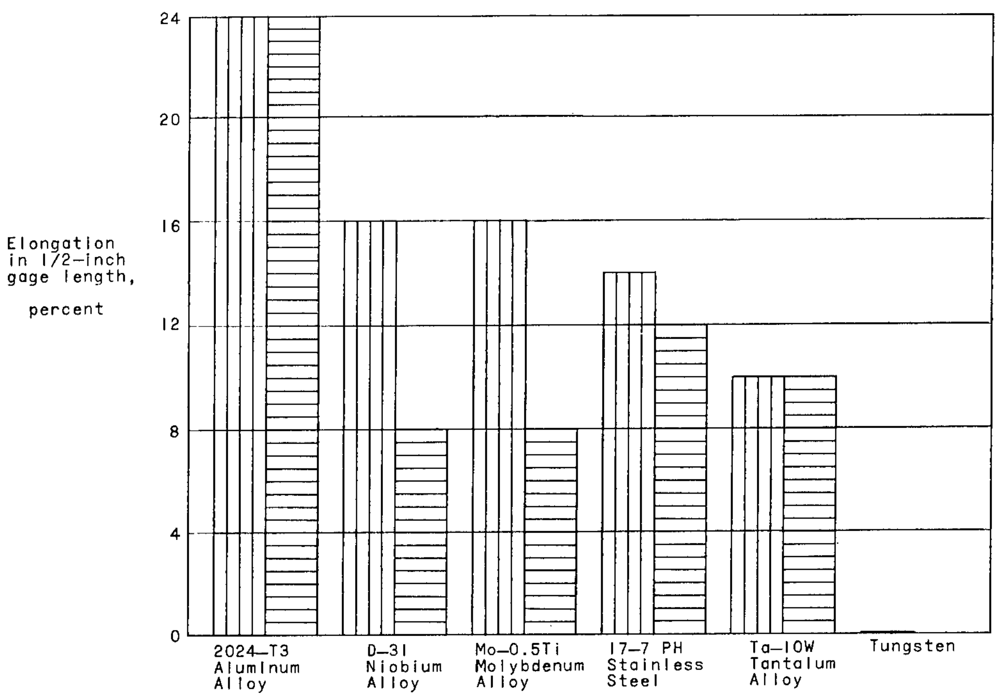


(c) Young's modulus.

Figure 4.- Concluded.



(a) 2-inch gage length.



(b) 1/2-inch gage length.

Figure 5.- Room-temperature tensile elongation of the various materials tested.

