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THE EFFECT OF GRAIN SIZE ON THE MECHANICAL PROPERTIES OF TITANIUM AND ITS ALLOYS

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FOREWORD

This report was prepared by the Battelle Memorial Institute under USAF Contract No. AF 33(616)-412. The contract was initiated under Project No. 7351, "Metallic Materials", Task No. 73510, "Titanium Metal and Alloys", formerly RDO No. 615-11, "Titanium Metal and Alloys" and was administered under the direction of the Materials Laboratory, Directorate of Research, Wright Air Development Center with Lt Donald Wruck acting as project engineer.

The research at Battelle was conducted by F. C. Holden, Principal Metallurgist, H. R. Ogden, Assistant Chief, and Dr. R. I. Jaffee, Chief of the Nonferrous Physical Metallurgy Division. The fatigue tests were conducted by R. R. Spencer, Principal Mechanical Engineer, and W. S. Hyler, Principal Mechanical Engineer of the Applied Mechanics Division. Dr. B. W. Gonser was project advisor.

ABSTRACT

A study has been made of the effects of grain size on the mechanical properties of commercial-purity titanium, an alpha-beta-titanium alloy, and a metastable beta-titanium alloy. The mechanical properties studied in this research were tensile, notched-tensile, hardness, bend, impact, and fatigue endurance.

For unalloyed titanium, grain size or shape has only a minor effect on the mechanical properties. Yield strengths are decreased slightly for specimens annealed in the alpha-beta range, because of the partition of impurities to the nonmatrix alpha. Impact resistance is highest for the smallest alpha grain sizes. Bend ductility and tensile ductility are excellent for all grain sizes. The fatigue endurance limit at 10^7 cycles is 79 per cent of ultimate strength for unnotched and 42 per cent for notched specimens.

The grain size of the metastable beta alloy (Ti-7.5Cr-7.5Mo) also has only a minor effect on the mechanical properties so long as the alloy is single phase. The presence of alpha in the structure lowered the bend ductility, tensile ductility, and impact resistance. Notched fatigue properties appear to be relatively unaffected by changes in grain size or microstructural condition. The plates of alpha phase in the beta matrix act as stress raisers similar to notches and lower the unnotched endurance limit.

The alpha-beta alloy (Ti-2.5Cr-2.5Mo) was tested in the stabilized condition so that the only variables would be grain size and grain shape. Only minor changes in properties occurred as a result of changing the alpha-beta grain size. Strengths were unaffected by changing grain shape, although the equiaxed alpha-beta specimens had higher tensile ductilities and impact resistance than the acicular alpha-beta specimens. The fatigue endurance limits generally were unaffected by grain size or shape. The unnotched fatigue strength was 34 per cent of the ultimate tensile strength, and the notched fatigue strength was 20 per cent of the ultimate tensile strength.

Vacuum annealing to remove hydrogen had little effect on the properties because these alloys contained only 30 to 60 ppm hydrogen originally.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

M. R. WHITMORE
Technical Director
Materials Laboratory
Directorate of Research

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THE EFFECT OF GRAIN SIZE ON THE MECHANICAL PROPERTIES OF TITANIUM AND ITS ALLOYS

INTRODUCTION

This report is a Summary Report on a study of the effect of grain size on the mechanical properties of titanium and its alloys. It covers the period from March 18, 1953, through June 30, 1954.

The purpose of this research was to determine how variations of grain size and shape would affect the mechanical properties of titanium and of representative titanium-base alloys. The mechanical properties of interest were those that describe fabrication and performance capabilities and that also may be affected by grain size. These include tensile properties, hardness, bend properties, flow properties, impact properties, and fatigue endurance limits.

For convenience and ease in understanding, the data in the body of this report are presented chiefly by the use of graphs to supplement the text. Complete tabulated data and flow curves are given in appendices.

EXPERIMENTAL PROCEDURES

Preparation of Alloys

Melting Stock

Commercial-purity sponge titanium was purchased from Du Pont for use in this study. The manufacturer's analysis showed the following percentages of impurities: iron, 0.17; nitrogen, 0.018; chlorine, 0.03. The hardness of the fusion-test button was reported as 126 Bhn.

This material was screened to eliminate all particles passing through a 16-mesh screen, and iron particles were removed by use of a magnet. The titanium in this condition was found satisfactory for the melting of small (1/2-pound) ingots. Excessive spatter, however, took place during the melting of larger ingots. This was attributed to the presence of entrapped gases and residual magnesium chloride in the sponge titanium. These factors were eliminated after leaching and degassing according to the following procedure:

(1) Leach in fresh methanol for three 72-hour periods.

(2) Dry at room temperature, then oven dry for 8 hours at 300 F.

(3) Degas under vacuum at room temperature and 150, 400, and 1250 F.

Although the melting characteristics were improved by this treatment, sufficient contaminants were introduced to raise the hardness level from about 126 to 150 Bhn. This corresponds to sponge titanium of average quality.

Alloy additions of chromium and molybdenum were made from high-purity material. Electrolytic chromium and ether-washed granulated molybdenum were thoroughly mixed with the titanium for charging into the melting furnace.

Alloy Compositions

For the study of the effects of grain size on mechanical properties, three basic types of titanium alloy were used. These included (1) an alpha alloy (commercial titanium), (2) a metastable beta alloy (Ti-7.5Cr-7.5Mo), and (3) an alpha-beta alloy (Ti-2.5Cr-2.5Mo). In addition, some preliminary studies were made on a second alpha-beta alloy (Ti-5.0Cr-5.0Mo).

Analyses of the alloys used in the detailed studies are shown below:

Nominal Composition	Analyzed Composition, per cent						
	Cr	Mo	N	C	Fe	O	H (in ppm)
Commercial titanium	--	--	0.014	0.03	0.29	0.10	31
Ti-7.5Cr-7.5Mo	7.60	6.66	0.026	0.03	0.32	0.13	44
Ti-2.5Cr-2.5Mo	2.32	2.58	0.015	0.04	0.27	0.13	60

Melting Procedures

All melting was done under a positive pressure of argon. The ingots were arc melted in cold-wall copper crucibles, with an inert tungsten electrode. To reduce segregation, the alloys containing chromium and molybdenum additions were melted three times.

The preliminary 1/2-pound ingots were approximately 2 inches in diameter and 1 inch thick. This size ingot is remelted conveniently by inverting the ingot in a round-bottom crucible and melting through the ingot.

This method has the advantage that little or no contamination is introduced by the process.

The 30-pound ingots were approximately 4 inches in diameter and 24 inches long. Figure 1 is a schematic diagram of the arc-melting furnace. These ingots were scalped and machined into chips on a shaper. The chips were then degreased in naphtha, washed in a hot detergent solution, rinsed, and dried. After remelting, the resulting ingot was forged, rolled to 100-mil sheet, mechanically descaled, pickled in a 10 per cent HF-30 per cent HNO_3 solution, and sheared into small pieces. These were degreased by the same procedure as used for the chips, and remelted into the final ingot.

Both the reduction procedures described have the effect of introducing some contamination into the melting stock. This was reflected in the hardness measurements, which showed a progressive increase (about 10 Bhn) with each remelt. The final ingots, however, were found to be of uniform composition, from microstructural observations and hardness measurements.

In spite of the triple-melting procedure, microstructures of the Ti-7.5Cr-7.5Mo alloy showed small particles of unmelted molybdenum. These are uniformly distributed and probably do not affect the properties of the alloy significantly.

Fabrication

Material for test specimens was prepared from the ingots by forging, rolling, and swaging operations. All fabrication and heating was done in air. The temperatures used are given below:

Alloy Composition	Forging Temperature, F	Rolling Temperature, F	Swaging Temperature, F
Commercial titanium	1600	1400	1300
Ti-7.5Cr-7.5Mo alloy	1800 to 1600[a]	1400	1500 to 1550
Ti-2.5Cr-2.5Mo alloy	1600	1400	1400
Ti-5.0Cr-5.0Mo alloy	1600	1400	--

(a) Forging finished at 1600 F.

The material from the 1/2-pound ingots was rolled to 40-mil sheet and mechanically descaled. Tensile and bend-test specimens were sheared. For the full-scale ingots, about a quarter of each forged billet was rolled to 1/16-inch sheet for tensile and bend-test specimens. The remaining

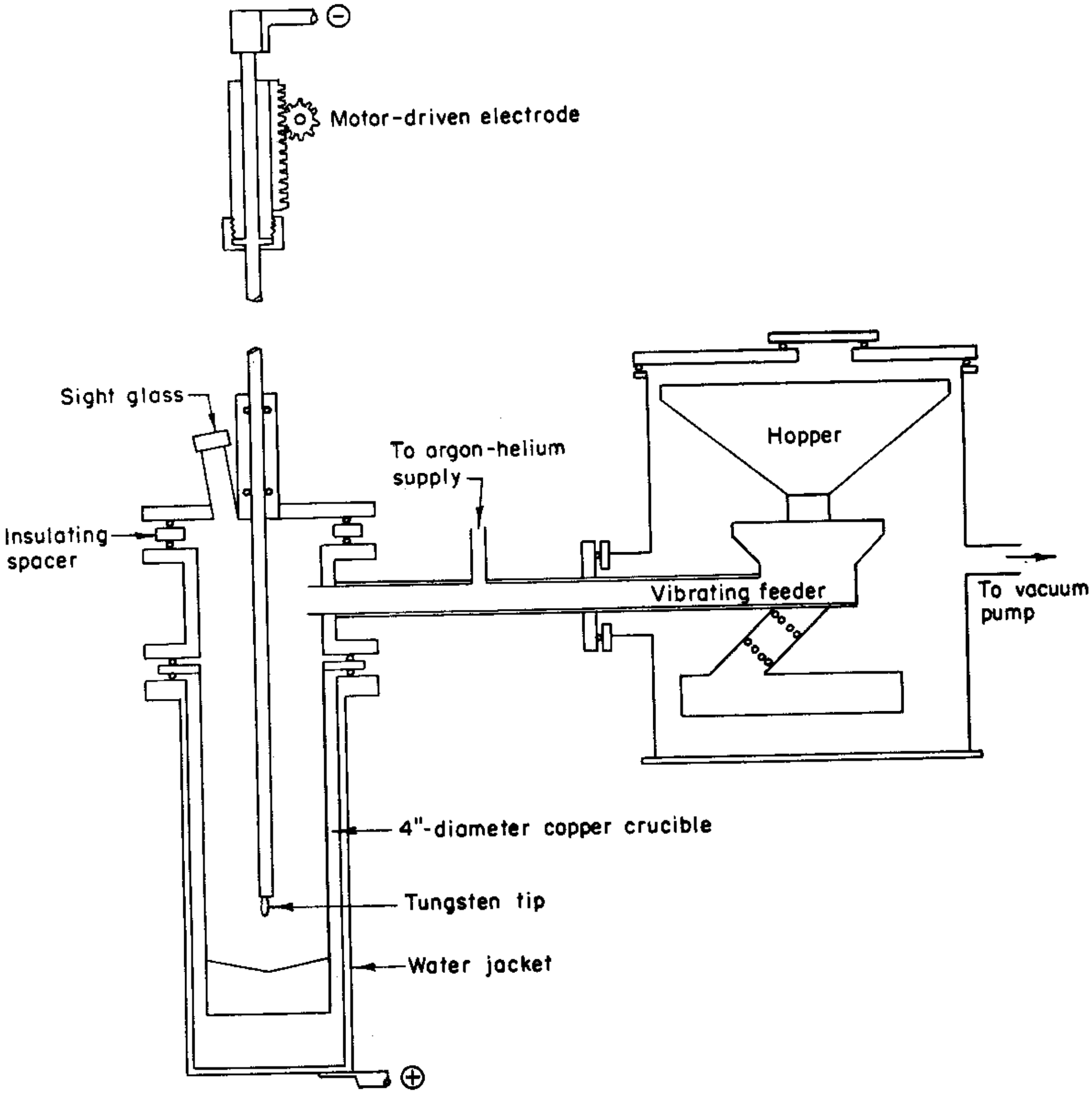

FIGURE I. SCHEMATIC VIEW OF ARC-MELTING FURNACE

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material was rolled to 5/8-inch-diameter rod and hot swaged to 0.302-inch-diameter rod. Tensile, notched tensile, micro impact, and fatigue specimens were cut from the 0.302-inch-diameter rod. V-notch Charpy impact test specimens were made from the 5/8-inch-diameter rod.

Before heat treatment, the fabricated sections were mechanically descaled and pickled in a 10 per cent HF-30 per cent HNO_3 solution to remove the oxide.

Heat Treatments

Heat treatments were done in potentiometer-controlled electric furnaces. Some preliminary heat treatments were made to determine the conditions under which significant contamination took place in an air atmosphere. From these tests, it was decided that anneals longer than 1 hour at 750 C or above should be done in a protective atmosphere.

A protective atmosphere was established by placing the specimens in a Vycor capsule under a partial pressure of argon. Contact with the Vycor was prevented by wrapping the specimens with tungsten wire. Specimens were quenched by breaking the tube in air to allow them to drop into water This method permits a rapid quench with negligible contamination. The protective tube was left intact until room temperature was reached, when the specimens were cooled in the furnace or in air.

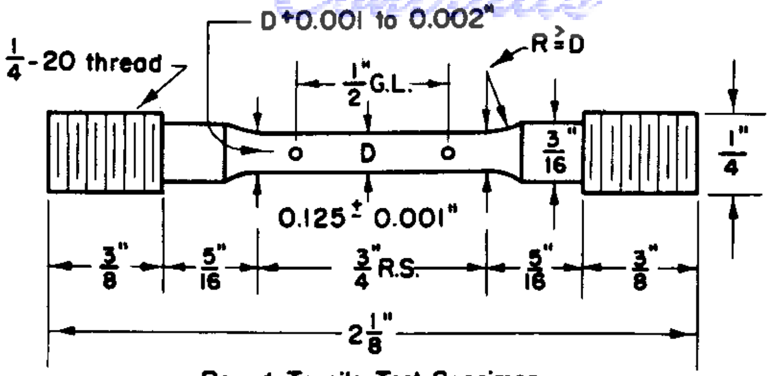
Some specimens were vacuum annealed to remove hydrogen. These treatments were done in a Globar-element tube furnace at 1600 F, under a limiting cold vacuum of 10^{-4} mm of mercury. The specimens were annealed approximately 24 hours and furnace cooled to room temperature.

Mechanical Testing

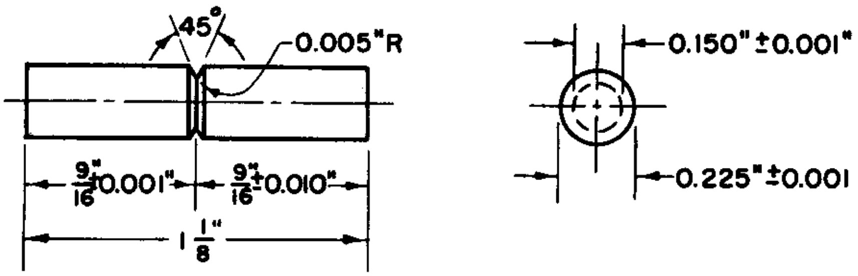
Tensile Testing

The testing program was designed to provide as much information as could reasonably be obtained from the available material. Three types of tensile-test specimens were used, and duplicate specimens were tested in each microstructural condition. Specifications for the tensile-test specimens are given in Figure 2.

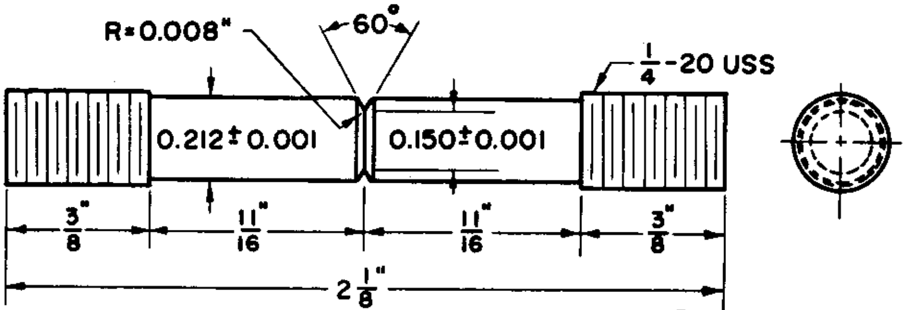
Strain readings on the sheet tensile specimens were obtained by the use of electrical-resistance gages (SR-4, Type A-1) to the gage limit and then by divider measurements up to the maximum load. In addition to the 1-inch gage marks in the reduced section, a set of auxiliary 2-inch gage marks was punched in the shoulders of the specimens. A correlation



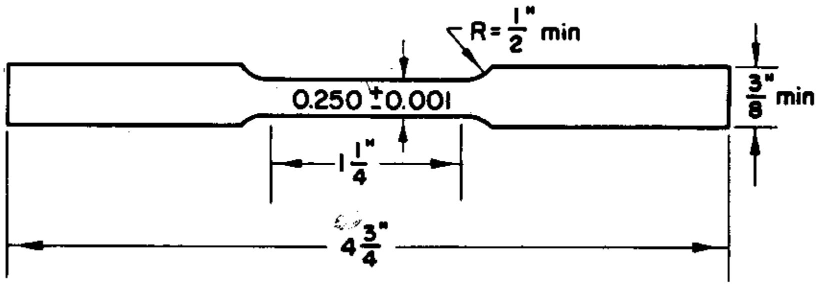
Round Tensile-Test Specimen



Micro Impact-Test Specimen



Notched Tensile-Test Specimen $K_t = 3$



Sheet Tensile-Test Specimen

FIGURE 2. SPECIFICATIONS FOR TEST SPECIMENS

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established between final elongations of the 1-inch and the 2-inch gage lengths was used to estimate elongations when fractures occurred outside the 1-inch gage length. Data obtained from divider measurements of the 1-inch gage marks in 0.01-inch increments were used to obtain the true-stress true-strain data, which are presented in the form of flow curves. Loads were measured on a conventional Baldwin-Southwark Universal Testing Machine, with a uniform crosshead rate of 0.02 inch per minute.

Tension tests also were made by using duplicate specimens with a round cross section. Substandard specimens were employed in order to conserve material. Specifications for these specimens, as taken from the 1948 Edition of the ASM Metals Handbook, are presented in Figure 2. Extensions were obtained by the use of electrical-resistance strain gages (SR-4, Type A-7) to the gage limit, and then by a lever-type extensometer set in 1/2-inch gage marks to the limit of uniform elongation. Auxiliary elongation measurements made from the shoulder distances were used to obtain estimated elongations for those specimens in which the fracture occurred at or outside the gage marks. True-stress true-strain data were computed from the elongations measured up to the point of maximum load. These data are presented in the form of flow curves. All tests were made on Baldwin-Southwark Universal Testing Machines, with a uniform crosshead rate of 0.005 inch per minute.

The plastic behavior of materials can be studied by the use of flow curves. It has been shown that, when the true stress is plotted against the true strain, the resulting curve for many materials can be expressed as an exponential equation of the form $\sigma = B\delta^n$, in which B and n are constants, and σ and δ represent, respectively, true stress and true strain. If, instead, the logarithms of σ and δ are plotted, the result should be a straight line whose slope is n and whose intercept at $\delta = 1.0$ is B. For titanium and many of its alloys, however, the resulting curve is not a straight line, but either is a sigmoidal curve or is composed of two straight-line segments of different slopes.

In this work, the values of B and n reported are determined by extrapolation of a straight line passing through the point of maximum load. The actual curves are included in Appendix B for reference purposes.

The notch sensitivity of the three titanium alloys was studied by the use of duplicate notched tensile specimens in each test condition. The specimens used are shown in Figure 2. Profiles before and after testing were traced on a 50X Shadowgraph, and reductions in area were determined from these data. These specimens were tested on Baldwin-Southwark Universal Testing machines at a uniform crosshead rate of 0.005 inch per minute.

Impact Testing

The effects of grain size and other structural variables on notched-bar impact resistance were studied. Substandard impact-test specimens, as shown in Figure 2, were used for all the conditions investigated. In addition, conventional V-notch Charpy impact test specimens were tested in one condition for each alloy to determine the correlation between the test specimens.