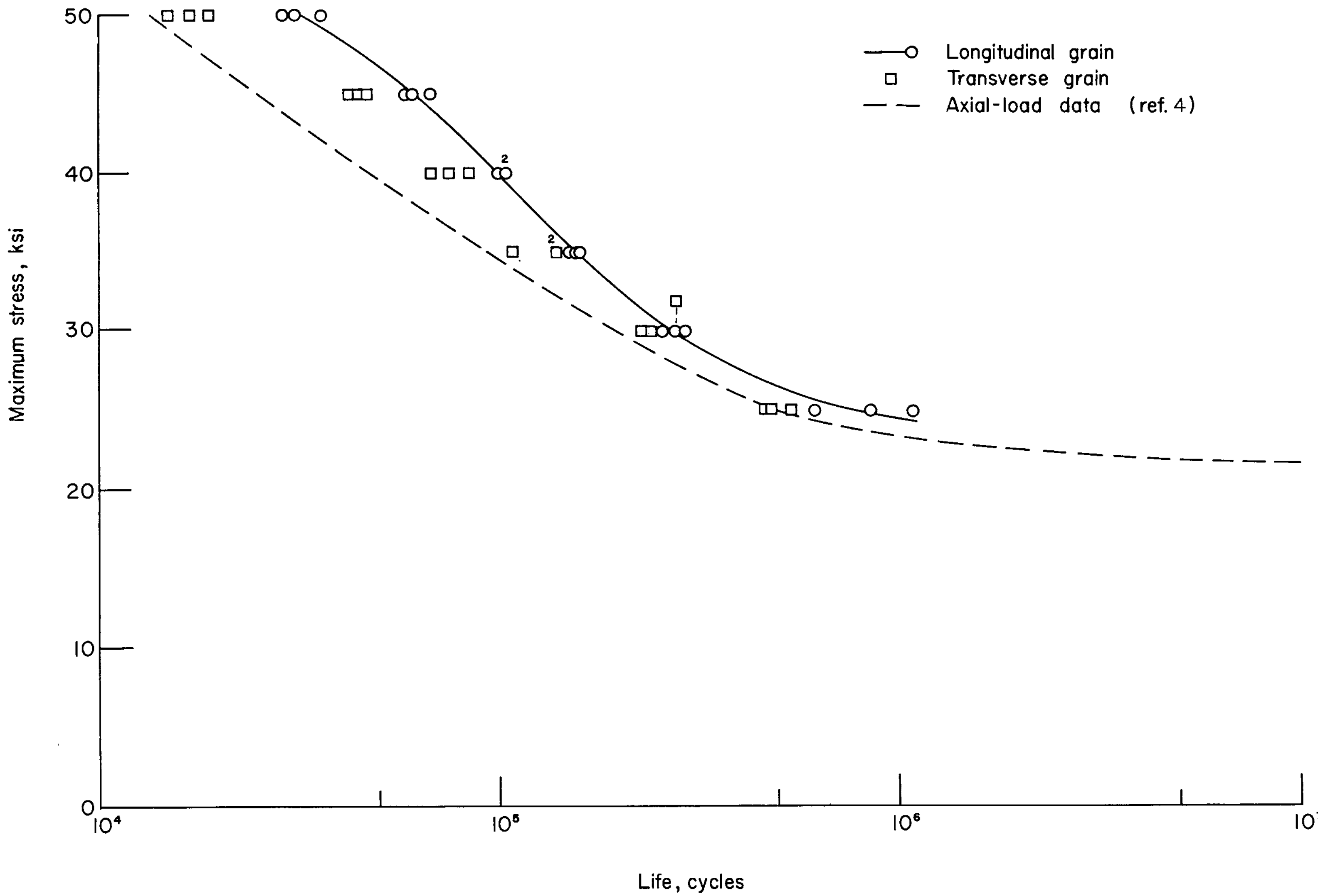


Figure 6.- Results of completely reversed sheet-bending fatigue tests on unnotched specimens of 2024-T3 aluminum alloy at room temperature.

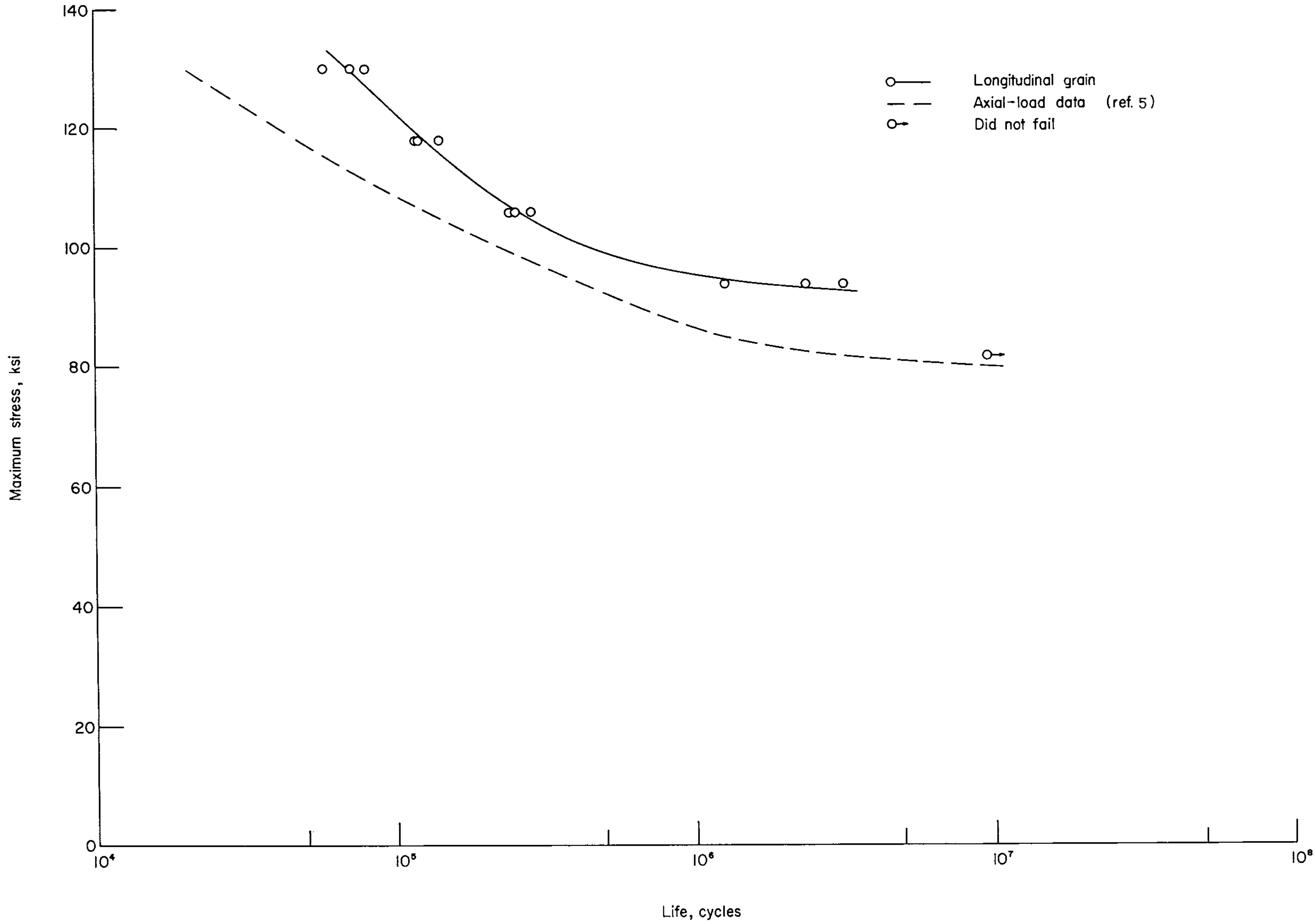


Figure 7.- Results of completely reversed sheet-bending fatigue tests on unnotched specimens of 17-7 PH stainless steel at room temperature.

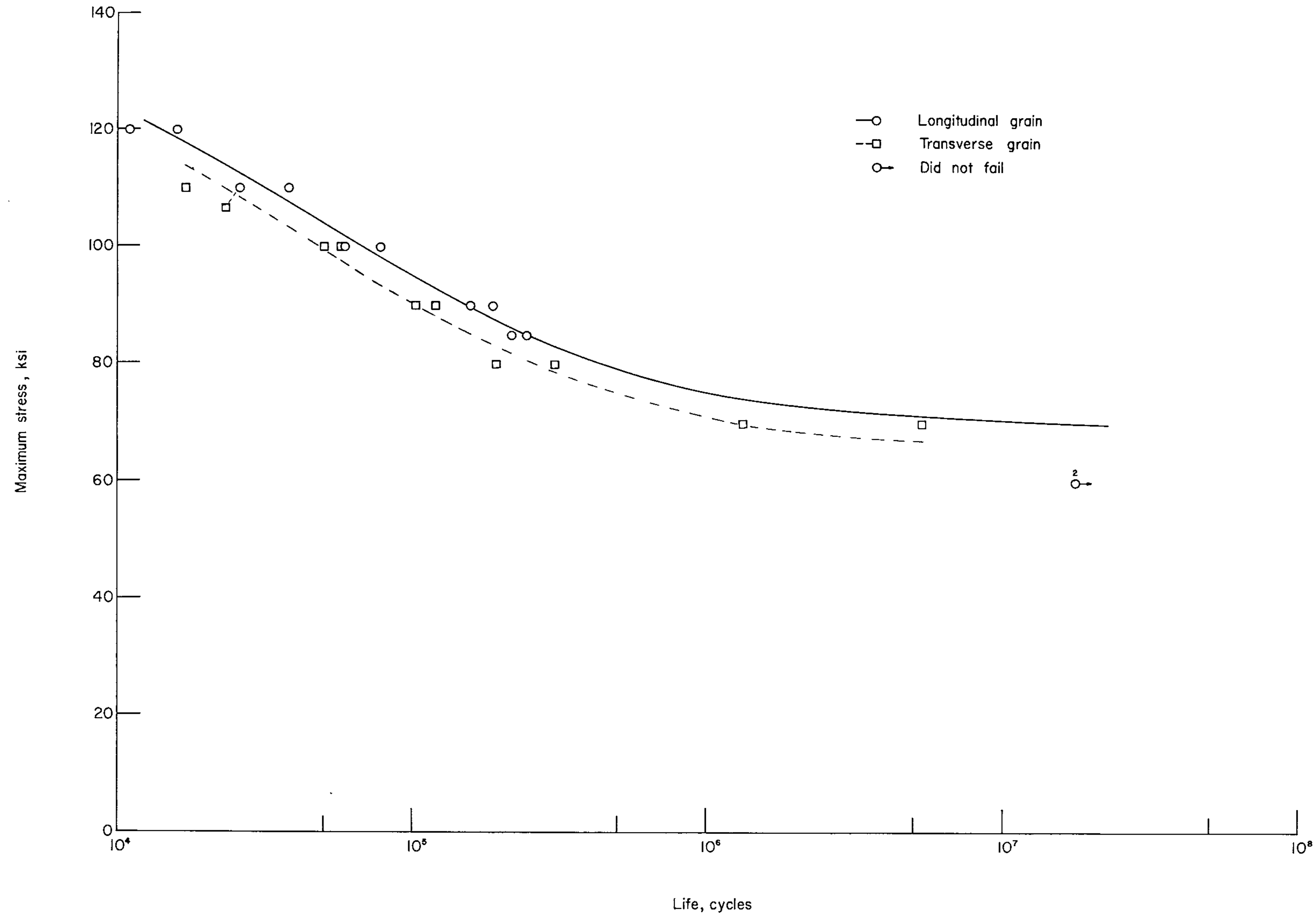


Figure 8.- Results of completely reversed sheet-bending fatigue tests on unnotched specimens of Ta-10W tantalum alloy at room temperature.