The micro impact-test specimens were tested in a Tinius Olsen Testing Machine with an impact velocity of 11.37 feet per second and a total available energy of 200 inch-pounds. The specimens were placed in a steel adapter block and impact loaded as a cantilever beam. Duplicate specimens were used for each testing temperature. The effects of testing temperature on impact-energy absorption were determined over a temperature range of -196 C to 400 C.

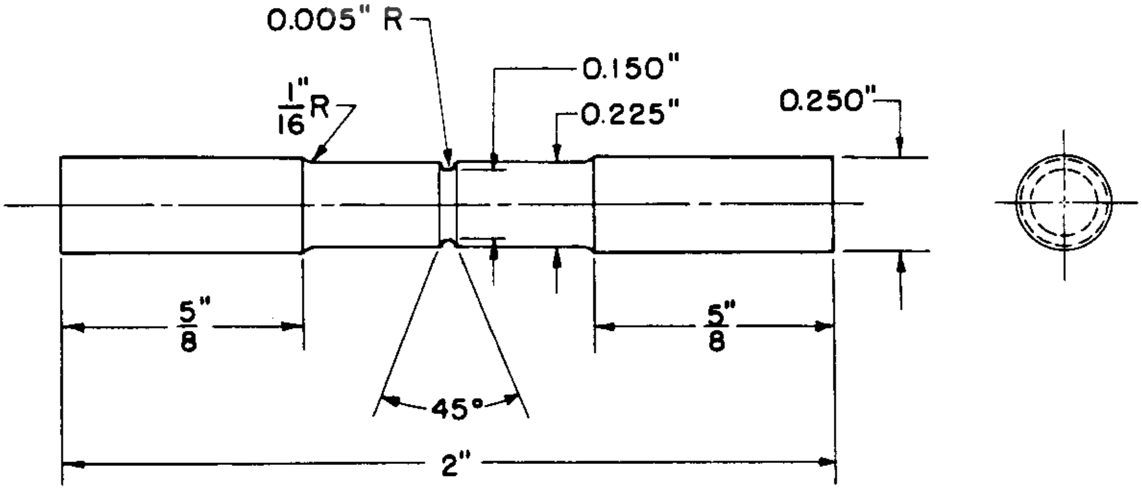
An Amsler machine was used for testing the V-notch Charpy impact specimens. The initial height of the pendulum may be adjusted to provide a range of impact velocities. Most of these tests were made at an impact velocity of 11.62 feet per second, which provides a total available energy of 70.0 foot-pounds. For those specimens showing high resistance to impact, it was necessary to increase the impact velocity and total energy by increasing the initial height of the pendulum. The effect of impact velocity on energy absorption was found to be small.

Bend Testing

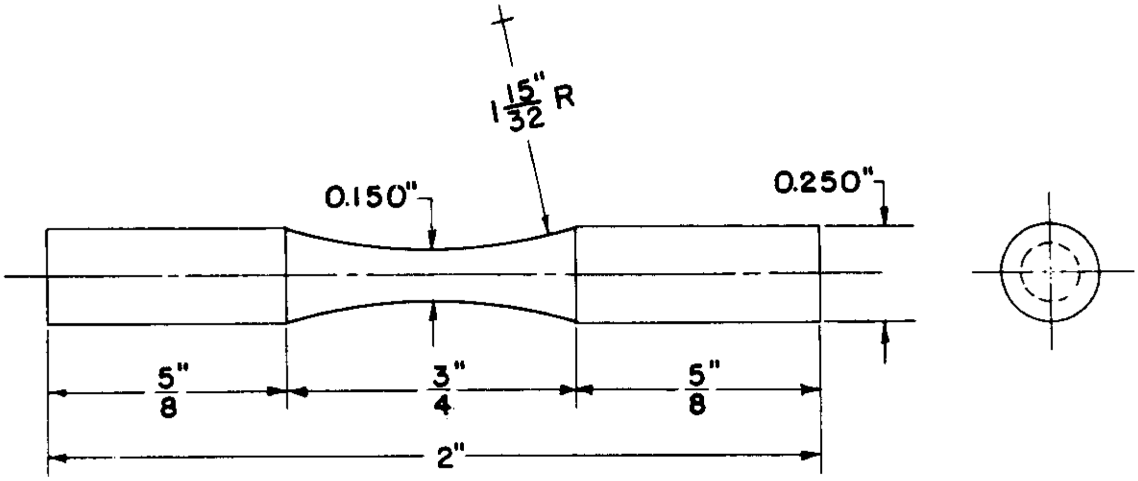
The bend ductility of titanium sheet was measured by use of a progressive-bend test. Tests were conducted in quadruplicate on specimens cut transverse and longitudinal with respect to the rolling direction. The test specimens used were approximately 1/16 x 1 x 3 inches. Bend tests were conducted on a laboratory press with 75-degree bend dies. Specimens were bent progressively over decreasing radii until a visible crack appeared. The results are presented (in T units) as the ratio of the radius of the last good die to the specimen thickness.

Fatigue Testing

The effects of grain size and other structural variables on resistance to alternating stresses were studied by means of rotating-beam fatigue specimens. Tests were conducted under a limited number of conditions with notched and unnotched test specimens. Specifications for the test specimens are presented in Figure 3. Tests were made on Krouse cantilever-type rotating-beam machines, at a rotational speed of 8,000 to 10,000 rpm. Approximately 20 specimens were used in the determination of the endurance limit. Specimens were machined and hand polished before



a. Rotating-beam notched fatigue specimen, $K_t = 3$



b. Rotating-beam, unnotched fatigue specimen

FIGURE 3. SPECIFICATIONS FOR ROTATING-BEAM FATIGUE SPECIMENS

A-9117

testing. Contrary to the results of other investigators(1)*, no heating of the specimens was apparent during these tests.

Hardness Measurements

Vickers hardness measurements were made on samples cut from bend- and tension-test specimens. Each value reported is the average of five impressions. The 5-kilogram load was used in all cases.

Metallographic Methods

Specimens to be examined metallographically were mounted in a cold-setting plastic to eliminate the possible aging effects from mounting in bakelite. Surfaces were hand ground through 600-grit paper. The first polish was done on a high-speed wheel by using a slurry of alumina and chromic acid. Polishing was finished on a slow-speed wheel charged with alumina. The surfaces were etched with either a 1-1/2 per cent HF-3-1/2 per cent HNO_3 or a 1 per cent HF etch. The latter is useful for alpha-beta alloys, since it stains the alpha phase.

Grain-Size Determinations

Because grain-size effects were of primary interest in this study, the effects of annealing time and temperature on grain size were investigated. Microstructure specimens were annealed at temperatures in the range of interest and water quenched after various times. Grain-size measurements were made by counting the grains contained in a specified area (Jefferies' Method). At least two fields were measured on each specimen. The results of these measurements are presented in later sections of this report. The heat treatments used in the alloy testing program were selected on the basis of these grain-size determinations.

PRELIMINARY ALLOY WORK

Work was done on five 1/2-pound alloys to establish heat-treatment and microstructural conditions for the full-scale program. Nominal compositions of the alloys used were as follows: commercial titanium, a Ti-2.5Cr-2.5Mo alloy, a Ti-5.0Cr-5.0Mo alloy, and two Ti-7.5Cr-7.5Mo alloys.

These alloys were forged at 1600 to 1800 F and rolled to 40-mil sheet at 1400 F. The first series of tension and bend tests was made on specimens annealed in air. The results are given in Table 1, and flow curves are included in Appendix B. Examination of these data shows that serious contamination is encountered when titanium is annealed in air at temperatures above about 800 C. This is evident from the large loss of ductility, particularly in the commercial titanium. Also, the appearance of an alpha case in the microstructures of the alpha-beta and beta alloys is evidence of oxygen and nitrogen contamination.

The effect of composition on the mechanical properties of these alloys is shown in the curves of Figure 4. Maximum strength and hardness occur at the Ti-5.0Cr-5.0Mo composition. The lowest ductilities are also obtained at this composition. The embrittlement at 900 C, which is apparent in both tensile and bend ductility, is caused probably by both beta instability and contamination during the air anneal. For the Ti-5.0Cr-5.0Mo alloy, embrittlement was severe enough to produce erratic tensile behavior.

Preliminary data on the effects of grain size on mechanical behavior were also obtained from these alloys. Heat treatments were made under a protective atmosphere and were designed to produce a number of grain sizes and other microstructural variations. The results of these tests are presented in Table 2. Flow curves are included in Appendix B.

The effects of alpha-grain size and shape on the mechanical properties of commercial titanium are slight. The specimens with transformed-beta structures have higher yield strengths than those with equiaxed-alpha structures. Tensile and bend ductilities, however, appear independent of microstructure. Both transverse and longitudinal bend-test specimens are very ductile (0 T) in all conditions tested. Results for the metastable beta alloy (Ti-7.5Cr-7.5Mo) are not consistent. The smaller grain size results in higher strength values, but ductility data are inconclusive. Bend ductility, determined for the 0.20-mm grain size, is good (0 T) in both transverse and longitudinal directions.

The Ti-2.5Cr-2.5Mo alpha-beta alloy was annealed to produce both equiaxed and coarse Widmanstätten structures of different degrees of fineness. These specimens were stabilized by furnace cooling to 550 C, followed by air cooling. The results, although not entirely conclusive, indicate that stabilization of the beta-annealed specimens may not have been completed by the 550 C treatment. The strength properties of the specimens with equiaxed alpha-beta structures decrease with increasing grain size, with a corresponding increase in ductility. Bend ductility is good in all three conditions. The beta-annealed specimens, however, have erratic strength values. Elongation and bend ductility are lowered as the prior beta-grain size is increased, but reductions in area remain about the same.

The alpha-beta alloy containing 5 per cent chromium and 5 per cent molybdenum additions was tested in the same microstructural conditions as the Ti-2.5Cr-2.5Mo alloy. The mechanical properties of the equiaxed-alpha-beta specimens were not affected by grain size. Increasing

TABLE 1. MECHANICAL PROPERTIES OF

Nominal Composition	Heat Treatment		Elongation, per cent in 1 inch	Reduction in Area, per cent	Ultimate Tensile Strength, psi	0.01% Offset Yield Strength, psi
	Time, hr	Temp, C				
Unalloyed titanium	As rolled		17	44	72,000	43,000
	1	600	21	53	64,000	41,000
	1	800	22	61	58,000	31,000
	1	900	7	38	71,000	42,000
Unalloyed Ti(a)	1	600	9	18	80,000	38,000
	1	800	20	47	75,000	38,000
Ti-2.5Cr-2.5Mo	As rolled		4	23	169,000	65,000
	1	600	10	29	105,000	73,000
	1	800	7	26	125,000	72,000
	1	900	1	6	169,000	112,000
Ti-5.0Cr-5.0Mo	As rolled		2	16	182,000	162,000
	1	600	5	20	161,000	128,000
	1	800	0	0	124,000	--
	1	900	0	0	56,000	--
Ti-7.5Cr-7.5Mo	As rolled		7	25	142,000	113,000
Ditto(b)	Ditto		6	26	134,000	124,000
" (b)	1	600	12	31	144,000	118,000
Ti-7.5Cr-7.5Mo	1	800	10	33	131,000	117,000
Ditto(b)	1	800	10	37	133,000	119,000
Ti-7.5Cr-7.5Mo	1	900	1	--	153,000	125,000
Ditto(b)	1	900	2	15	136,000	114,000

(a) These specimens were vacuum annealed 6 hours at 900 C.

(b) These alloys were made by using molybdenum wire as the alloying addition.

(c) "Brittle" refers to brittle failure in 1/4-inch die. This corresponds to about an 8 to 10-T bend radius for 0.040-inch sheet.

TITANIUM ALLOYS ANNEALED IN AIR AND AIR COOLED

0.1% Offset Yield Strength, psi	0.2% Offset Yield Strength, psi	Flow Constants ($\sigma = B\delta^n$)			Vickers Hardness Number (5-Kg Load)	Minimum Bend Radius, T(c)	
		B, psi	n	δ_{max}, in./in.		Longitudinal	Transverse
56,000	61,000	90,000	0.057	0.044	175	0	0
47,000	49,000	90,000	0.103	0.086	165	0	0
36,000	37,000	89,000	0.140	0.100	145	0	0
55,000	58,000	98,000	0.088	0.045	169	0.9	Brittle
45,000	54,000	107,000	0.079	0.054	195	0.4	0
49,000	51,000	111,000	0.125	0.090	172	1.2	1.6
92,000	108,000	--	--	--	347	5.7	2.8
86,000	91,000	--	--	--	250	0	0.7
94,000	101,000	--	--	--	295	1.1	1.0
148,000	158,000	--	--	--	375	Brittle	Brittle
176,000	178,000	--	--	--	444	2.3	Brittle
145,000	151,000	--	--	--	340	1.3	2.6
--	--	--	--	--	500	Brittle	Brittle
--	--	--	--	--	503	Brittle	Brittle
129,000	133,000	--	--	--	315	0	0.3
130,000	132,000	--	--	--	318	0	0
130,000	133,000	--	--	--	323	0	2.1
127,000	128,000	--	--	--	300	0	0
127,000	128,000	--	--	--	296	0	--
149,000	--	--	--	--	380	Brittle	Brittle
130,000	134,000	--	--	--	311	Brittle	Brittle

TABLE 2. MECHANICAL PROPERTIES OF TITANIUM ALLOYS

Heat Treatment	Microstructure	Elongation, per cent in 1 inch	Reduction in Area, per cent	Ultimate Tensile Strength, psi	Proportional Limit, psi
					Commercial
Annealed 2 hours at 825 C and argon cooled	0.025-mm equiaxed alpha, with intergranular beta	26	35	60,000	14,000
Annealed 100 hours at 825 C and argon cooled	0.06-mm equiaxed alpha, with intergranular beta	21	56	54,000	14,000
Annealed 1 hour at 900 C and argon cooled	Serrated alpha grains; 0.30-mm prior beta-grain size	20	31	56,000	27,000
Annealed 2 hours at 1000 C and argon cooled	Serrated alpha grains; 0.40-mm prior beta-grain size	15	44	56,000	28,000
					Ti-7.5Cr-
Annealed 2 hours at 850 C and water quenched	0.20-mm equiaxed beta grains	10	13	123,000	59,000
Annealed 4 hours at 1000 C and water quenched	0.50-mm equiaxed beta grains	3	19	93,000	36,000
					Ti-2.5Cr-
Annealed 1 hour at 750 C; furnace cooled to 550 C; argon cooled	0.002-mm equiaxed-alpha-beta structure	13	31	118,000	98,000
Annealed 16 hours at 750 C; furnace cooled to 550 C; argon cooled	0.01-mm equiaxed-alpha-beta structure	11	40	116,000	(b)
Annealed 64 hours at 750 C; furnace cooled to 550 C; argon cooled	0.015-mm equiaxed-alpha-beta structure	21	39	93,000	70,000
Annealed 1 hour at 850 C; furnace cooled to 550 C; argon cooled	Basket-weave alpha-beta structure; 0.25-mm prior beta-grain size	11	25	86,000	47,000
Annealed 2 hours at 900 C; furnace cooled to 550 C; argon cooled	Basket-weave alpha-beta structure; 0.35-mm prior beta-grain size	12	32	121,000	98,000

IN VARIOUS MICROSTRUCTURAL CONDITIONS(a)

0.01% Offset Yield Strength, psi	0.1% Offset Yield Strength, psi	0.2% Offset Yield Strength, psi	Flow Constants ($\sigma = B\delta^n$)			Vickers Hardness Number (5-Kg Load)	Minimum Bend Radius, T	
			B, psi	n	δ max, in./in.		Longitudinal	Transverse
Titanium								
18,000	32,000	36,000	87,000	0.12	0.11	139	0	0
19,000	30,000	33,000	84,000	0.15	0.10	139	0	0.8
30,000	40,000	43,000	81,000	0.11	0.12	142	0	0
32,000	41,000	44,000	68,000	0.05	0.06	142	0	0
7.5Mo Alloy								
65,000	83,000	89,000	204,000	0.17	0.10	302	0	0
42,000	66,000	74,000	--	--	--	301	--	--
2.5Mo Alloy								
104,000	112,000	114,000	--	--	--	232	0	0.4
(b)	(b)	(b)	--	--	--	227	0	1.1
74,000	83,000	83,000	134,000	0.12	0.13	227	0	0
54,000	67,000	71,000	118,000	0.09	0.07	236	0	1.2
104,000	(b)	(b)	--	--	--	234	2.4	2.3

TABLE 2.

Heat Treatment	Microstructure	Elongation, per cent in 1 inch	Reduction in Area, per cent	Ultimate Tensile Strength, psi	Proportional Limit, psi
					Ti-2.5Cr-
Annealed 4 hours at 1000 C; furnace cooled to 550 C; argon cooled	Basket-weave alpha-beta structure; 0.60-mm prior beta-grain size	4	28	114,000	(b)
					Ti-5.0Cr-
Annealed 1 hour at 700 C; furnace cooled to 550 C; argon cooled	Elongated beta grains, with unresolved alpha precipitate; beta-grain size 0.07 mm	15	40	116,000	86,000
Annealed 16 hours at 700 C; furnace cooled to 550 C; argon cooled	Elongated beta grains, with alpha precipitate resolved in beta grains and grain boundaries; beta-grain size 0.07 mm	14	40	114,000	81,000
Annealed 64 hours at 700 C; furnace cooled to 550 C; argon cooled	Equiaxed beta grains, with alpha precipitate resolved in beta grains and grain boundaries; beta-grain size 0.07 mm	18	30	115,000	78,000
Annealed 1 hour at 750 C; furnace cooled to 550 C; argon cooled	Equiaxed beta grains, with alpha precipitate resolved in beta grains and grain boundaries; beta-grain size 0.08 mm	12	36	116,000	75,000
Annealed 2 hours at 900 C; furnace cooled to 550 C; argon cooled	Acicular alpha precipitated in 0.25-mm equiaxed beta grains	3	14	146,000	99,000
Annealed 4 hours at 1000 C; furnace cooled to 550 C; argon cooled	Acicular alpha precipitated in 0.60-mm equiaxed beta grains	5	7	145,000	73,000

(a) These alloys were double arc melted, forged at 1600 to 1800 F, rolled to 0.040-inch sheet at 1400 F, descaled, and annealed under argon.

(b) Limit of SR-4 strain gage low, and these values not determined.