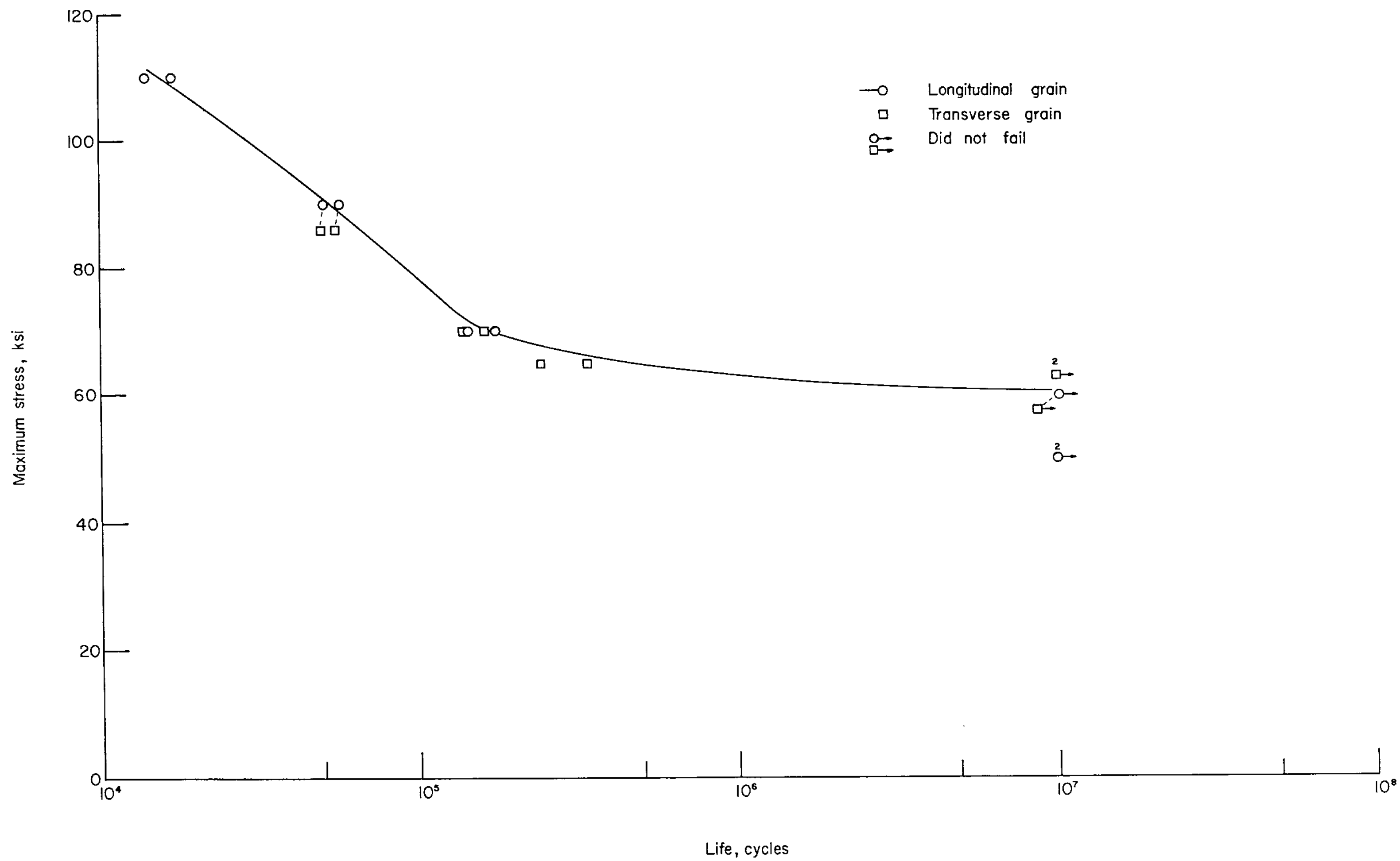


Figure 9.- Results of completely reversed sheet-bending fatigue tests on unnotched specimens of D-31 niobium alloy at room temperature.

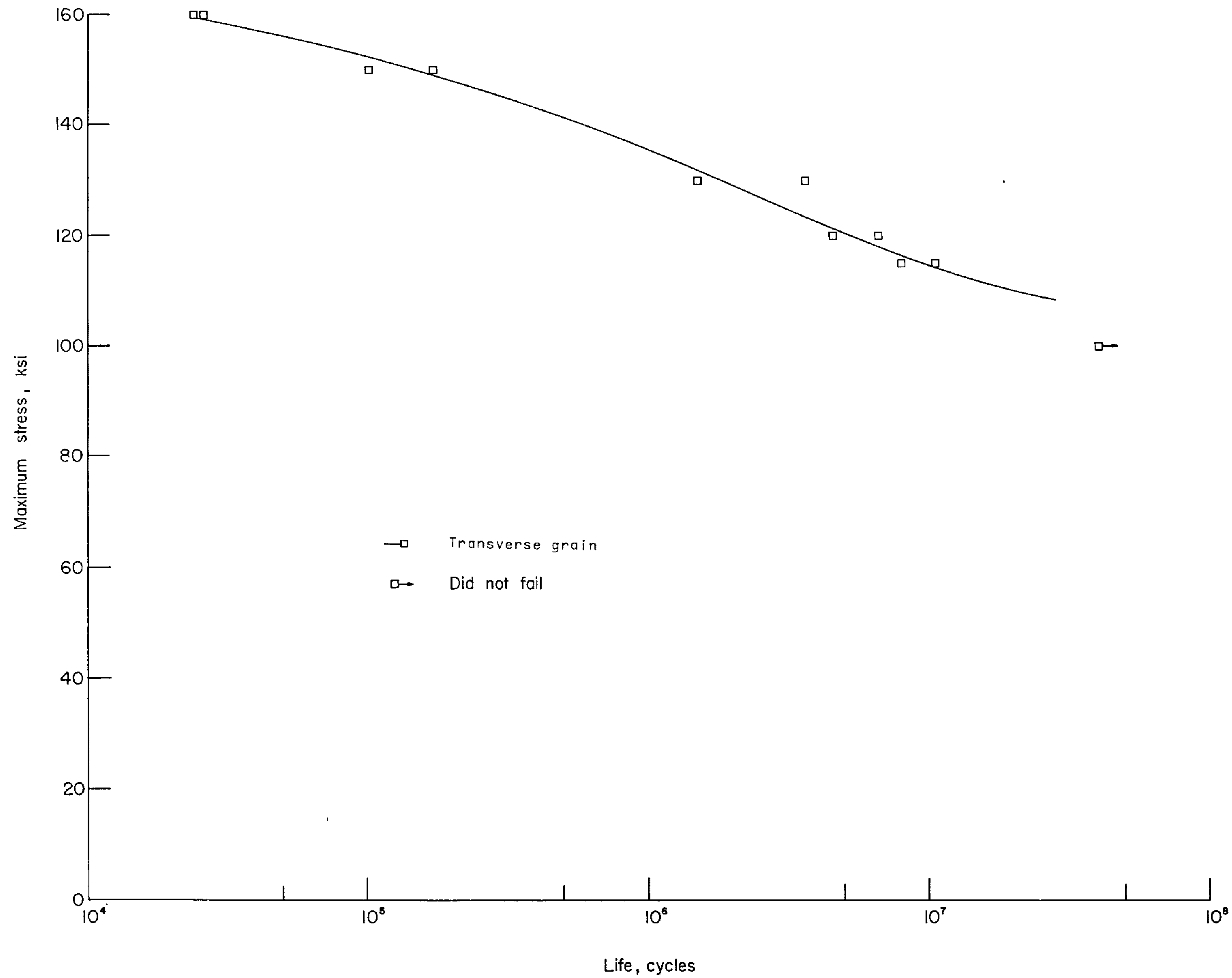


Figure 10.- Results of completely reversed sheet-bending fatigue tests on unnotched specimens of pure tungsten at room temperature.