(Continued)

0.01% Offset Yield Strength, psi	0.1% Offset Yield Strength, psi	0.2% Offset Yield Strength, psi	Flow Constants ($\sigma = B\delta^n$)			Vickers Hardness Number (5-Kg Load)	Minimum Bend Radius, T	
			B, psi	n	δmax, in./in.		Longitudinal	Transverse
2.5Mo Alloy								
(b)	(b)	(b)	--	--	--	239	5.7	4.6
5.0Mo Alloy								
91,000	(b)	(b)	147,000	0.06	0.06	288	0	1.2
87,000	101,000	104,000	151,000	0.08	0.09	275	0	0.8
86,000	101,000	104,000	162,000	0.10	0.11	278	0	0.8
83,000	98,000	103,000	158,000	0.09	0.08	283	0	1.2
107,000	(b)	(b)	--	--	--	352	2.4	2.3
89,000	127,000	135,000	--	--	--	346	5.7	4.6

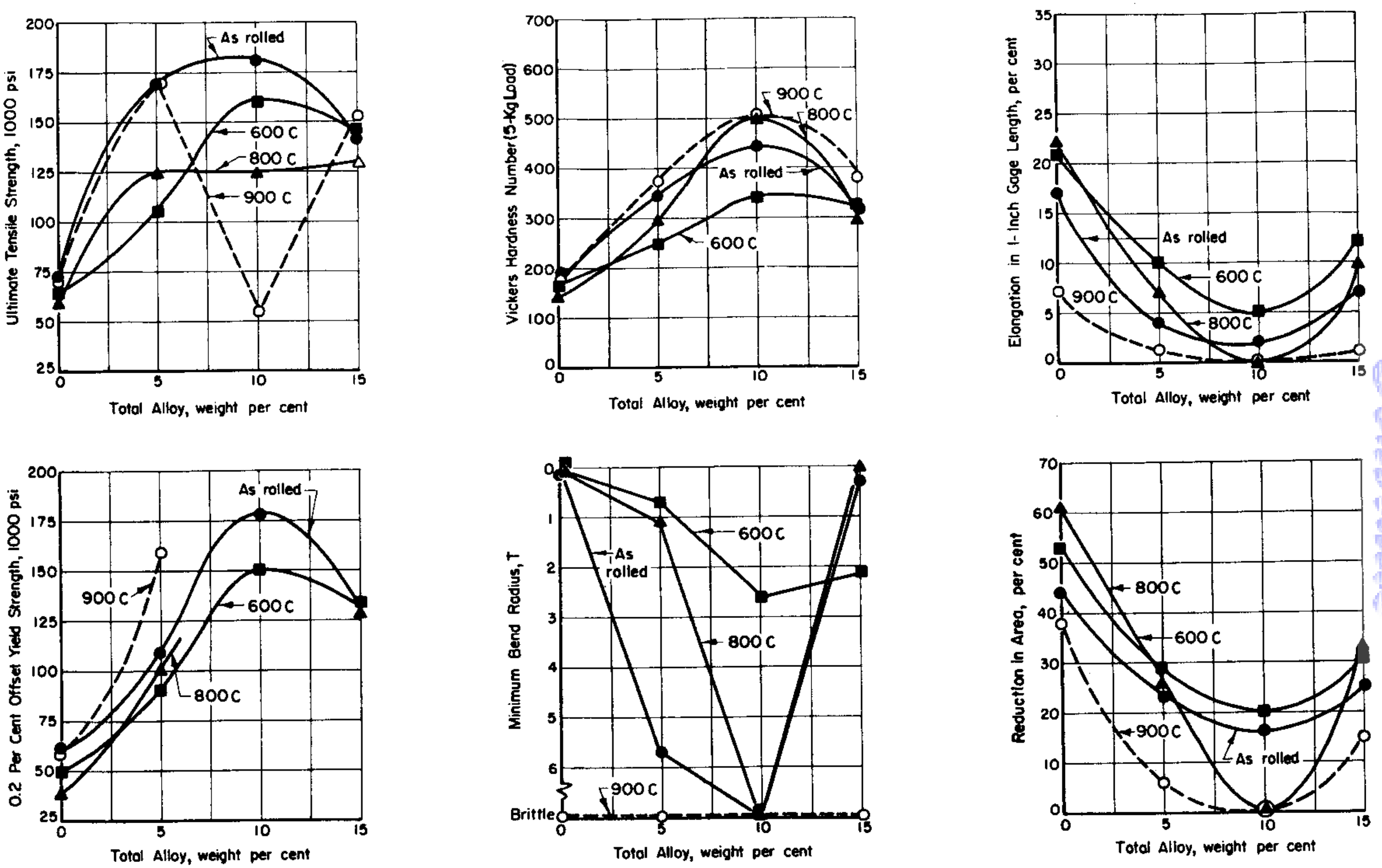


FIGURE 4. MECHANICAL PROPERTIES OF TITANIUM ALLOYS ANNEALED 1 HOUR IN AIR AND AIR COOLED
Chromium and molybdenum are present in equal quantities

A-8208

prior beta-grain size for the beta-annealed specimens results in a considerable increase in strength, with loss of both tensile and bend ductility. The alpha that forms during cooling in the furnace to 550 C is a fine acicular precipitate, whereas the corresponding alpha formed in the Ti-2.5Cr-2.5Mo alloy is much coarser. This indicates a tendency for the stability of the beta-annealed specimens to be affected by prior beta-grain size.

As a consequence of these data, the full-scale alloy program was set up in such a manner that the alpha-beta alloy (Ti-2.5Cr-2.5Mo) received both an equilibrating and a stabilizing treatment in the alpha-beta field. Also, the effect of prior beta-grain size on the rate of stabilization was investigated for the metastable beta alloy.

COMMERCIAL TITANIUM

Unalloyed high-purity titanium exists in two allotropic forms, of which the hexagonal alpha phase is stable at room temperature. The body-centered cubic beta phase is stable at temperatures above about 885 C. The beta structure cannot be retained at lower temperatures, but transforms on cooling to plates of alpha phase, which tend to form serrated colonies of alpha. The presence of impurities in commercial titanium, however, introduces a two-phase transformation region, in place of the single transition temperature. The retention of small quantities of beta phase is also made possible by the presence of beta-stabilizing impurities, whereas the presence of hydrogen in quantities in excess of the solubility limit results in the appearance of TiH particles.

Grain Size and Microstructure

The effects of annealing time and temperature on the grain size of commercial titanium are shown in Figure 5. It may be noted that the two upper curves, which represent beta-grain size, are considerably above the curves representing alpha-grain size. Also, the annealing temperature, rather than annealing time, is the dominant factor in determining the final grain size.

The microstructure of unalloyed titanium is dependent on the annealing treatment. If worked and annealed below the transformation temperature, the structure is equiaxed alpha. If annealed above the transformation temperature, the structure consists of plates of alpha phase that were produced during cooling from the beta field. Photomicrographs of samples of unalloyed titanium in the conditions of testing are given in Figures 6, 7, and 8.

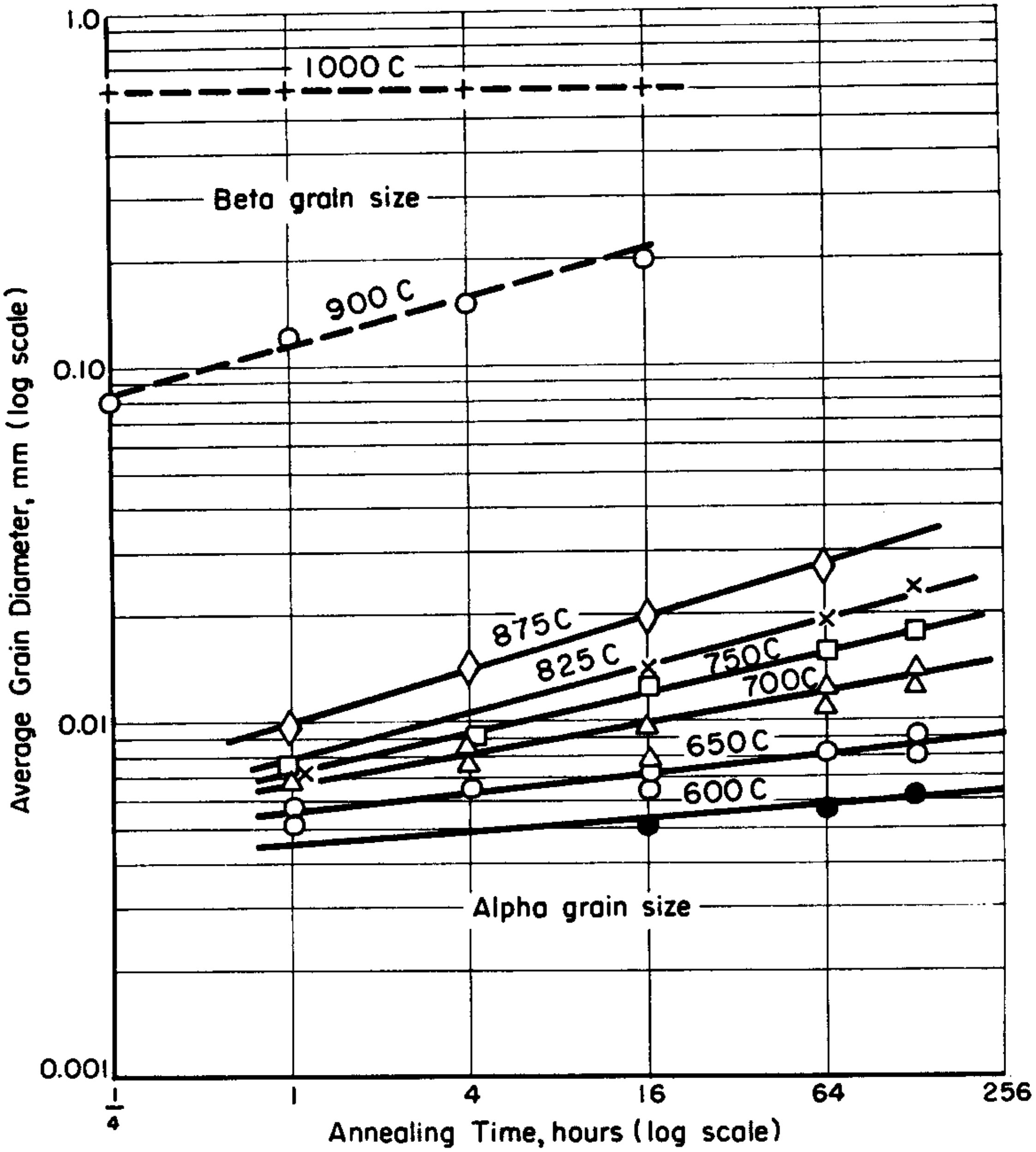
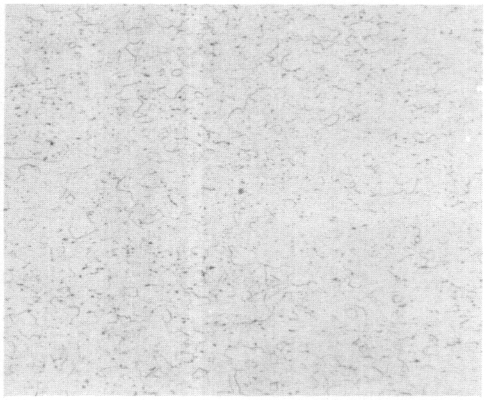


FIGURE 5. EFFECT OF HEAT-TREATING TEMPERATURE AND TIME ON THE GRAIN SIZE OF COMMERCIAL TITANIUM

A-12055

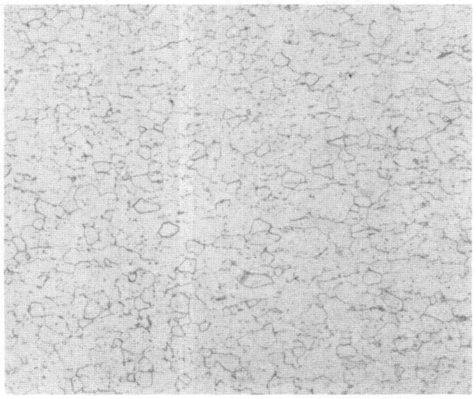
250X N11566

As Fabricated at 1400 F



250X N11559

Annealed 1 Hour at 600 C and Air Cooled



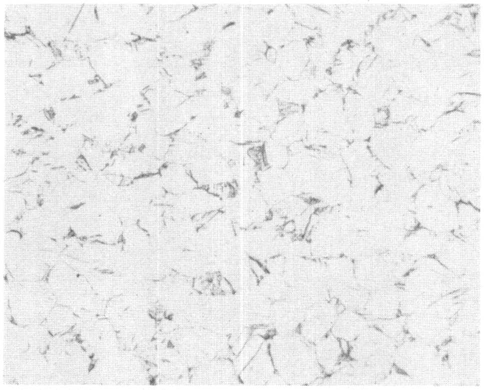
250X N11560

Annealed 2 Hours at 700 C and Air Cooled

FIGURE 6. PHOTOMICROGRAPHS OF COMMERCIAL TITANIUM ANNEALED AT 600 AND 700 C

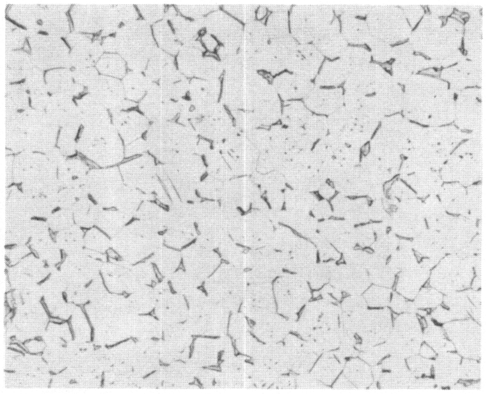
250X **N11561**

Annealed 4 Hours at 825 C and Air Cooled



250X **N11562**

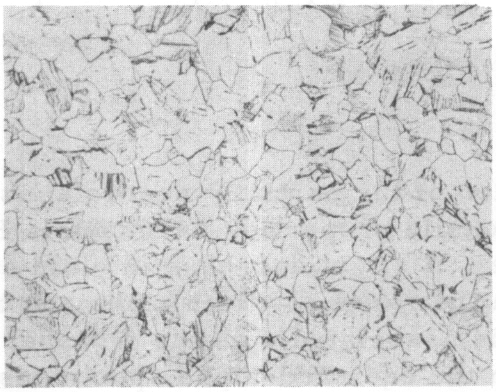
Annealed 16 Hours at 875 C and Air Cooled



250X **N11565**

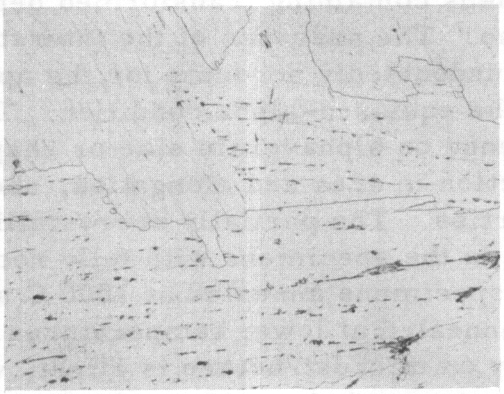
Vacuum Annealed 18 Hours at 875 C
and Furnace Cooled

FIGURE 7. PHOTOMICROGRAPHS OF COMMERCIAL TITANIUM ANNEALED AT 825 AND 875 C



250X N11563

Annealed 1 Hour at 900 C and Air Cooled



250X N11564

Annealed 2 Hours at 1000 C and Air Cooled

FIGURE 8. PHOTOMICROGRAPHS OF COMMERCIAL TITANIUM ANNEALED AT 900 AND 1000 C

Mechanical Properties

Complete mechanical properties for commercial titanium are presented in Tables A-1, A-5, and A-8 of Appendix A.

Tensile Properties

With the exception of the partially recrystallized specimen (600 C-annealed condition), tensile properties as shown in Figure 9 are insensitive to microstructure. A slight decrease in yield strength occurs for specimens annealed in the range at which alpha and beta phases coexist (875 to 900 C). This is associated with the disappearance of the yield point, which occurs in the equiaxed-alpha specimens, but not in those containing transformed beta.

The yield-point behavior occurs in specimens annealed at 600 or 700 C. Similar yield points have been observed previously in high-purity alloys containing interstitial alpha-stabilizing additions (C, N)(2, 3), but do not appear in unalloyed high-purity titanium(4). The disappearance of the yield point for specimens containing transformed beta is not completely understood at this time. The presence of the interstitial impurities in commercial titanium undoubtedly accounts for the appearance of the yield-point phenomenon in the equiaxed-alpha condition. Tensile strengths show no significant dependence on alpha-grain size or shape. Tensile ductilities, as measured by reduction in area and elongation, show more scatter than do the strength properties. The partially recrystallized specimens have lower ductilities than do the specimens with fully recrystallized structures. The ductilities of the specimens annealed at 1000 C are slightly lower than those for specimens annealed at lower temperatures. In general, the dependence of ductility on microstructure is slight, with highest values obtained for the specimens annealed at 825 to 900 C.

Tensile properties were obtained from both sheet and round unnotched specimens, and from notched round specimens. The same strength values were obtained from both the sheet and the round unnotched specimens. The effect of geometry is reflected in the ductility, however, since both reductions in area and elongations are higher for the round specimens. Per cent elongation is measured over a 1-inch gage length for the flat specimens, and a 1/2-inch gage length was used for the rounds. The ultimate tensile strengths of the notched specimens are increased over those of the unnotched specimens by 56 to 70 per cent. Ductility, as measured by reduction in area, is reduced to 41 to 55 per cent of the unnotched condition. This is shown in Figure 10. The notched-tension-test values obtained show that this material is notch insensitive in all conditions according to the usual standards.

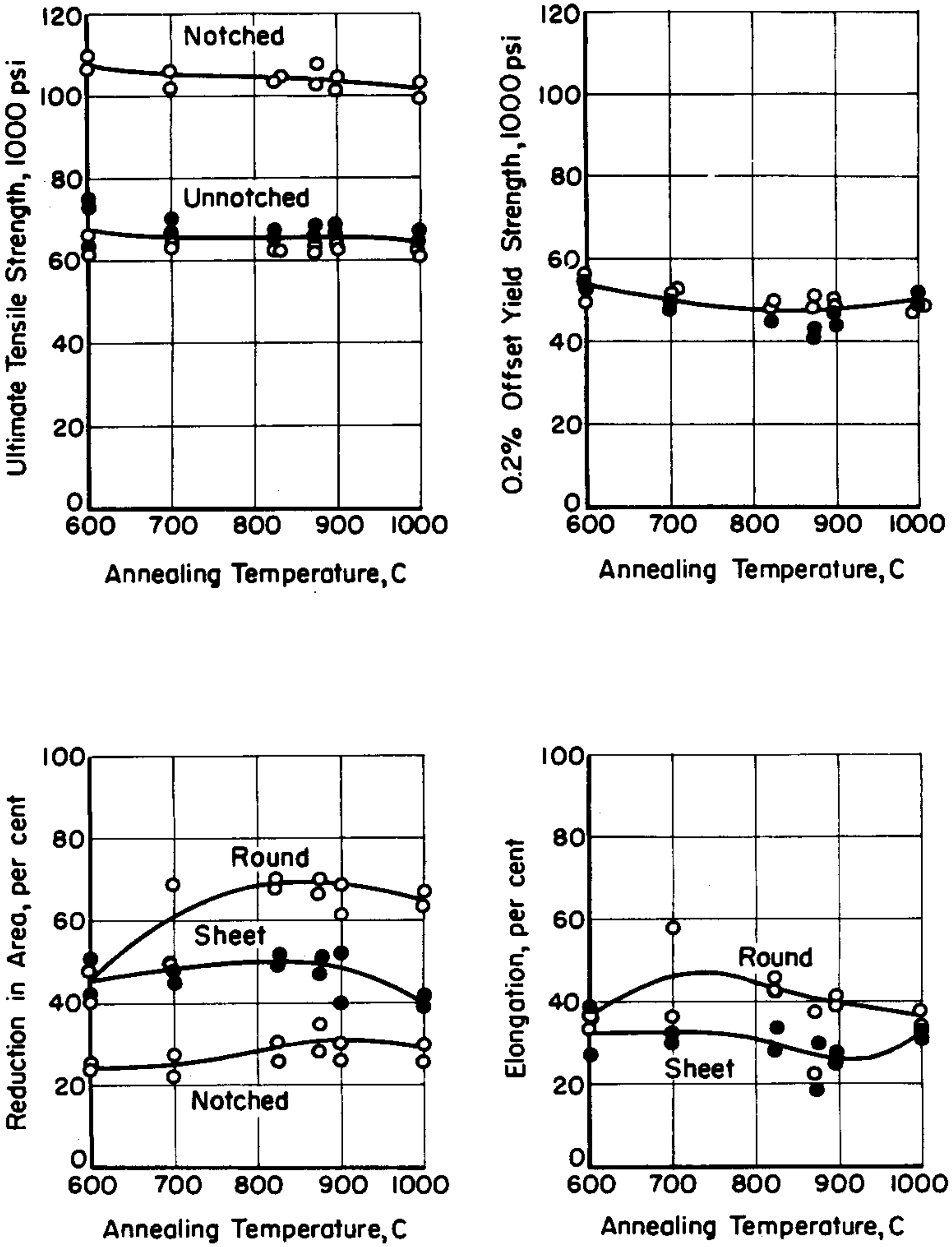


FIGURE 9. TENSILE PROPERTIES OF COMMERCIAL TITANIUM

A-12056

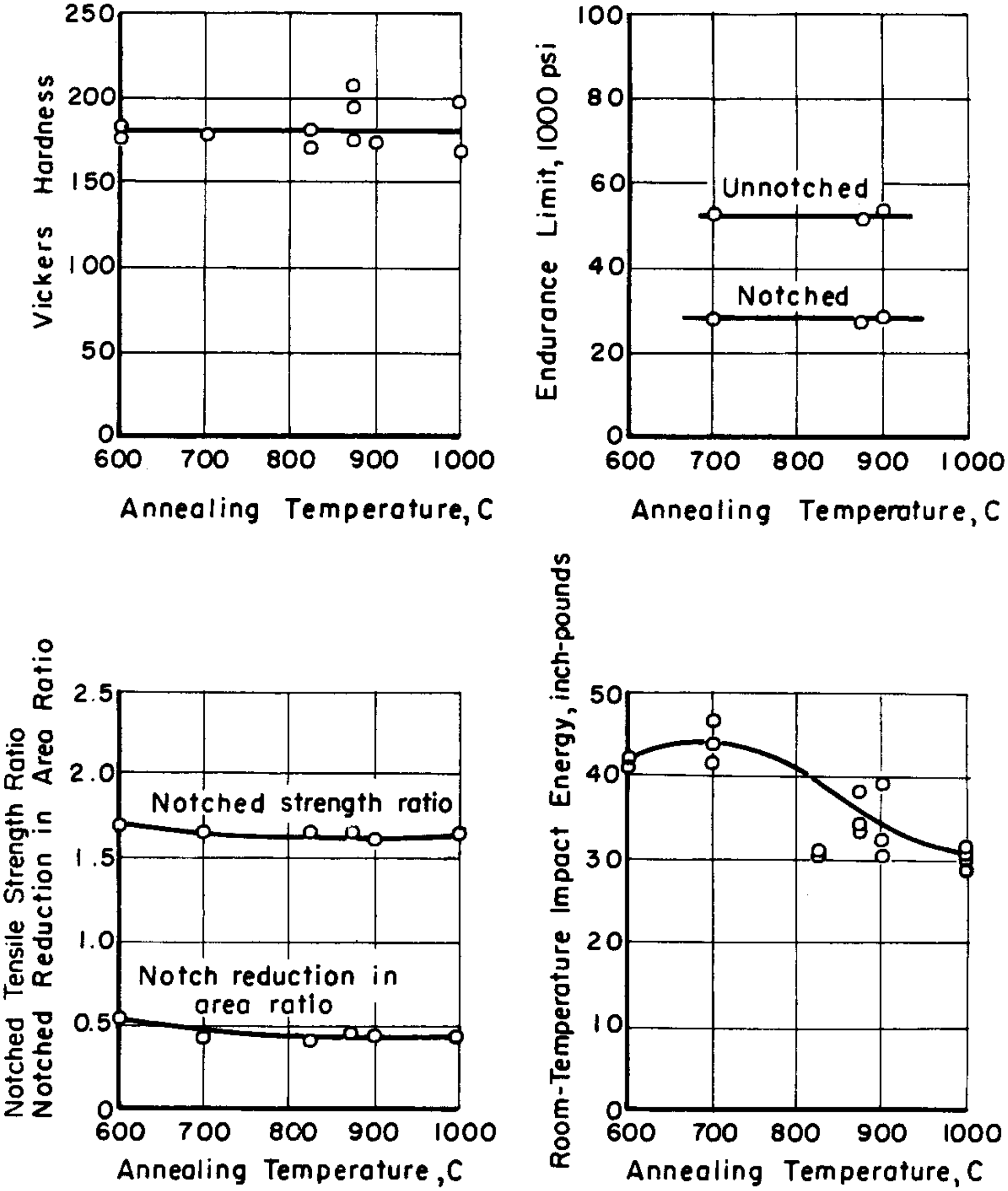


FIGURE 10. MECHANICAL PROPERTIES OF COMMERCIAL TITANIUM

A-12057

Fatigue Properties

The fatigue endurance limit of commercial titanium was determined for a limited number of microstructural conditions. The values obtained for both notched and unnotched specimens are given in Table 3. Endurance limits are shown as functions of annealing temperature in Figure 10. Complete S-N curves are given in Figures C-1 through C-4 in Appendix C.

As for most of the other mechanical properties, no effect of grain size or shape on the endurance limit was observed. The unnotched endurance limit at 10^7 cycles is about 80 per cent and that of the notched specimens about 43 per cent, of the ultimate tensile strength.

TABLE 3. FATIGUE STRENGTHS OF COMMERCIAL TITANIUM

Annealing Treatment		Mean Stress at 10^7 Cycles, psi		Tensile Strength, psi	Endurance-Limit Tensile-Strength Ratio	
Time, hr	Temp, C	Unnotched	Notched		Unnotched	Notched
2	700	52,700± 1300	27,700± 2500	64,000	0.82	0.43
16	875	51,200± 1300	27,700± 1100	64,000	0.80	0.43
16	875[(a)]	49,000± 1300	21,700± 2300	62,000	0.78	0.34
1	900	53,400± 2500	28,000± 800	64,000	0.83	0.44

Note: The method by which the fatigue limits and standard deviations were obtained is outlined in Appendix C.

(a) Vacuum annealed.

Bend Ductility

The bend ductilities of commercial titanium are excellent for all conditions of testing. No dependence of bend ductility on grain size or shape was found.

Impact Tests

The micro-impact test was used to determine the effects of microstructure on notched-bar toughness. Results obtained at room temperature (Figure 10) show that the specimens with partially recrystallized and small alpha-grain sizes have the highest resistance to impact. Impact-energy values obtained for specimens with large alpha-grain sizes and with transformed-beta structures are about 25 per cent lower than those for the fine-grained alpha specimens.

Impact-energy values were also obtained over a range of testing temperatures, and these results are shown in the curves of Figure 11. Each point represents the average of at least two measurements. No effect of testing temperature is observed from -196 C to room temperature. From room temperature up to 400 C, the specimens with equiaxed-alpha structure show a considerable increase in impact resistance, whereas those with transformed-beta structures show only a slight increase.

Conclusions

From the results obtained in this study of commercial titanium, the following conclusions are drawn:

(1) The effects of microstructure (alpha-grain size and shape) on mechanical properties are definitely minor. Yield strengths are decreased slightly for specimens annealed in the alpha-beta range because of the partition of interstitials to the nonmatrix alpha. Impact resistance is higher for the small-equiaxed-alpha structures than for large-alpha or transformed-beta structures.

(2) Excellent bend ductility is obtained in all microstructural conditions tested.

(3) The notched-strength ratio is high (1.6 to 1.7) for all conditions, indicating a relatively notch-insensitive material, on the basis of tensile strength.

(4) The endurance limit at 10^7 cycles is 80 per cent of the ultimate tensile strength for unnotched and 43 per cent for notched specimens. No structural dependence was found.

METASTABLE BETA ALLOY

A titanium alloy containing additions of 7.5 per cent chromium and 7.5 per cent molybdenum was studied as an example of a metastable beta alloy. Specimens quenched from the beta field have a retained-beta structure that is unstable when reheated to temperatures below the beta

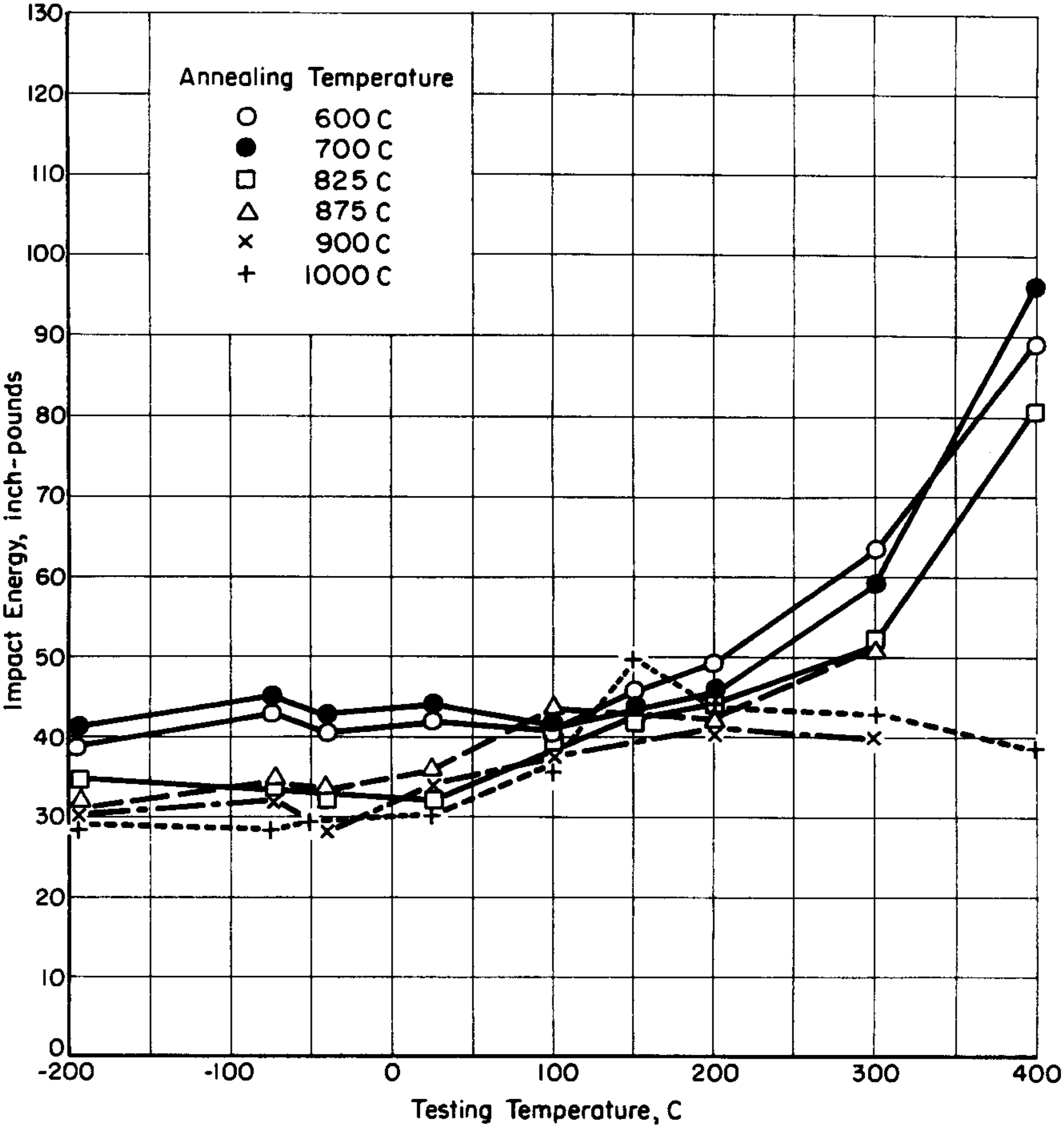


FIGURE 11. EFFECT OF TESTING TEMPERATURE ON THE IMPACT-ENERGY VALUES OF COMMERCIAL TITANIUM

A-12058

transus. The precipitation of alpha under such conditions may have considerable effect on the microstructure and mechanical properties.

The basic heat treatments for this alloy were designed to determine the effects of beta-grain size on the mechanical properties. These studies also included the effects of prior beta anneals on specimens slow cooled to 700 C. These treatments were intended to separate the effects of beta-grain size from those of quenching temperature. The 700 C anneal, however, was slightly below the beta transus, so that approximately 5 per cent of equilibrium alpha was formed.

The effects of prior heat treatment on stability were studied using specimens given a 100-hour stability check at 200, 300, 400, and 500 C. These were evaluated by single tension and bend tests. A complete evaluation was made on samples quenched from 700 C and aged 100 hours at 300 C.

Beta-Quenched Condition

Grain Size and Microstructure

The rates of beta-grain growth were determined for two annealing temperatures. The effects of annealing time and temperature on beta-grain size are illustrated in the curves of Figure 12. It is seen that both time and temperature are significant factors in the control of grain size. Figure 13 presents photomicrographs of specimens in these conditions, in addition to the as-worked condition.

The microstructure of the as-worked material shows the elongated beta grains resulting from work in the beta field. The fine particles of alpha were formed during the air cooling to room temperature. The 700 C anneal was below the beta transus, and the resulting structure consists of intragranular and grain-boundary alpha in an equiaxed-beta matrix. The microstructures for the 850 and 1000 C anneals show the large equiaxed-beta structures. The particles in the microstructure of the specimen quenched from 1000 C have not been identified, but probably are associated with the interstitial content of the alloy. Similar structures have been observed in high-purity beta-stabilized alloys to which intentional nitrogen additions have been made(5).

Mechanical Properties

Complete mechanical-property data for these conditions are given in Tables A-2, A-3, A-6, and A-9 of Appendix A. Tensile properties are summarized in Figure 14, and the mechanical properties are shown in Figure 15.

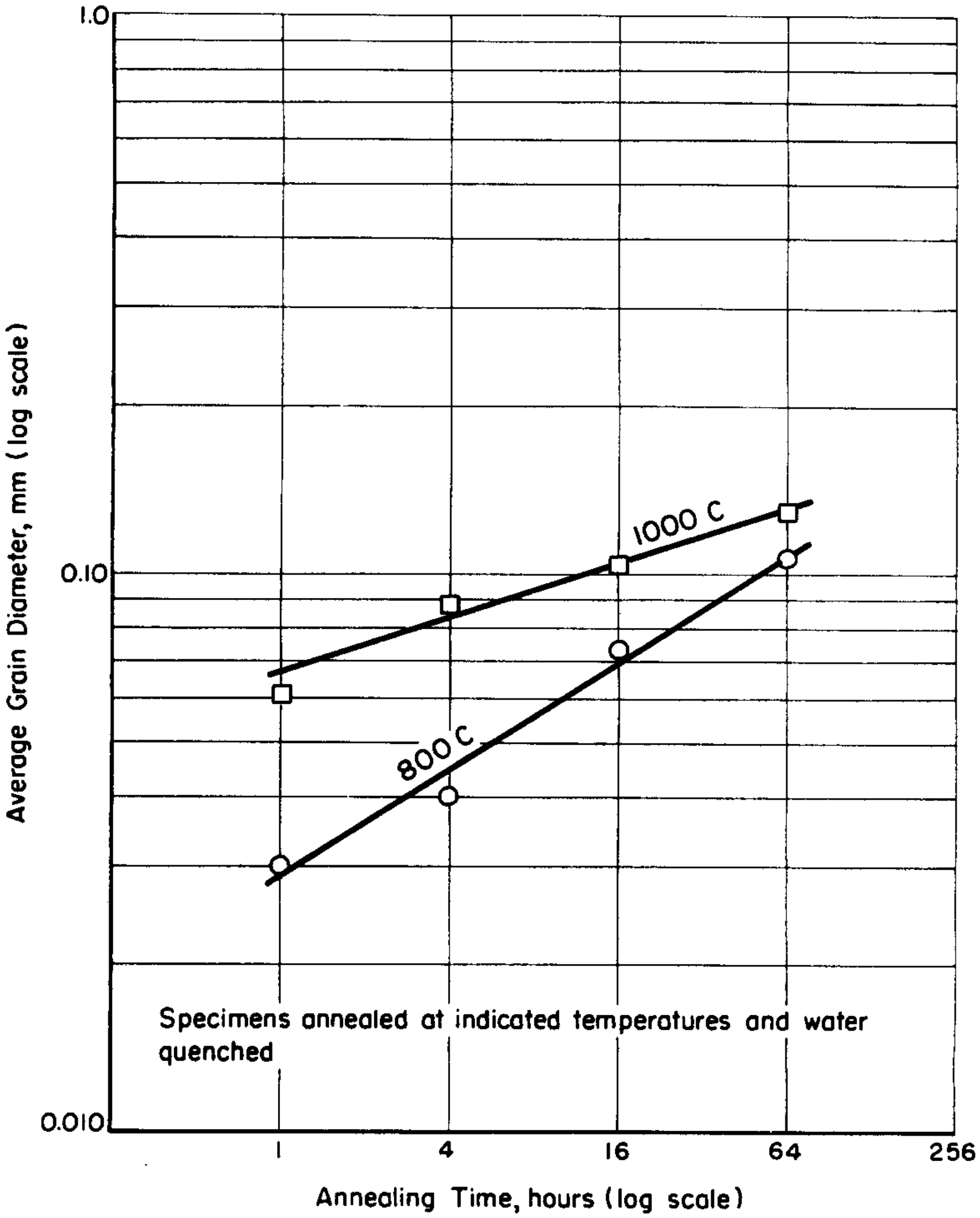
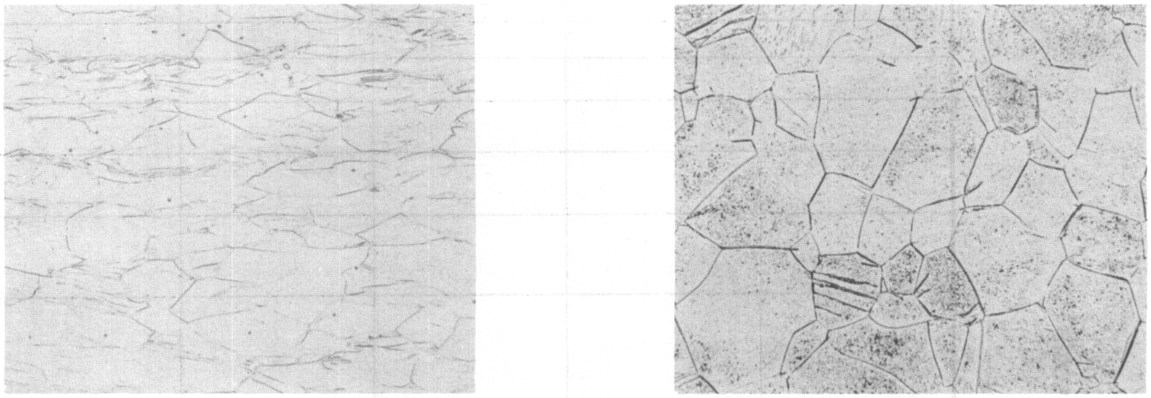