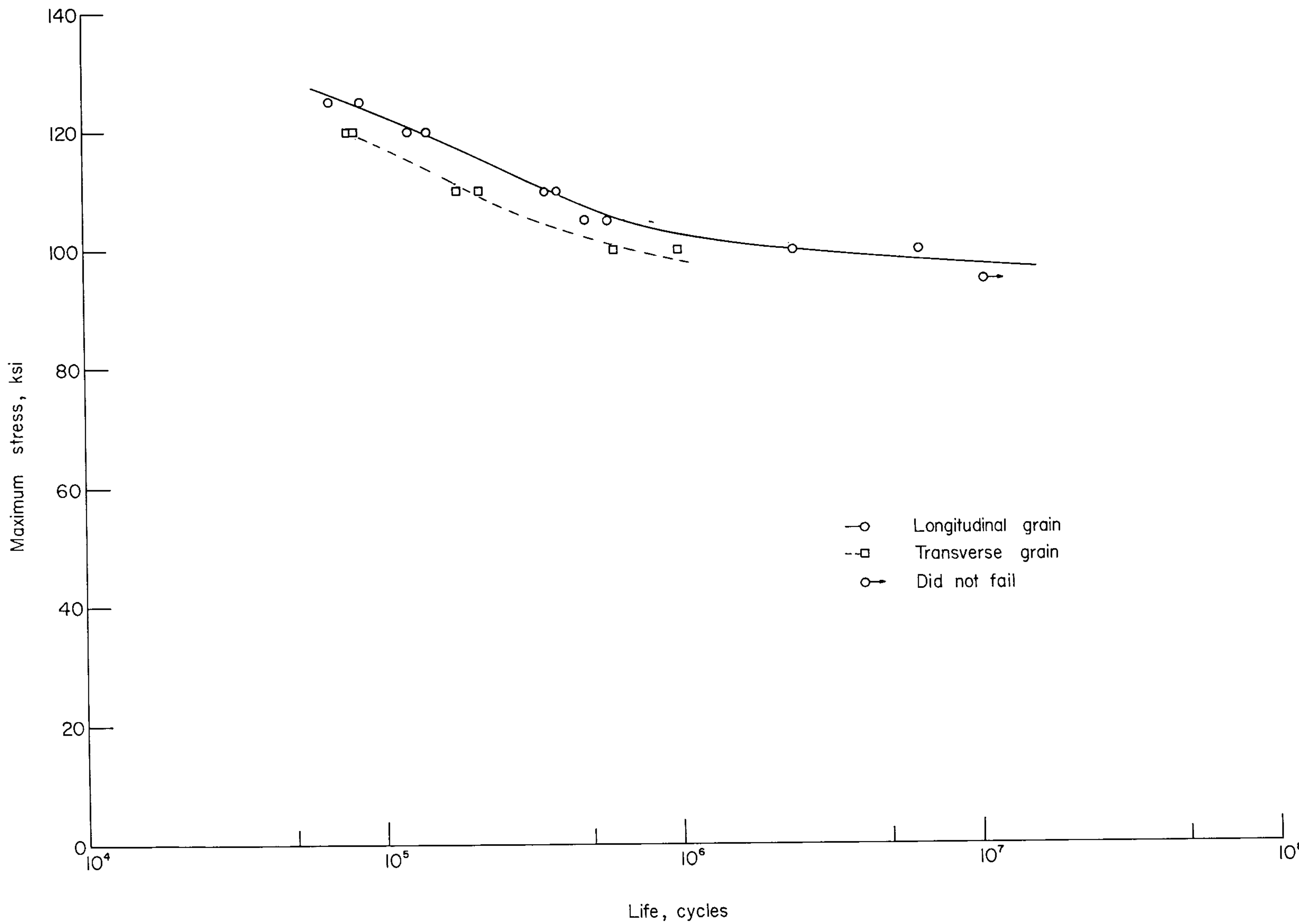


Figure 11.- Results of completely reversed sheet-bending fatigue tests on unnotched specimens of Mo-0.5Ti molybdenum alloy at room temperature.