FIGURE 12. EFFECT OF ANNEALING TEMPERATURE AND TIME ON THE GRAIN SIZE OF A Ti-7.5Cr-7.5 Mo ALLOY

A-12059

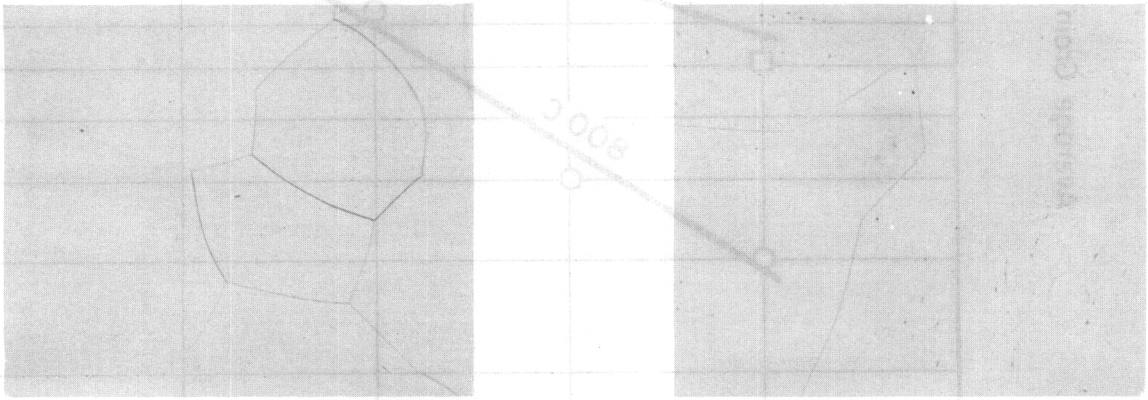


250X N11586

As Fabricated at 1400 F

250X N11575

Annealed 1 Hour at 700 C and Quenched



250X N11577

Annealed 2 Hours at 850 C and Quenched

250X N11579

Annealed 4 Hours at 1000 C and Quenched

FIGURE 13. PHOTOMICROGRAPHS OF A Ti-7.5Cr-7.5Mo ALLOY IN VARIOUS MICROSTRUCTURAL CONDITIONS

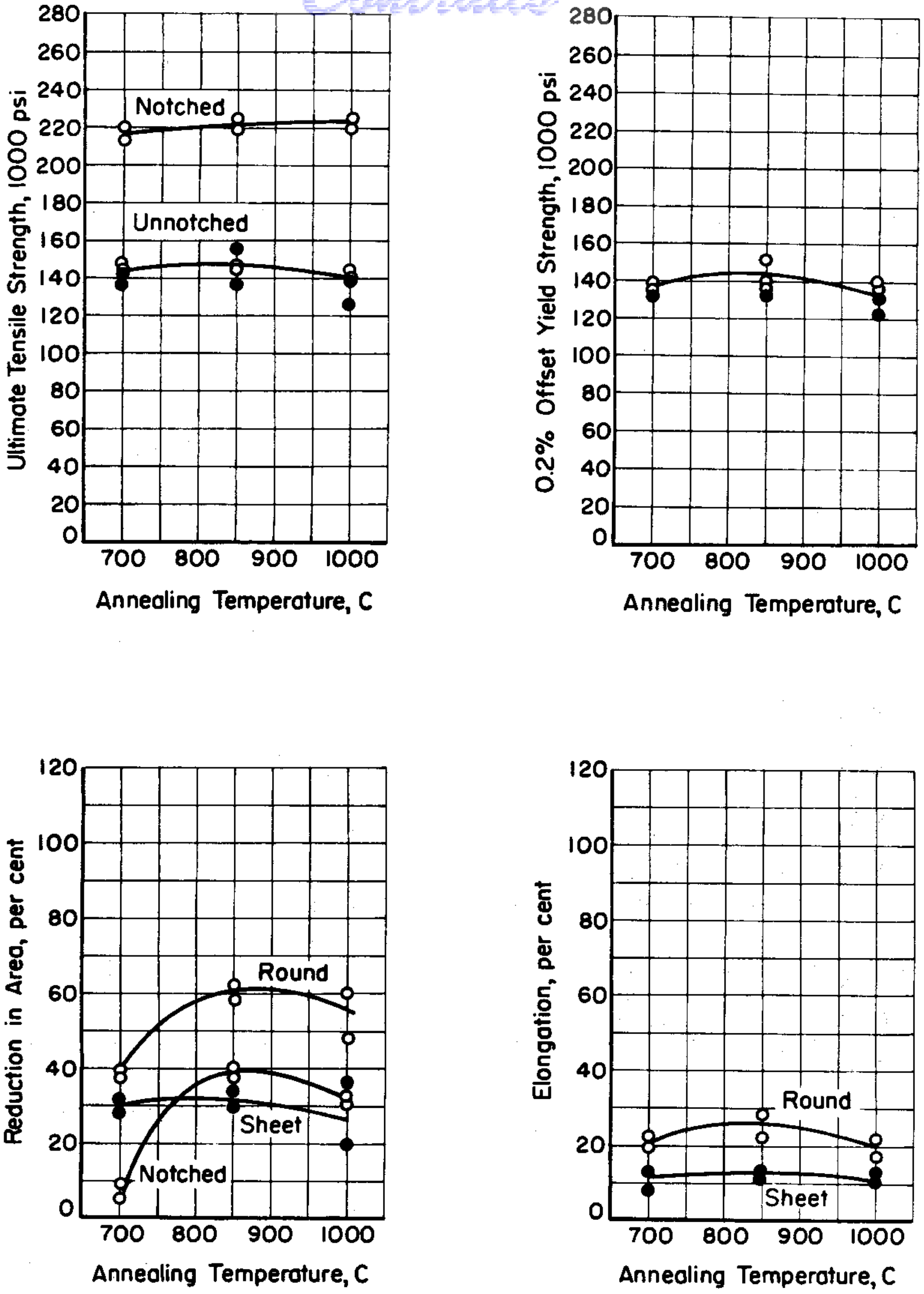


FIGURE 14. TENSILE PROPERTIES OF A Ti-7.5 Cr-7.5 Mo ALLOY QUENCHED FROM VARIOUS TEMPERATURES

A-12060

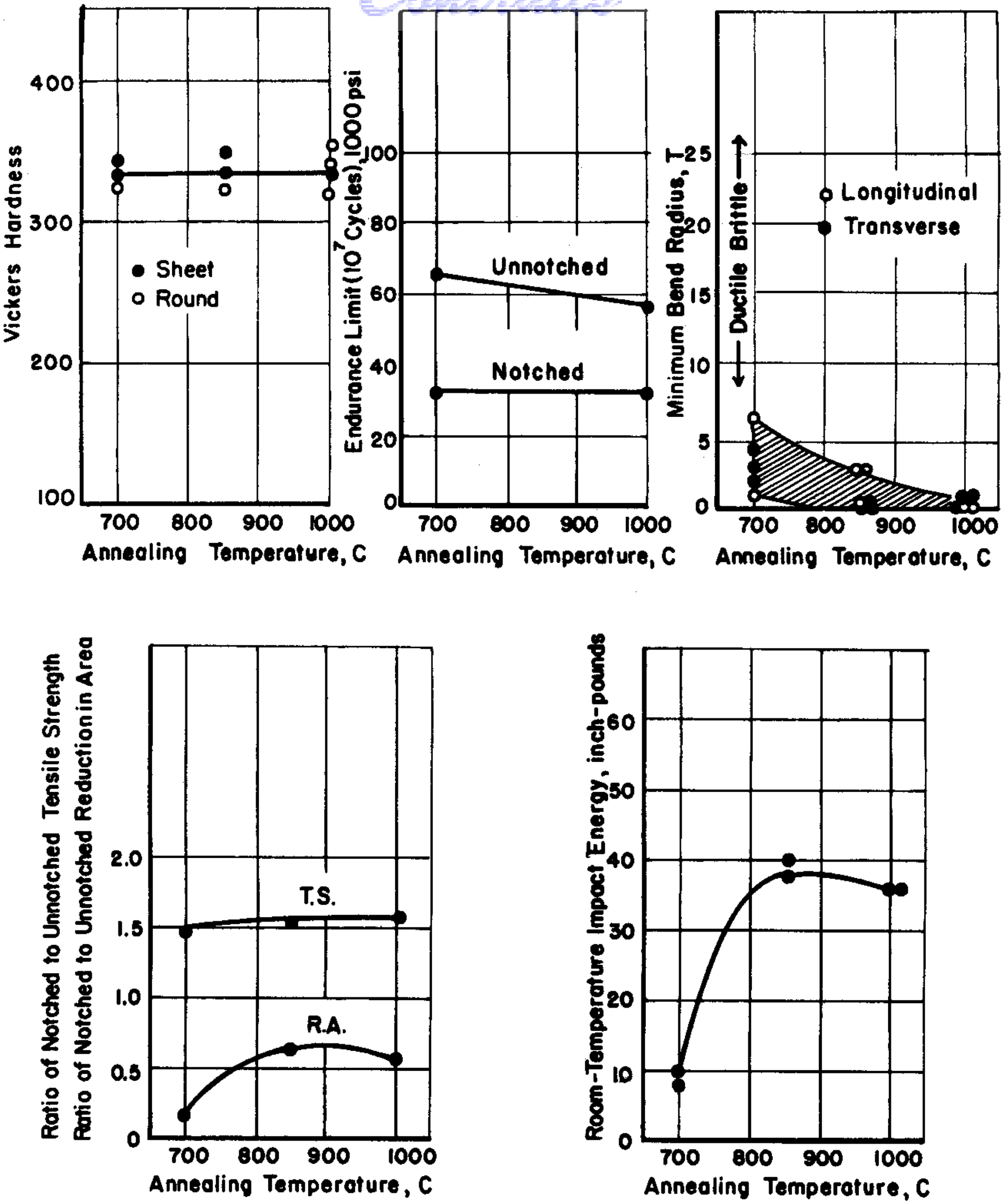


FIGURE 15. MECHANICAL PROPERTIES OF A Ti-7.5 Cr-7.5 Mo ALLOY QUENCHED FROM VARIOUS TEMPERATURES

A-12061

Tensile strengths show no significant variation with annealing temperature. This is also the case for tensile ductility, except for the reduction-in-area values for the 700 C anneal. Because these specimens contained alpha phase, the loss of ductility is attributed to the presence of this second phase. Elongations are not affected appreciably by annealing temperature. The unidentified precipitate in the microstructure of the 1000 C quenched specimens does not appear to affect the tensile properties.

The effects of annealing temperature on the strength and ductility of notched tensile specimens were determined. The notched strength is unaffected by annealing temperature. Reductions in area, however, are lowered considerably by the presence of alpha phase in the specimens annealed at 700 C. Using the ratio of notched to unnotched reduction in area as a measure of notch sensitivity (see Figure 15), the alloy is more sensitive to notches when alpha is present in the microstructure. The ratio of tensile strengths is unaffected by annealing temperature.

The fatigue endurance limits were obtained for specimens annealed at 700 and 1000 C. The endurance limit in the unnotched condition was higher for the specimens annealed at 700 C, as shown by the data in Table 4. On the basis of ultimate tensile strength, the endurance limit of the 700 C-annealed condition is 46 per cent of 144,000 psi, and that of the 1000 C-annealed condition is 41 per cent of 141,000 psi.

TABLE 4. FATIGUE STRENGTHS OF A Ti-7.5Cr-7.5Mo ALLOY

Annealing Treatment[a]		Mean Stress at 10^7 Cycles, psi		Tensile Strength, psi	Endurance-Limit Tensile-Strength Ratio	
Time, hr	Temp, C	Unnotched	Notched		Unnotched	Notched
1	700	66,500±5700	33,000±4200	144,000	0.46	0.23
4	1000	57,200±4100	32,600±3700	141,000	0.41	0.23

Note: The method by which the fatigue limits and standard deviations were obtained is outlined in Appendix C.

(a) Quenched from the annealing treatment.

In the notched condition, the endurance limit was found to be the same for both the 700 C- and 1000 C-annealed conditions. Ratios of endurance limit to ultimate tensile strength were 0.23 for both conditions.

Both notched and unnotched endurance-limit ratios (to ultimate tensile strength) are considerably lower than those for the unalloyed titanium.

Bend ductility was determined for the three quenched conditions. Four longitudinal and four transverse specimens were tested in each condition. No consistent effect of direction was observed in any condition. Bend ductility is improved as the quenching temperature is increased. This probably is caused by both the elimination of the alpha phase and the increase in beta-grain size as the temperature is increased. The scatter of data points also decreases as the annealing temperature is increased.

From these results, it may be concluded that specimens having retained-beta structures have good bend ductility. Ductility is increased slightly as the beta-grain size is increased. The presence of alpha phase in the microstructure, however, decreases bend ductility.

The effects of microstructure on the impact resistance of the quenched alloys were studied using micro-impact-test specimens. The effects of annealing temperature on room-temperature impact-energy values are shown in Figure 15. The presence of alpha in the microstructures of the 700 C-quenched specimens has a very deleterious effect on impact resistance. The effects of beta-grain size, as determined by comparison with the specimens annealed at 850 and at 1000 C, are minor. The level of impact-energy values for the specimens containing all retained beta is high (36 to 39 inch-pounds), and compares favorably with that for unalloyed titanium.

The effects of testing temperature were also studied for the same conditions, and results are shown in the curves of Figure 16. A definite transition behavior is apparent for this alloy. This is typical of retained-beta alloys. The transition occurs between -50 C and 200 C for the specimens annealed at 850 and 1000 C. The transition behavior of the 700 C-annealed specimens is less apparent, because of the presence of the alpha phase. The impact-energy values are lower for a given temperature, and the transition temperature is increased. There is no distinct difference between the curves for the 850 C- and 1000 C-annealed material. Room temperature occurs as a point in the transition range for this alloy.

Effect of Prior Treatment on Properties of Specimens Quenched From 700 C

Because beta-grain size is largely controlled by annealing temperature, specimens were annealed at 850 and 1000 C to develop large beta-grain structures. These specimens were then slow cooled to 700 C and quenched. This provided material of three beta-grain sizes quenched from the same temperature, so that quenching temperature could be eliminated as a variable. Unfortunately, the 700 C-annealing treatment is in the

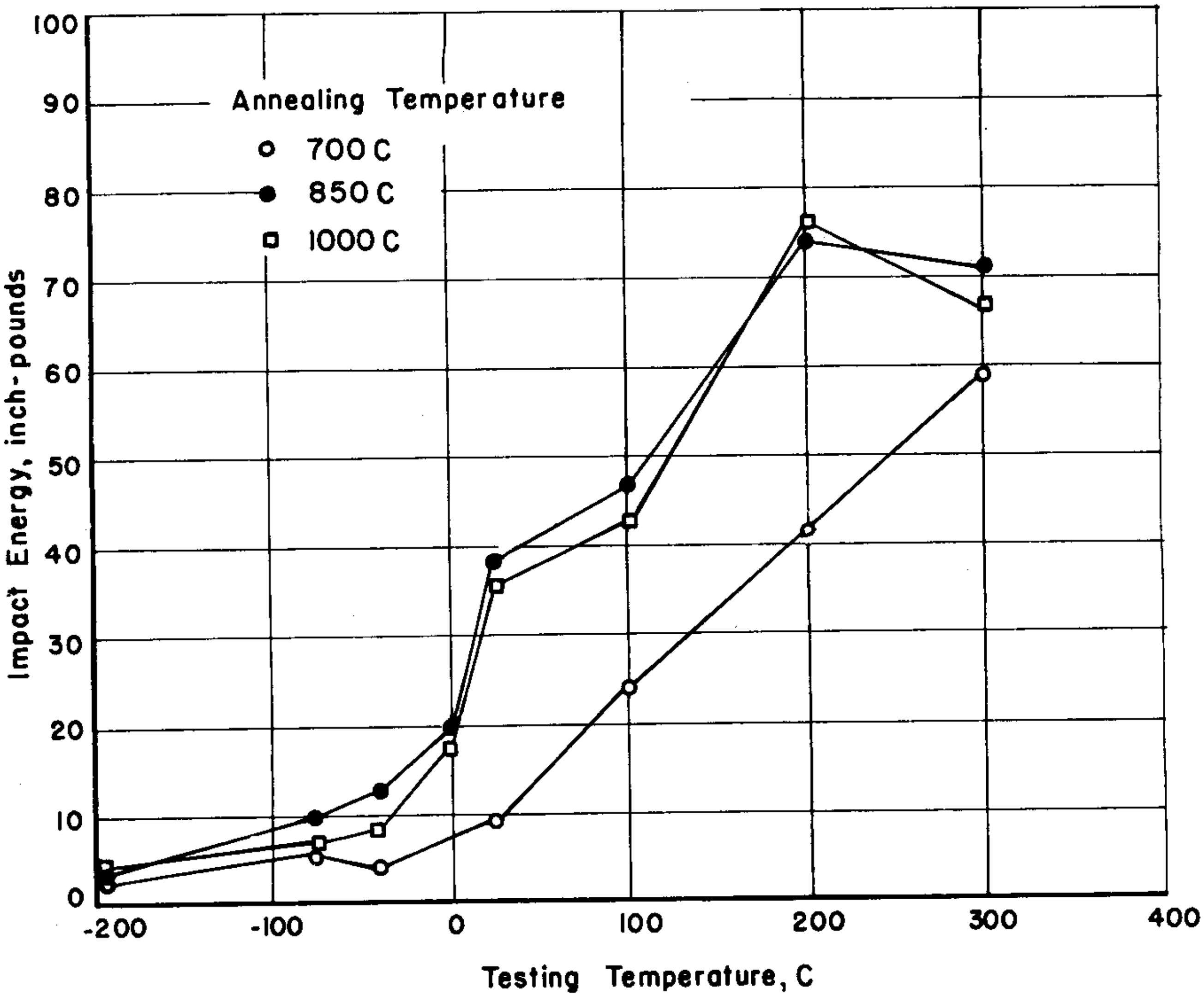


FIGURE 16. EFFECT OF TESTING TEMPERATURE ON THE IMPACT BEHAVIOR OF A Ti-7.5 Cr-7.5 Mo ALLOY QUENCHED FROM VARIOUS TEMPERATURES

A-12062

alpha-beta field. The structure of samples annealed at 700 C after fabrication is composed of equiaxed beta with an intragranular coarse alpha precipitate. However, when samples are furnace cooled from the beta, the structure is composed of equiaxed beta with intragranular alpha plates. Microstructures of these conditions are presented in Figure 17.

The mechanical properties for these conditions are presented in Figures 18 and 19, and test data are listed in Appendix A.

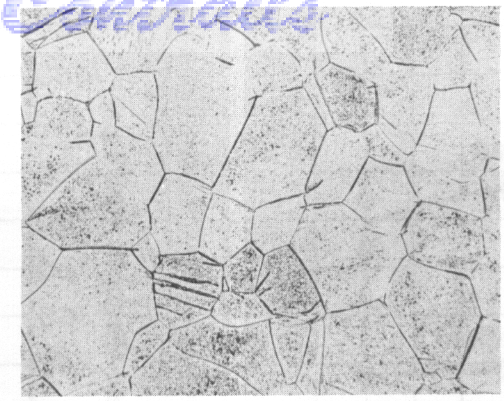
The ultimate tensile strengths of these alloys are affected only slightly by beta-grain size. Both notched and unnotched specimens, however, show a slight decrease in tensile strength with an increase in beta-grain size. Yield strengths remain constant with increasing annealing temperature, and are very close to the ultimate tensile strengths. Hardness values also show no consistent effect of grain size. Ductilities, both reduction in area and elongation, do not appear to be affected by annealing temperature.

The ratio of notched to unnotched tensile strength is nearly constant, ranging from 1.5 to 1.45. Reductions in area of the notched specimens are reduced to 0.16 to 0.24 of the unnotched values. This indicates a more notch-sensitive condition than for the same alloy in the all-beta condition. The notch sensitivity of the 700 C-quenched specimens was not affected by beta-grain size.

The fatigue endurance limit at 10^7 cycles for the 700 C-quenched condition, and for the 1000 C-furnace-cooled-to-700 C- and-quenched condition are given in Table 5. There is no significant difference between the notched endurance limits for these two conditions. However, the unnotched endurance limit for the furnace-cooled-to-700 C sample is much lower than that for the 700 C-quenched sample. This indicates that the alpha plates present probably act as stress raisers, similar to notches, and decrease the fatigue resistance.

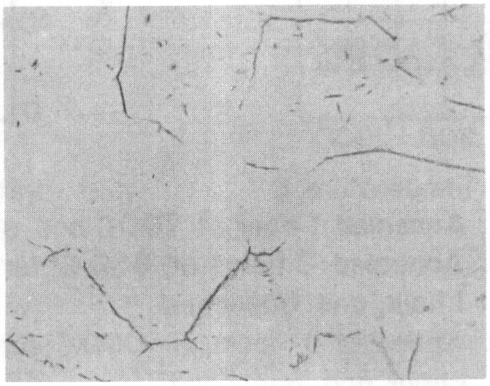
Bend ductilities, both longitudinal and transverse, were determined for these conditions. Four specimens were used for each test. Although the scatter of the data points was large, at least one specimen of the 850 C- and 1000 C-annealed conditions failed in a brittle manner. This indicates that the specimens slow cooled to 700 C and quenched are more susceptible to embrittlement than the specimens annealed at 700 C and quenched. This, again, points out the detrimental effect on properties of the alpha plates in the microstructure.

Impact-energy values at room temperature decrease with an increase in beta-grain size. This is pointed out further by the transition behavior, shown in Figure 20. The energy level is lower and the transition temperature is higher for the specimens with the larger beta-grain sizes. This behavior is just the opposite of that observed for the same alloys when the alpha phase is not present, again illustrating the detrimental effect of the alpha plates in the structure.