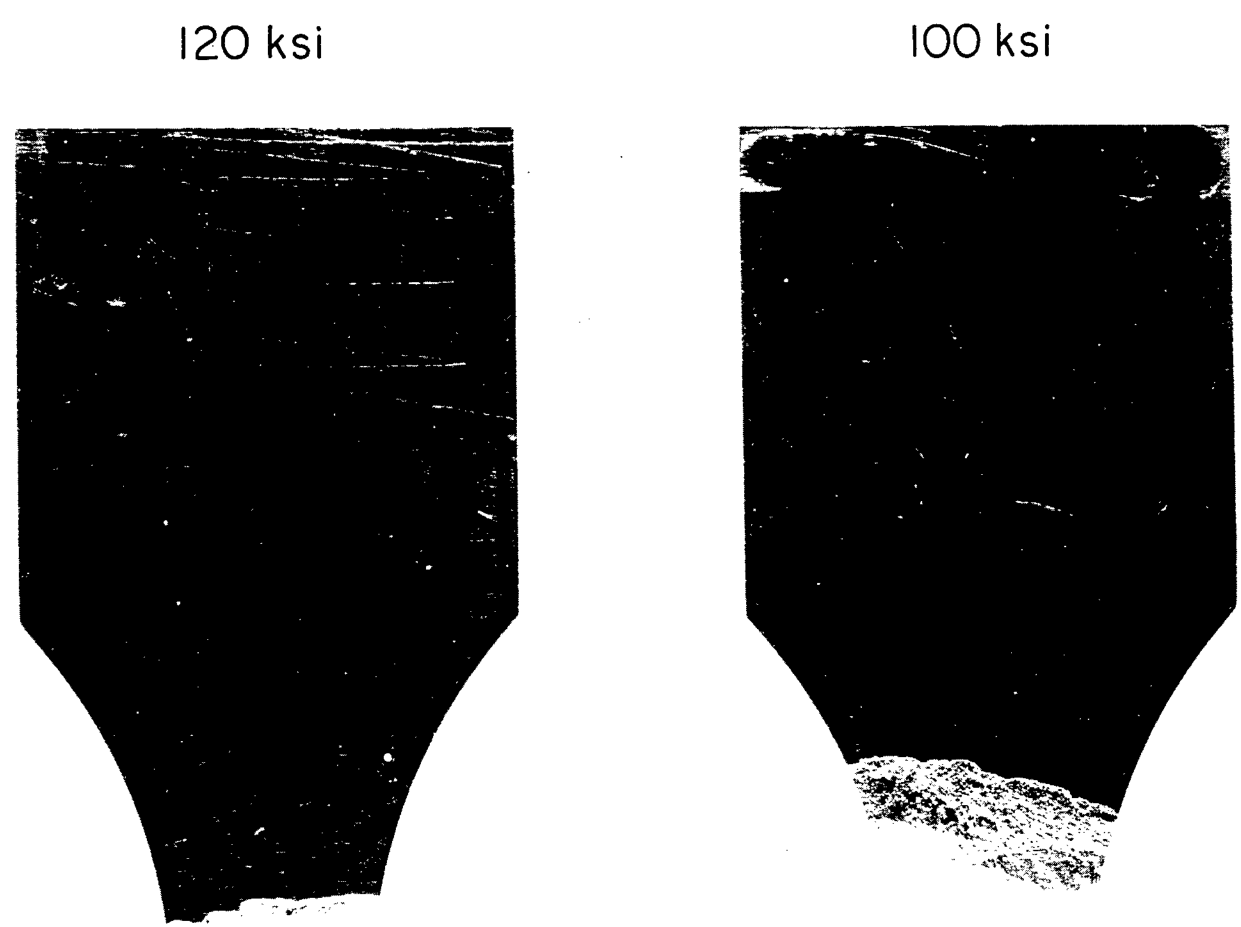


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Figure 12.- Fracture surface of Mo-0.5Ti molybdenum-alloy specimens after sheet-bending fatigue test.

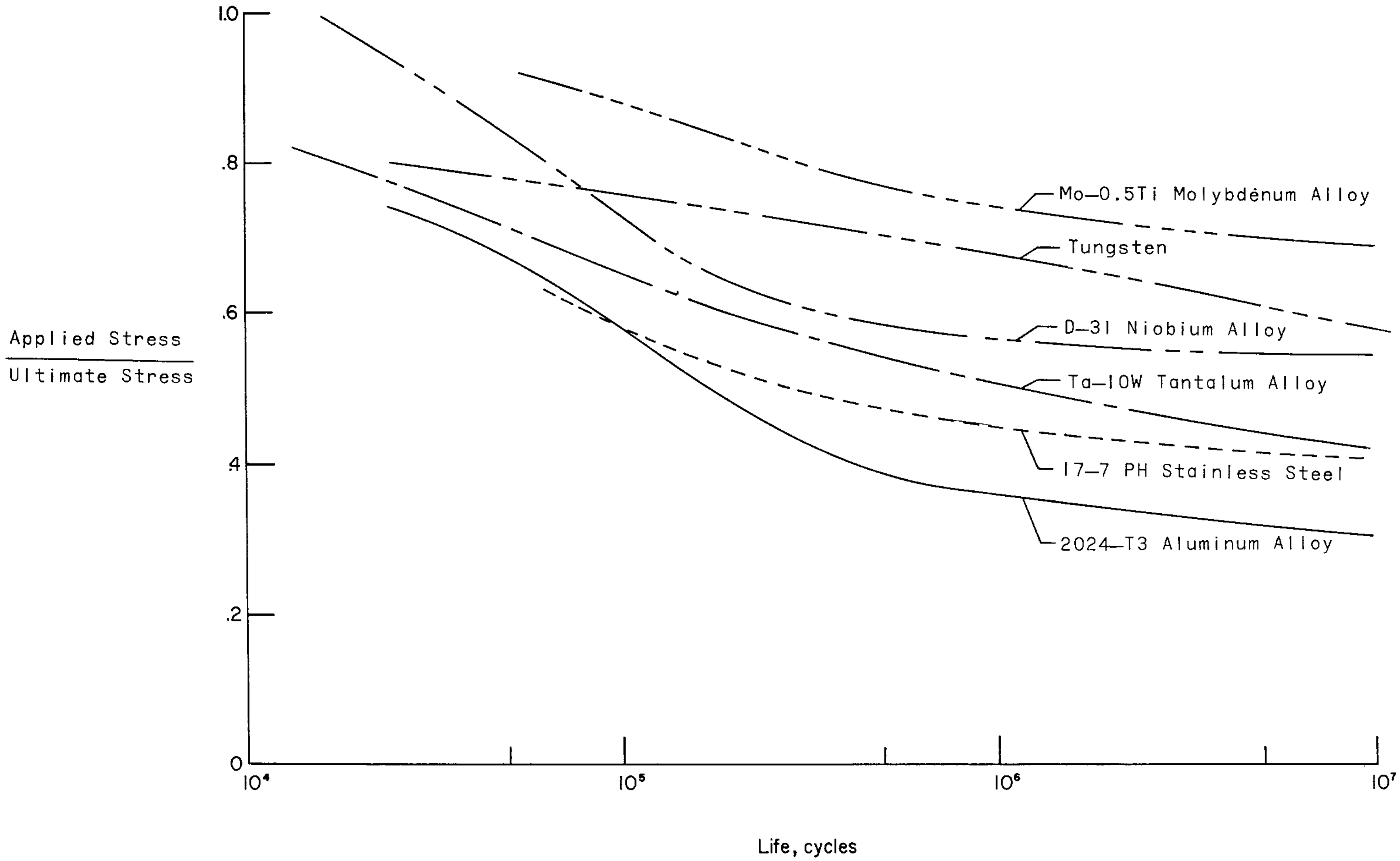

Figure 13.- Comparison of fatigue properties of unnotched sheet specimens on the basis of the applied-stress—ultimate-stress ratio.

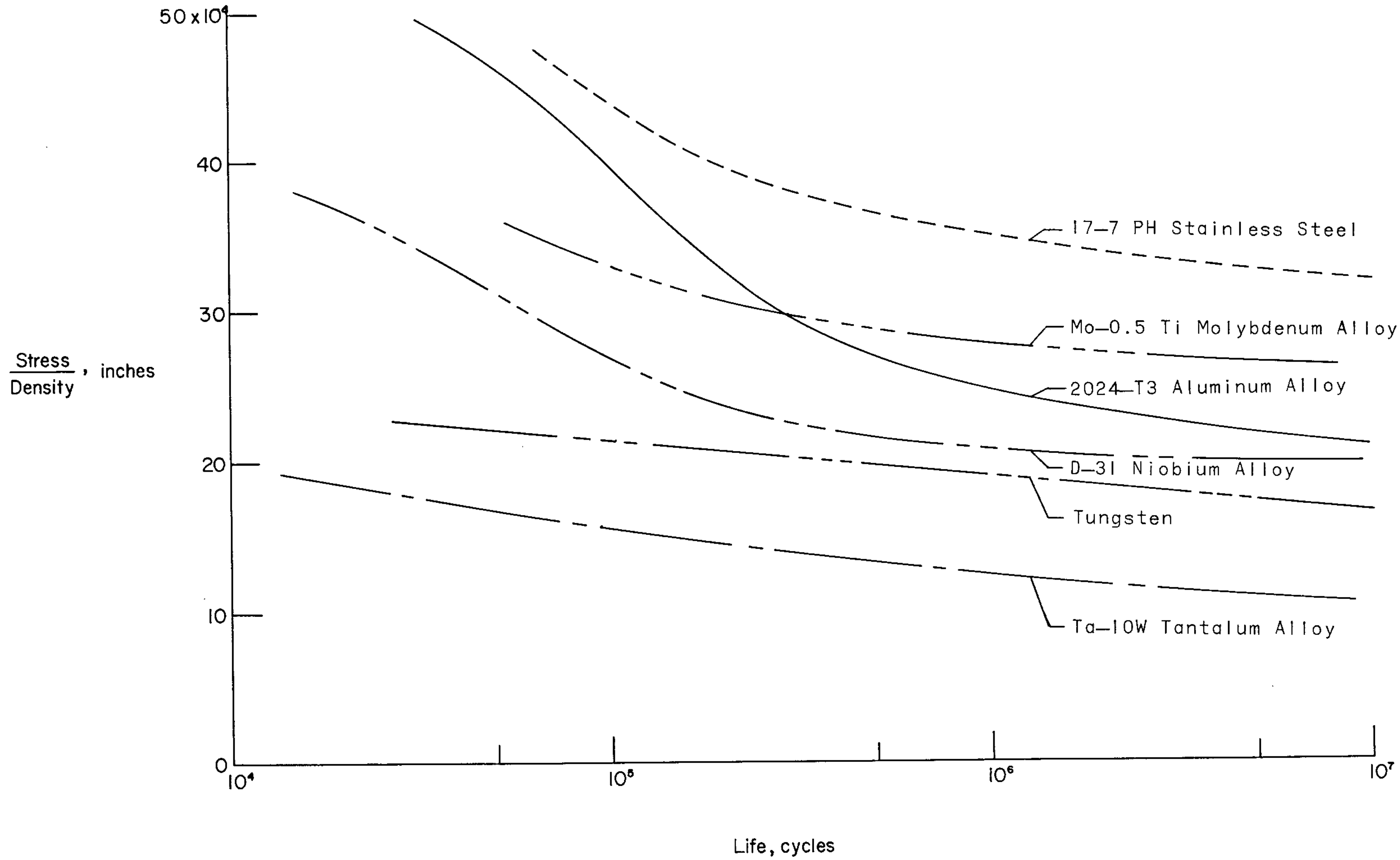

Figure 14.- Comparison of fatigue properties of unnotched sheet specimens on the basis of the stress-density ratio.

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