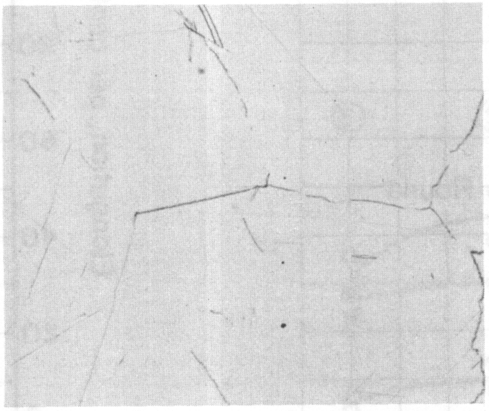
250X N11575

Annealed 1 Hour at 700 C and Quenched



250X N11581

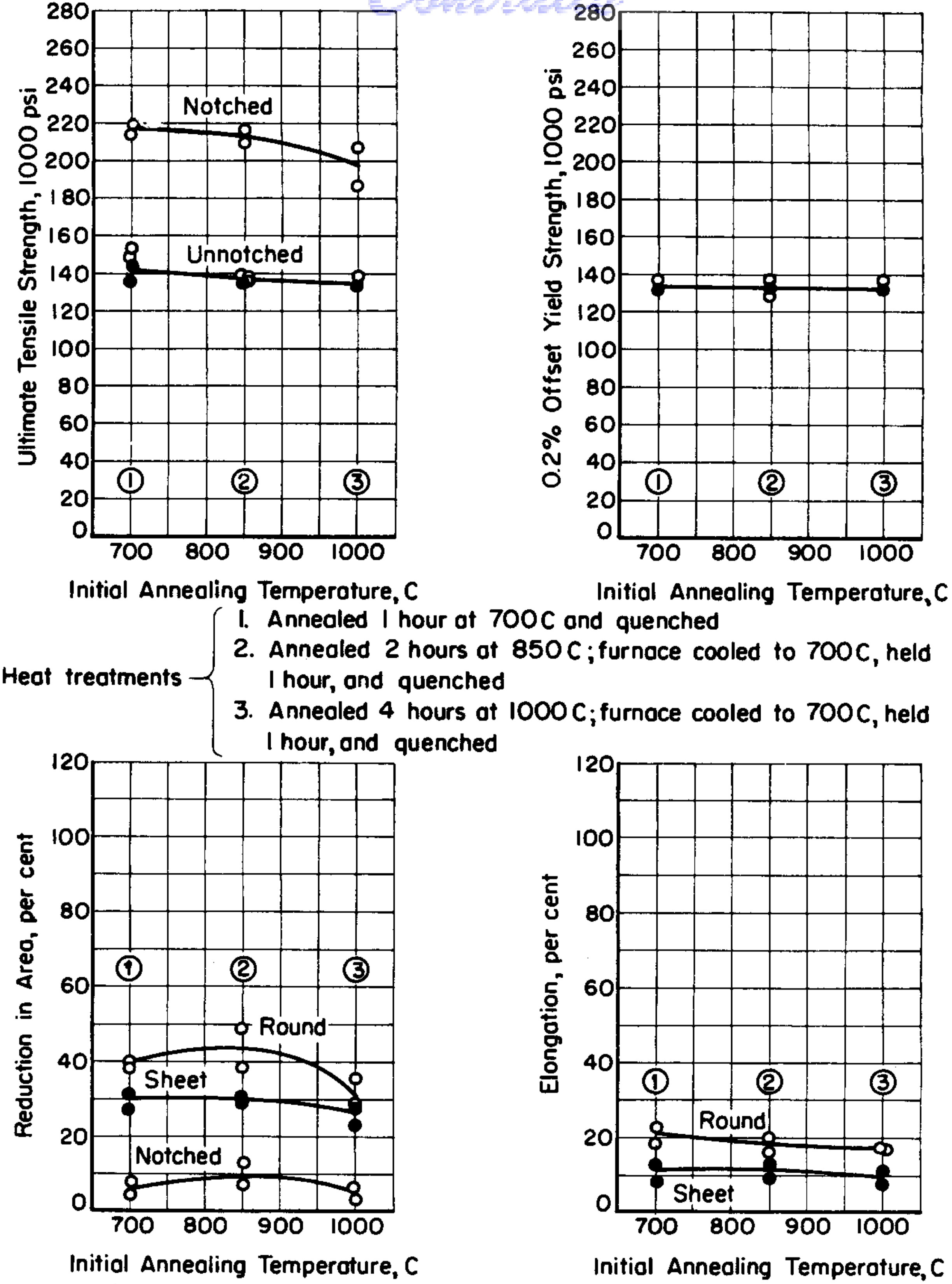
Annealed 2 Hours at 850 C; Furnace Cooled to 700 C, Held 1 Hour, and Quenched



250X N11583

Annealed 4 Hours at 1000 C; Furnace Cooled to 700 C, Held 1 Hour, and Quenched

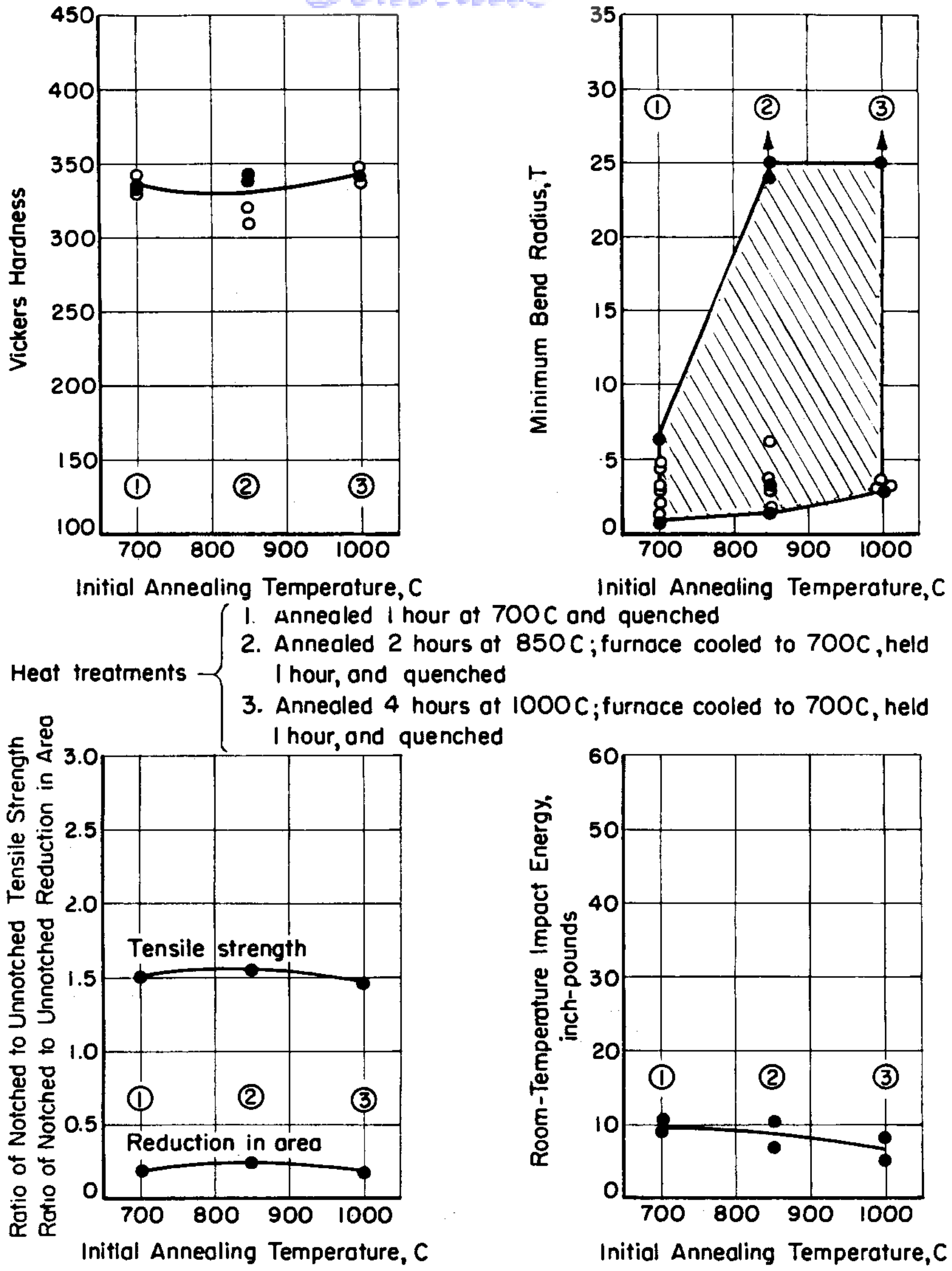
FIGURE 17. PHOTOMICROGRAPHS OF A Ti-7.5Cr-7.5Mo ALLOY QUENCHED FROM 700 C



Heat treatments —
1. Annealed 1 hour at 700 C and quenched
2. Annealed 2 hours at 850 C; furnace cooled to 700 C, held 1 hour, and quenched
3. Annealed 4 hours at 1000 C; furnace cooled to 700 C, held 1 hour, and quenched

FIGURE 18. EFFECT OF PREVIOUS BETA ANNEALING TREATMENT ON TENSILE PROPERTIES OF A Ti-7.5 Cr-7.5 Mo ALLOY
All specimens quenched from 700 C

A-12063



Heat treatments
1. Annealed 1 hour at 700 C and quenched
2. Annealed 2 hours at 850 C; furnace cooled to 700 C, held 1 hour, and quenched
3. Annealed 4 hours at 1000 C; furnace cooled to 700 C, held 1 hour, and quenched

FIGURE 19. EFFECT OF PREVIOUS BETA ANNEALING TREATMENT ON MECHANICAL PROPERTIES OF A Ti-7.5Cr-7.5 Mo ALLOY
All specimens quenched from 700 C

A-12064

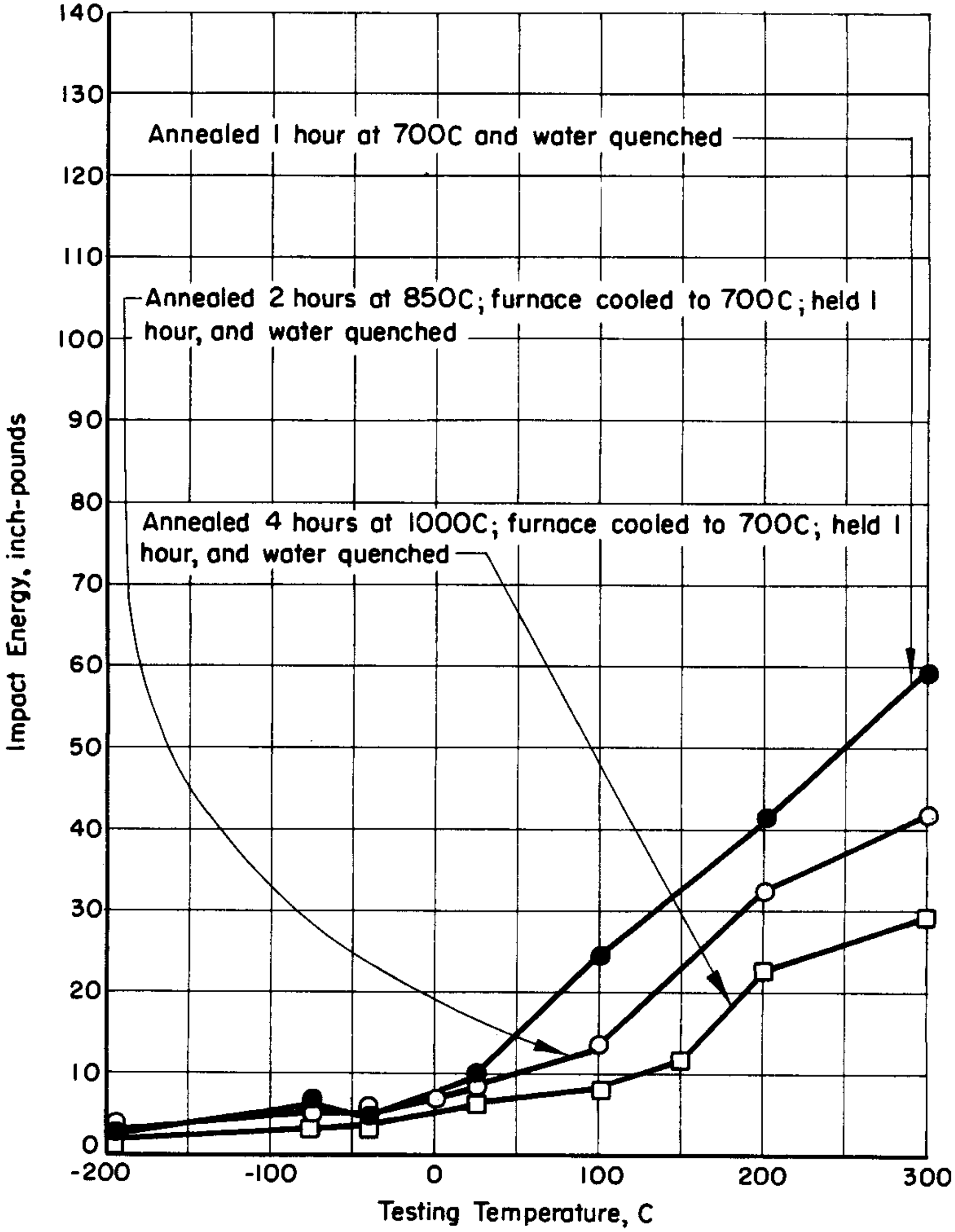


FIGURE 20. EFFECT OF PREVIOUS BETA ANNEALING TREATMENT ON IMPACT BEHAVIOR OF A Ti-7.5 Cr-7.5 Mo ALLOY
All specimens quenched from 700C

A-12065

TABLE 5. FATIGUE PROPERTIES OF A Ti-7.5Cr-7.5Mo ALLOY QUENCHED FROM 700 C

Heat Treatment	Mean Stress at 10^7 Cycles, psi		Tensile Strength, psi	Endurance-Limit Tensile-Strength Ratio	
	Unnotched	Notched		Unnotched	Notched
1 hour at 700 C and quenched	66,500± 5700	33,000± 4200	144,000	0.46	0.23
4 hours at 1000 C; furnace cooled to 700 C; held 1 hour at 700 C; quenched	48,000± 1400	32,900± 1400	138,000	0.35	0.24

Note: The method by which the fatigue limits and standard deviations were obtained is outlined in Appendix C.

Stability of the Metastable Beta Alloy

To evaluate the stability of this alloy, a series of stability checks was made on the five conditions previously described. The stability checks were made by 100-hour treatments at 200, 300, 400, and 500 C. The evaluation was made on a single sheet tensile specimen and a longitudinal bend-test specimen. The results of these tests are presented in Figure 21.

In almost every case, ductility is markedly decreased by the 100-hour treatment. Embrittlement is very severe at 300 and 400 C. At 200 C, the ductility is not completely lost, and overaging is apparent for the 500 C treatments. Hardness values increase to a maximum at 300 to 400 C, and decrease as the temperature is increased to 500 C. Tensile strengths do not follow the same pattern because of the excessive embrittlement. Bend ductilities are lowered to a minimum at 300 to 400 C, and some ductility is recovered by overaging at 500 C.

The effects of prior condition on stability are not entirely clear from these data. In general, the stability of specimens with large beta-grain sizes appears to be less than that for the smaller beta-grain size. This is also observed in the microstructures, in which the alpha precipitation appears to be more extensive for the larger beta-grain sizes for any one stability check. This is shown in Figure 22. The unusual microstructure of Figure 22d is composed of alpha plates formed during the 700 C anneal, with the dark-etching alpha precipitate formed during the stability check.

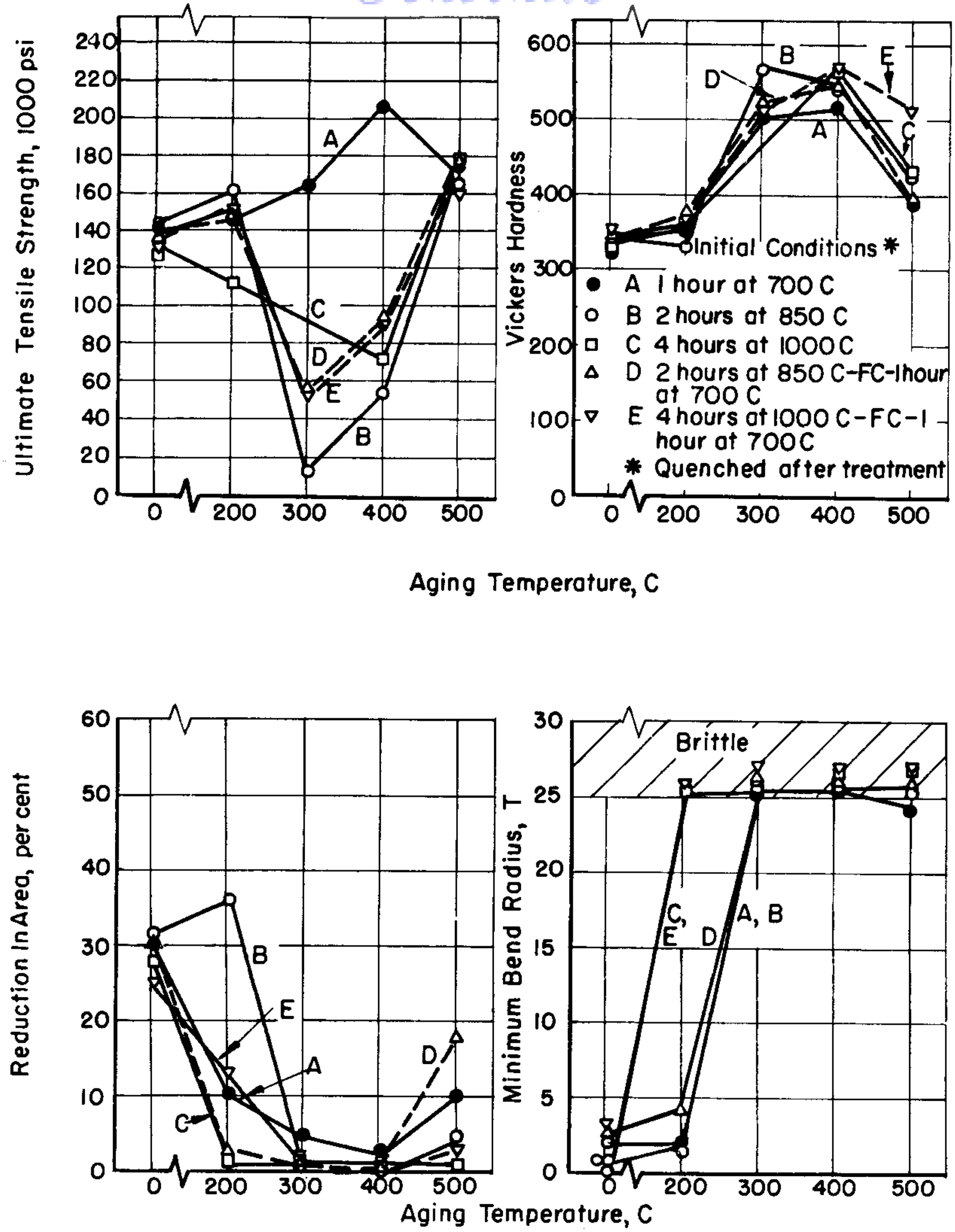
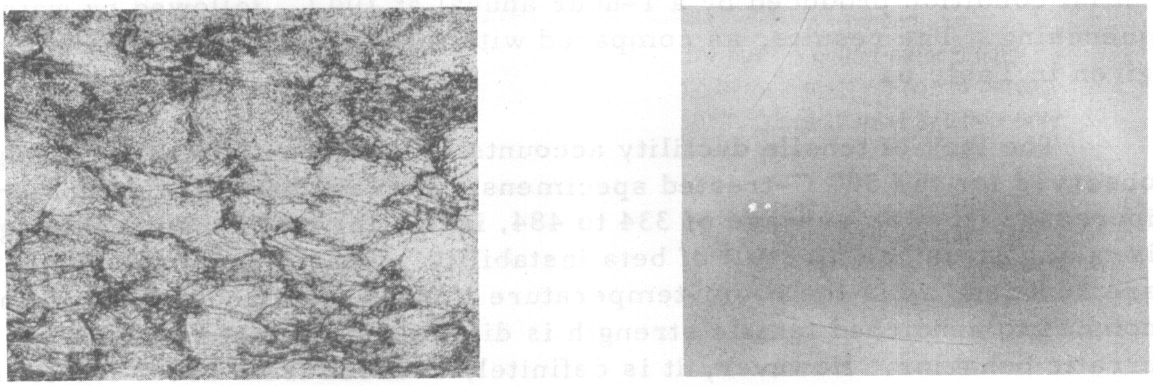


FIGURE 21. EFFECT OF AGING TEMPERATURE ON THE PROPERTIES OF A BETA-QUENCHED Ti-7.5 Cr-7.5 Mo ALLOY AGED FOR 200 HOURS

A-12066

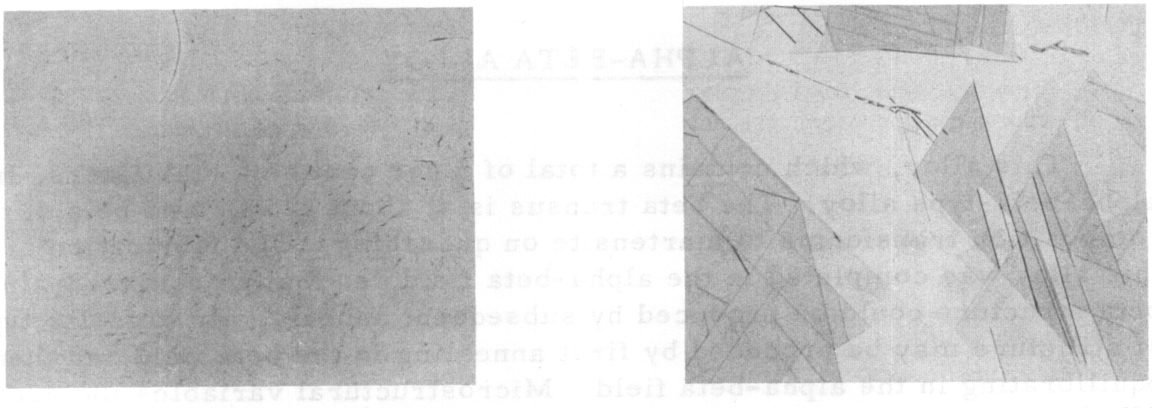


250X N11576

250X N11578

a. 1 Hour at 700 C and Quenched Plus
200 Hours at 400 C

b. 2 Hours at 850 C and Quenched Plus
200 Hours at 400 C



250X N11580

250X N11584

c. 4 Hours at 1000 C and Quenched Plus
200 Hours at 400 C

d. 4 Hours at 1000 C, Furnace Cooled
to 700 C, Held 1 Hour and
Quenched, Plus 400 Hours
at 400 C

FIGURE 22. MICROSTRUCTURES OF A Ti-7.5Cr-7.5Mo ALLOY IN AGED CONDITIONS

A more complete program of evaluation was included for a single stability check. This included a 100-hour treatment at 300 C, with the initial condition produced by a 1-hour anneal at 700 C, followed by water quenching. The results, as compared with the as-quenched condition, are given in Table 6.

The lack of tensile ductility accounts for the erratic tensile strength observed for the 300 C-treated specimens. Vickers hardness values are increased from an average of 334 to 484, indicating that considerable aging is taking place, as a result of beta instability. Tensile and bend ductilities are reduced, as is the room-temperature impact resistance. The ratio of notched to unnotched tensile strength is difficult to evaluate because of erratic behavior. However, it is definitely reduced from about 1.5 to less than 1.0, indicating a change to a notch-sensitive condition. Unlike the tensile and bend properties, the fatigue endurance limit is not changed significantly by the aging treatment. Thus, it appears that the embrittlement caused by the low-temperature precipitation of alpha is not shown up by fatigue tests. The deviation or scatter observed is greatest for the unnotched condition.

ALPHA-BETA ALLOY

This alloy, which contains a total of 5 per cent beta stabilizers, is an alpha-beta-type alloy. The beta transus is at about 825 C, and beta of this composition transforms to martensite on quenching. The fabrication of this alloy was completed in the alpha-beta field, so that an equiaxed-alpha-beta structure could be produced by subsequent anneals. An acicular type of structure may be produced by first annealing in the beta field and then equilibrating in the alpha-beta field. Microstructural variables include the grain size and shape of the equilibrated alpha-beta structures, and the prior beta-grain size of the transformed structures.

The heat treatments in the alpha-beta field may be designated as equilibrating or as stabilizing treatments. An equilibrating treatment is usually done at a relatively high temperature, and has the effect of decreasing the alpha-to-beta ratio as the equilibrating temperature increases. A stabilizing treatment may consist of either an isothermal anneal or a slow-cooling or step-cooling process, finishing at a relatively low temperature in the alpha-beta field. Its primary objective is to reject sufficient alpha that subsequent heating in the service-temperature range of 300 to 500 C will not cause precipitation of fine alpha, with a resultant loss in ductility.

These specimens were stabilized at 650 C, as a consequence of the erratic behavior of the specimens stabilized at 550 C in the preliminary studies. The effects of various equilibration treatments on mechanical

TABLE 6. MECHANICAL PROPERTIES OF A Ti-7.5Cr-7.5Mo ALLOY BEFORE AND AFTER AGING AT 300 C

	Annealed 1 Hour at 700 C and Water Quenched	Annealed 1 Hour at 700 C and Water Quenched; Annealed 100 Hours at 300 C and Water Quenched
Vickers Hardness	334	484
Ultimate Tensile Strength, psi	143,000	111,000-163,000
0.2% Offset Yield Strength, psi	135,000	--
Reduction in Area, per cent	34	0
Elongation, per cent	16	0
Notched Tensile Strength, psi	217,000	101,000
Notched Reduction in Area, per cent	7	5
Minimum Bend Radius, T	3	>24 (Brittle)
Room-Temperature Impact Energy, inch-pounds	10	2
Endurance Limit (10^7 Cycles), psi		
Unnotched Specimen	66,500 (±5800)	68,100 (±26,200)
Notched Specimen	33,000 (±4200)	39,500 (±3400)

TABLE 7. MECHANICAL PROPERTIES

Heat Treatment	Tensile Specimen[a]	Reduction in Area, per cent	Elongation, per cent	Ultimate Tensile Strength, psi	Proportional Limit, psi
Annealed 1 hour at 750 C; furnace cooled to 650 C; air cooled	Sheet(A)	34	20	106,000	59,000
Annealed 2 hours at 750 C; furnace cooled to 650 C; air cooled	Sheet(C)	38	13	99,000	63,000
Annealed 4 hours at 750 C; furnace cooled to 650 C; air cooled	Sheet(F)	29	18	107,000	72,000
Annealed 2 hours at 750 C; furnace cooled to 700 C; held 1 hour; furnace cooled to 650 C; held 2 hours; air cooled	Sheet(A)	32	19	104,000	61,000
Annealed 1 hour at 1000 C; furnace cooled to 650 C; air cooled	Sheet(A)	36	25	96,000	52,000
Annealed 1 hour at 1000 C; furnace cooled to 750 C; held 1 hour; furnace cooled to 650 C; air cooled	Sheet	26	20	107,000	67,000
Annealed 1 hour at 1000 C; furnace cooled to 750 C; held 2 hours; furnace cooled to 650 C; air cooled	Sheet(B)	34	19	106,000	65,000
Annealed 1 hour at 1000 C; furnace cooled to 750 C; held 4 hours; furnace cooled to 650 C; air cooled	Sheet(C)	36	23	101,000	63,000
Annealed 1 hour at 1000 C; furnace cooled to 750 C; held 2 hours; furnace cooled to 700 C; held 1 hour; furnace cooled to 650 C; held 2 hours; air cooled	Sheet(B)	33	18	96,000	59,000

(a) The letters in parentheses identify individual specimens.

OF A Ti-2.5Cr-2.5Mo ALLOY

0.01% Offset Yield Strength, psi	0.1% Offset Yield Strength, psi	0.2% Offset Yield Strength, psi	Vickers Hardness, 5-Kg Load	Flow Constants, $\sigma = B\delta^n$		
				B, psi	n	δ_{max}, in./in.
71,000	90,000	94,000	281	156,000	0.124	0.118
70,000	84,000	86,000	256	148,000	0.126	0.116
78,000	92,000	96,000	308	152,000	0.102	0.125
74,000	88,000	92,000	295	150,000	0.114	0.144
59,000	76,000	81,000	273	142,000	0.128	0.129
73,000	86,000	90,000	288	159,000	0.132	0.117
71,000	85,000	89,000	278	165,000	0.148	0.152
69,000	82,000	85,000	296	152,000	0.128	0.126
65,000	79,000	82,000	279	143,000	0.130	0.134

properties were determined using single tensile and bend tests for evaluation. The full evaluation was made under selected conditions.

Effects of Equilibration Treatments on Mechanical Properties

The equilibration treatments used in this program were designed to produce equiaxed and acicular alpha-beta structures of various degrees of fineness. In addition, the effects of equilibration time and cooling procedure were investigated.

Heat treatments and the resulting mechanical properties for these tests are presented in Table 7. These data provide a comparison between isothermal holding times for both equiaxed and acicular alpha-beta structures. The comparison between a direct furnace cool and a step cool to the stabilizing temperature can also be made for both equiaxed and acicular conditions.

These results show no consistent dependence of mechanical properties on either alpha-beta grain size or shape. The final schedule of heat treatments was designed, accordingly, to produce a much greater variation of alpha-beta-grain size. Also, equilibrated acicular alpha-beta structures were prepared from two prior beta-grain sizes.

Effects of Alpha-Beta-Grain Size and Shape on Mechanical Properties

The full-scale testing program for the Ti-2.5Cr-2.5Mo alloy was carried out using two equiaxed alpha-beta-grain sizes and equilibrated acicular alpha-beta structures of two prior beta-grain sizes. The effects of annealing temperature and annealing time on grain size were studied. Grain-size measurements were made using Jefferies' method, although the finer structures were difficult to measure. Results of the grain-size measurements are presented graphically in Figure 23. These data show that grain growth in the equiaxed alpha-beta structures is slow, particularly at the lower temperatures. The beta-grain sizes, produced by annealing above the beta transus, are much larger, and may be varied by varying the time and temperature.

Photomicrographs of the test conditions are presented in Figure 24. All structures were equilibrated at 750 C, and stabilized by furnace cooling to 650 C. The same alpha-to-beta ratio is found in all four microstructures.

Complete mechanical-property data for this alloy are presented in Appendix A. Tension-test results are summarized in Figure 25, and other mechanical properties are shown in Figure 26.

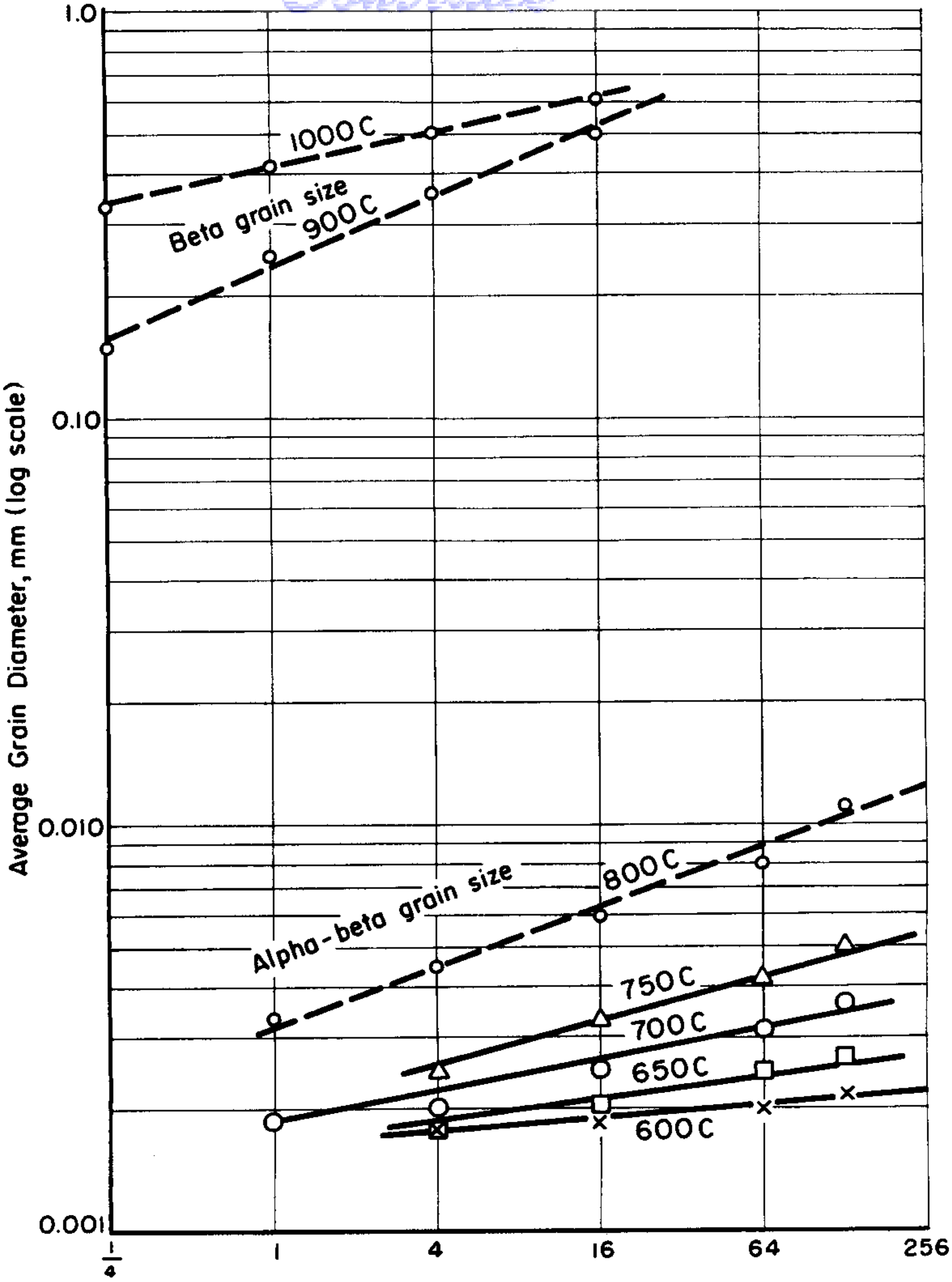
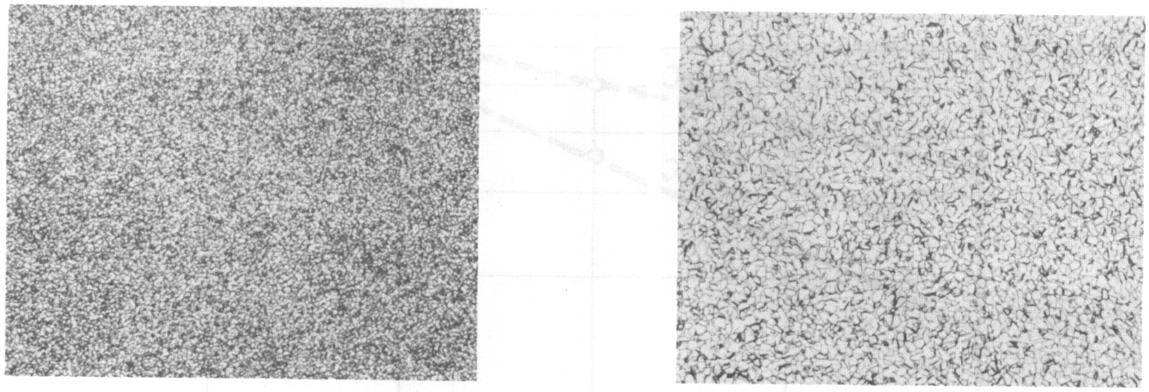


FIGURE 23. EFFECT OF ANNEALING TEMPERATURE AND TIME ON THE GRAIN SIZE OF A Ti-2.5 Cr-2.5 Mo ALLOY

A-12067

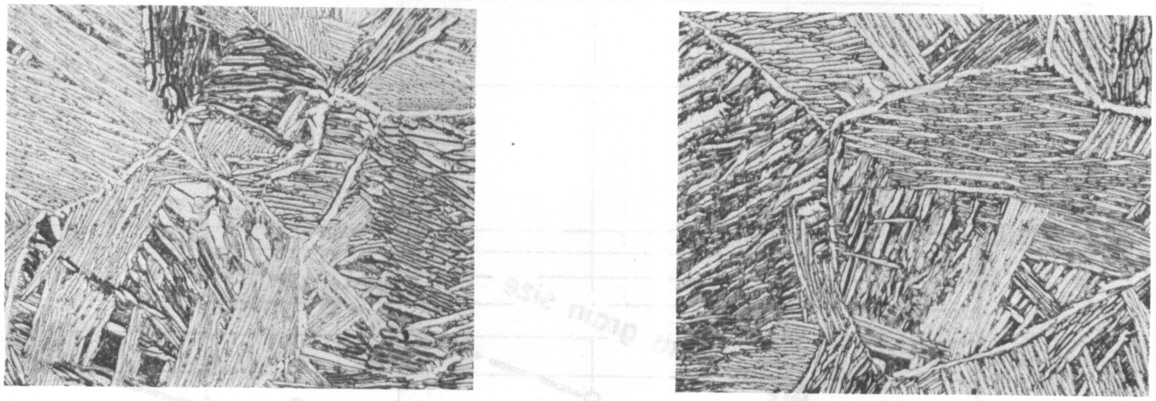


250X N15424

a. Annealed 1 Hour at 750 C, Furnace Cooled to 650 C, and Air Cooled

250X N15421

b. Annealed 64 Hours at 750 C, Furnace Cooled to 650 C, and Air Cooled



250X N15422

c. Annealed 1/2 Hour at 900 C, Furnace Cooled to 750 C, Held 1 Hour, Furnace Cooled to 650 C, and Air Cooled

250X N15423

d. Annealed 1 Hour at 1000 C, Furnace Cooled to 750 C, Held 1 Hour, Furnace Cooled to 650 C, and Air Cooled

FIGURE 24. MICROSTRUCTURES OF A Ti-2.5Cr-2.5Mo ALLOY

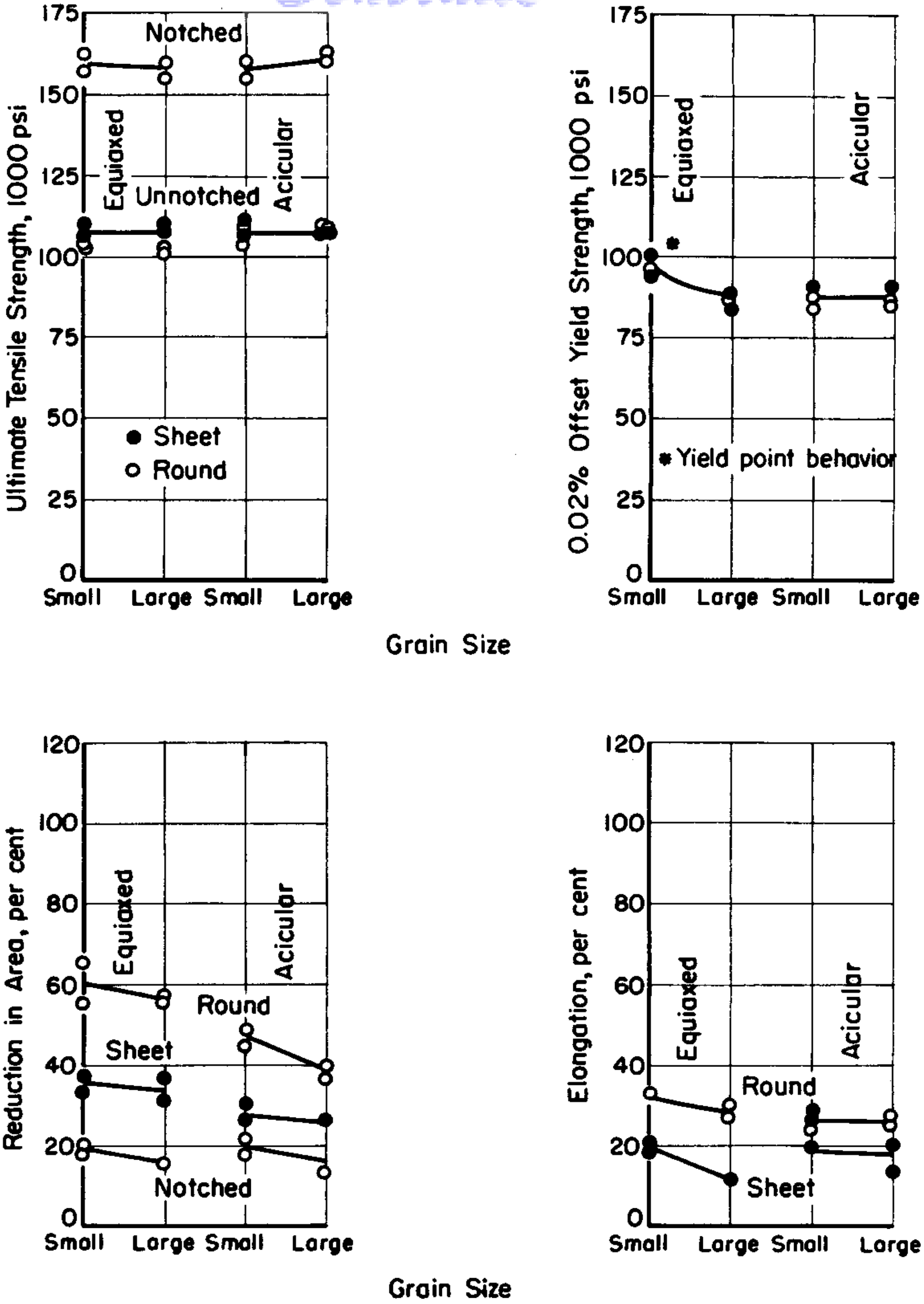


FIGURE 25. EFFECT OF ALPHA-BETA GRAIN SIZE AND SHAPE ON TENSILE PROPERTIES OF A Ti-2.5 Cr-2.5 Mo ALLOY

A-12068

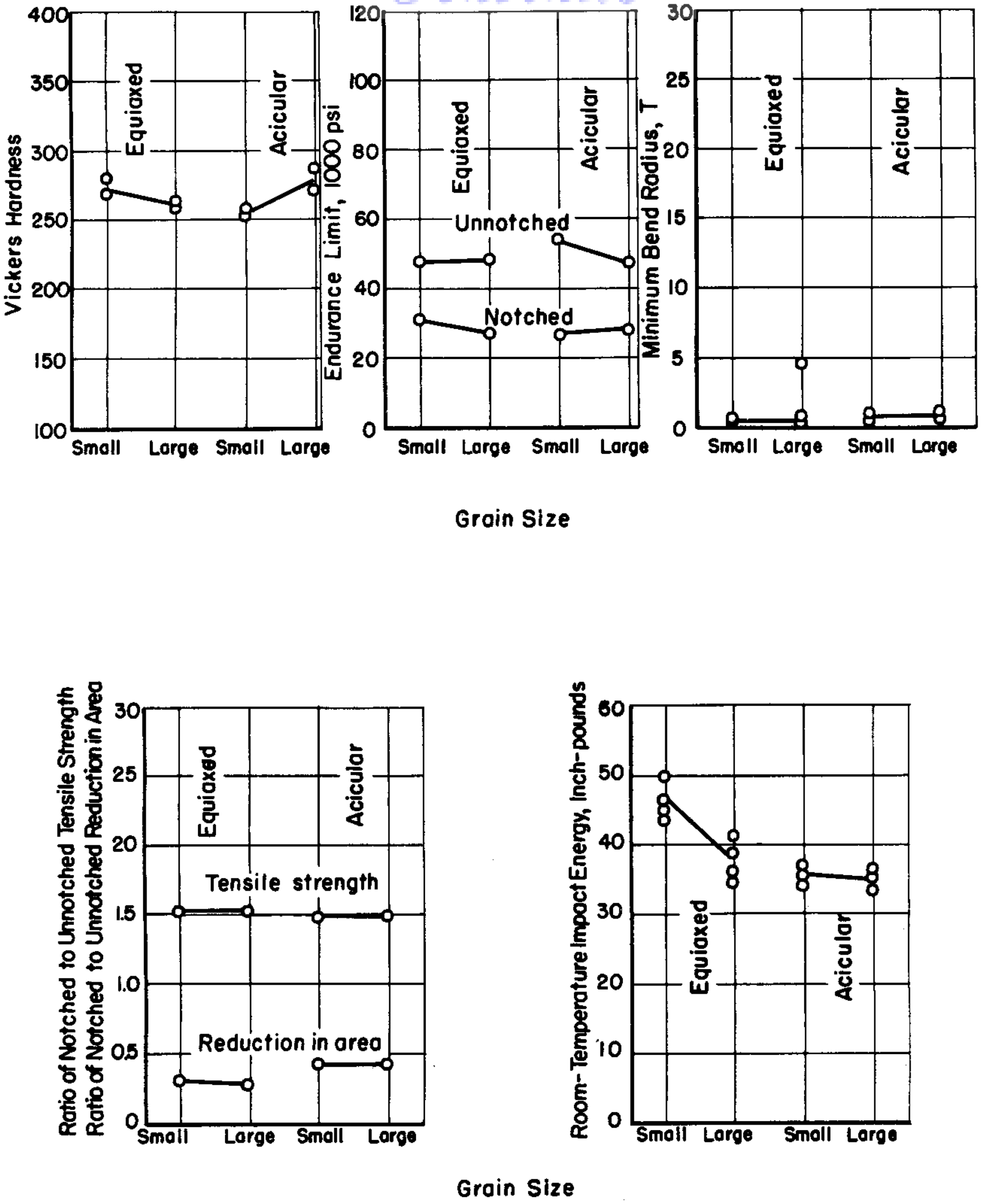


FIGURE 26. EFFECT OF ALPHA-BETA GRAIN SIZE AND SHAPE ON MECHANICAL PROPERTIES OF A Ti-2.5 Cr-2.5 Mo ALLOY

A-12069

Tensile strength is not affected appreciably by either the shape or the size of the alpha-beta structure. This is the case for notched and unnotched round specimens, and for unnotched sheet specimens. Yield strengths, except for the small equiaxed alpha-beta structure, also are unaffected by microstructure. The increased yield strength observed for the small equiaxed alpha-beta structure may be the result of yield-point behavior observed in this condition. The yield point was observed in this alloy only for the shortest annealing time at the lowest annealing temperature, 1 hour at 750 C. The factors governing its appearance are not known. Such behavior usually is associated with interstitial additions, but is not uncommon in alpha-beta alloys. Ductilities, particularly reductions in area, are higher for the equiaxed than for the acicular-type structures. Ductilities are also better for the finer grained equiaxed alpha-beta specimens than for the coarse-grained specimens.

Vickers hardnesses decrease slightly as the alpha-beta-grain size is increased; however, an increase in prior beta-grain size increases the hardness. This may be caused by increased diffusion of contaminants from the surface during heat treatment, although a protective atmosphere was used.

The ratio of notched to unnotched tensile strength varies from 1.50 to 1.55, indicating no structural effect and a generally notch-insensitive condition.

Although the reduction-in-area values of unnotched equiaxed specimens are greater than those of the acicular specimens, about 60 per cent, as compared with 45 per cent, the reduction in area of notched specimens is about the same in both conditions, about 20 per cent. These high reduction-in-area values for notched tensile specimens indicate lack of notch sensitivity at room temperature.

The results of the fatigue tests are given in Table 8. Except for the small-acicular-grain-size condition (1/2 hour at 900 C), there is no significant change in endurance limit with change in microstructure. The unnotched endurance limit for the small-acicular-grain-size condition is the highest obtained for this alloy. The ratio of endurance limit to tensile strength is excellent for all conditions, ranging from 0.44 to 0.55 for the unnotched condition and from 0.26 to 0.29 for the notched condition. These data show that alpha-beta alloys can be produced that have high endurance limit ratios.

Bend ductility, both longitudinal and transverse, was found to be high for both equiaxed and acicular conditions. No dependence of bend ductility on microstructure or rolling direction was observed. These tests were conducted on quadruplicate specimens for each rolling direction and microstructural condition.

TABLE 8. FATIGUE PROPERTIES OF A Ti-2.5Cr-2.5Mo ALLOY

Heat Treatment	Mean Stress at 10^7 Cycles, psi		Tensile Strength, psi	Endurance-Limit Tensile-Strength Ratio	
	Unnotched	Notched		Unnotched	Notched
1 hour at 750 C; furnace cooled to 650 C; air cooled	48,200±1300	31,500±2600	109,000	0.44	0.29
64 hours at 750 C; furnace cooled to 650 C; air cooled	49,100±2900	27,800±2100	102,000	0.48	0.27
1/2 hour at 900 C; furnace cooled to 750 C; held 1 hour; furnace cooled to 650 C; air cooled	55,000±4000	27,200±1300	106,000	0.52	0.26
1 hour at 1000 C; furnace cooled to 750 C; held 1 hour; furnace cooled to 650 C; air cooled	48,000±3800	28,200±1700	108,000	0.45	0.26

The room-temperature impact resistance was found to be greater for small than for large equiaxed-grain sizes. Also, the specimens with equiaxed structures are more resistant to impact than those with acicular structures. The effects of grain size and shape on impact-energy values are more pronounced at higher temperatures. This is illustrated by the curves of Figure 27.

The impact resistance of equiaxed-alpha-beta specimens increases almost linearly with testing temperature up to about 300 C, with higher values apparent for the smaller grain size. Impact-energy values for the specimens with acicular structures also increase with testing temperature, but much less rapidly. No effect of prior beta-grain size is apparent.

The impact-energy-temperature curves of this type are typical of alpha-beta alloys, and illustrate a condition between transition (beta) and nontransition (alpha) behavior. The advantage of the fine-grained equiaxed-alpha-beta structure is clear in this test.

From the data presented above, the following conclusions may be drawn:

(1) Tensile strengths are unaffected by alpha-beta-grain size and/or shape. Yield-point behavior is observed for the fine equiaxed-alpha-beta condition; otherwise, yield strengths are not influenced by grain size or shape.

(2) Ductilities and impact-energy values are higher in the equiaxed than in the acicular condition. Also, the specimens with fine alpha-beta structures are tougher and more ductile than those with coarser structures. This implies that some loss of ductility and toughness may be expected when an alpha-beta alloy is heated into the beta field. Acceptable levels of toughness and ductility may be produced, however, by proper equilibration treatment.

Aging Response of an Alpha-Beta Alloy

The instability of the beta phase in an alpha-beta alloy may be expected when the stabilization treatment is not employed. Samples were annealed for 1 hour at 750 C and water quenched for use in these studies. The aging treatments consisted of 1-, 4-, 16-, and 64-hour treatments at 400 and at 500 C. Typical microstructures are presented in Figures 28 and 29. Evaluation was made on the basis of tensile tests (notched and unnotched), hardness, bend tests, and impact tests at a number of temperatures. The results of these tests are presented in Appendix A.

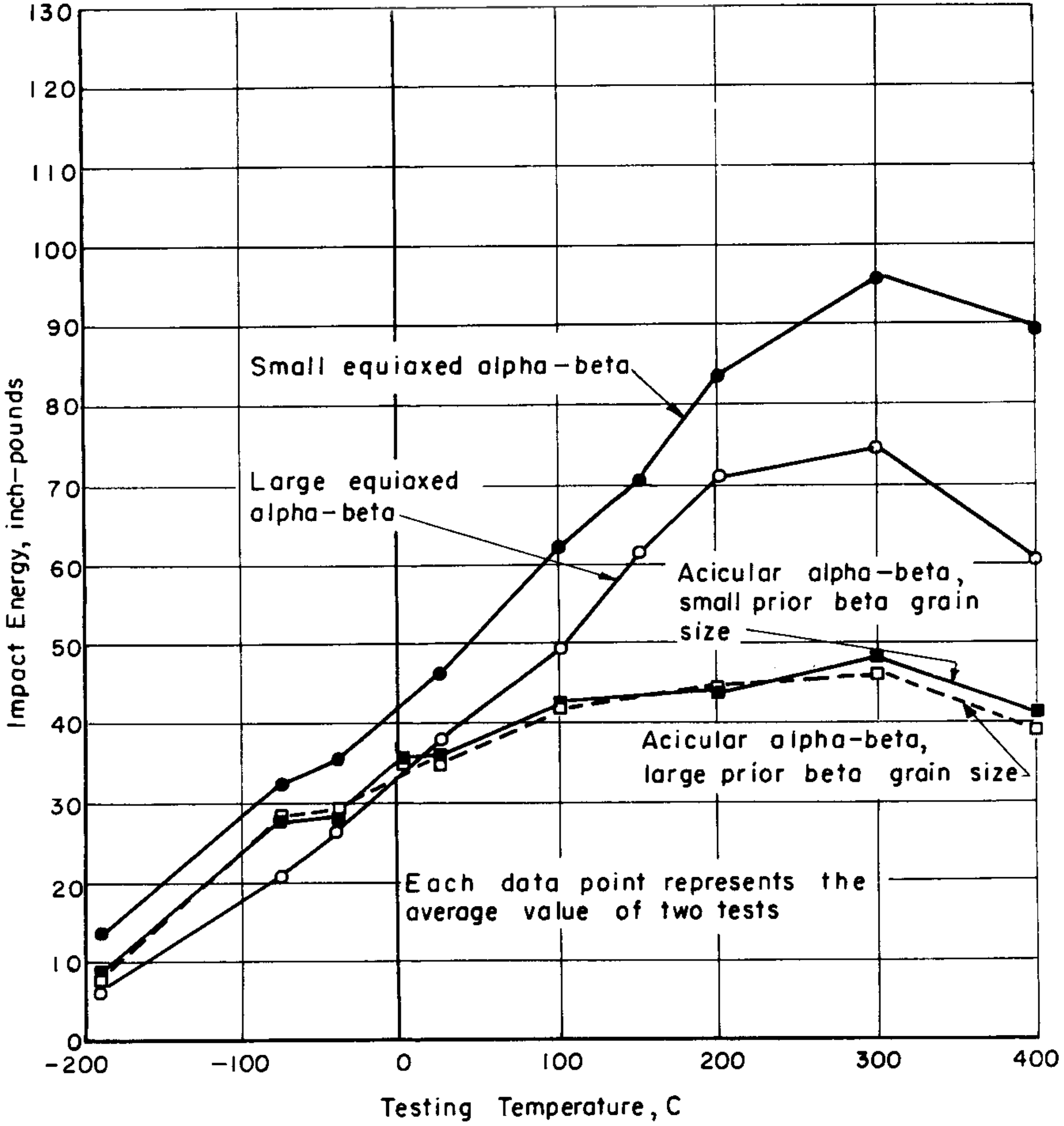
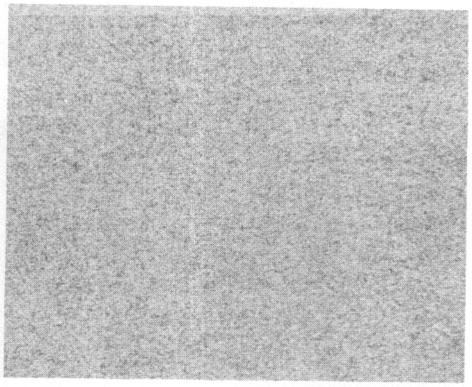
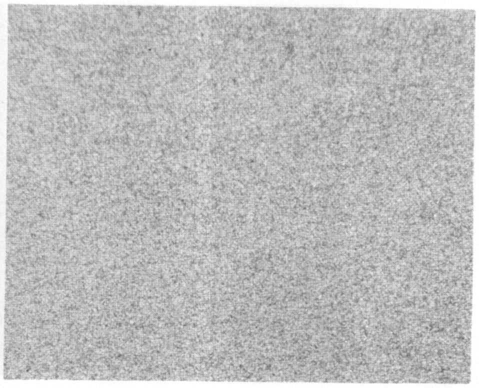


FIGURE 27. EFFECT OF TESTING TEMPERATURE ON IMPACT BEHAVIOR OF A Ti-2.5 Cr-2.5 Mo ALLOY IN THE EQUIAXED AND ACICULAR ALPHA-BETA CONDITIONS

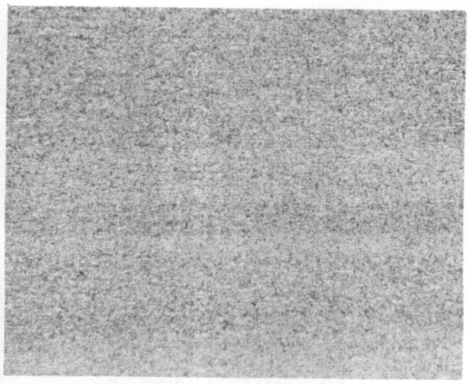
A-12070



a. Annealed 1 Hour at 750 C and Quenched;
No Aging Treatment

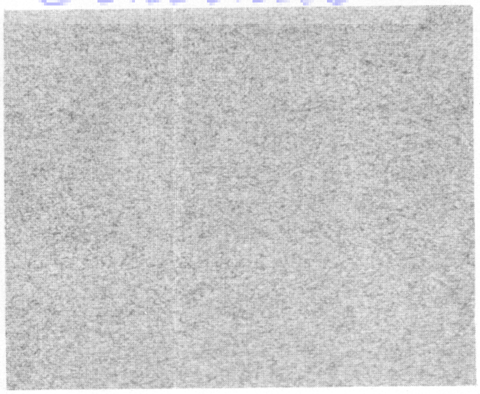


b. Annealed 1 Hour at 750 C and Quenched;
Aged 1 Hour at 400 C and Quenched



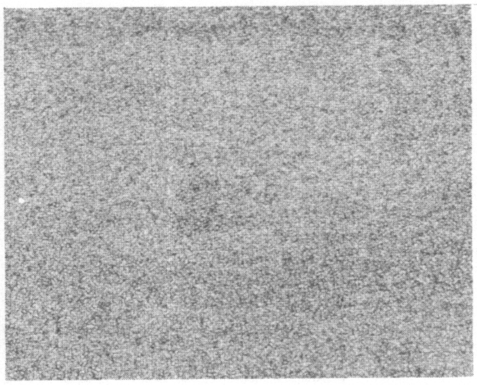
c. Annealed 1 Hour at 750 C and Quenched;
Aged 16 Hours at 400 C and Quenched

FIGURE 28. MICROSTRUCTURES OF A Ti-2.5Cr-2.5Mo ALLOY AGED AT 400 C



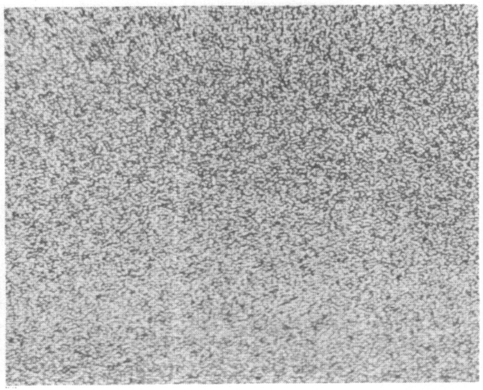
250X N11569

a. Annealed 1 Hour at 750 C and Quenched; No Aging Treatment



250X N11572

b. Annealed 1 Hour at 750 C and Quenched; Aged 1 Hour at 500 C and Quenched



250X N11573

c. Annealed 1 Hour at 750 C and Quenched; Aged 16 Hours at 500 C and Quenched

FIGURE 29. MICROSTRUCTURES OF A Ti-2.5Cr-2.5Mo ALLOY AGED AT 500 C

The specimens in the initial quenched condition have a tensile strength about 30 per cent higher than that of the equivalent stabilized alloy. This is a result of the lower alpha-to-beta ratio in the quenched condition. The instability of the quenched specimens is shown graphically in Figures 30, 31, and 32, which show the effects of low-temperature aging on mechanical properties.

Greatest response is observed for the 400 C aging treatments. Maximum tensile strength and hardness, and very low ductilities, occur at aging times of from 1 to 16 hours. Overaging is apparent after 64 hours, although ductility is not restored completely. Peak hardness and tensile strength are produced by the 4-hour aging at 400 C. Bend ductility is completely lost for aging treatments up to 64 hours at 400 C, but shows a tendency toward recovery with overaging at 500 C. The notched tensile strengths appear to be controlled by ductility, and the tensile strength lost initially is restored as the ductility is increased with overaging.

Overaging occurs quite rapidly for specimens treated at 500 C. Strength and hardness decrease with increasing aging time, whereas ductilities remain nearly constant. Bend ductilities show some scatter, but show no consistent effect of aging at this temperature.

Aging at 400 or 500 C adversely affects the notched toughness, as shown in Figure 33. The impact resistance decreases markedly when this alloy is aged at either 400 or 500 C.

EFFECTS OF VACUUM ANNEALING ON MECHANICAL PROPERTIES

The effects of hydrogen on the mechanical properties of titanium and its alloys are known to be significant in many cases. Although this work has not been concerned primarily with this problem, one condition for each alloy was studied before and after a vacuum annealing treatment. The vacuum annealing treatment used consisted of a 24-hour anneal at 1600 F, at a limiting cold vacuum of 10^{-4} to 10^{-5} mm of mercury. The effect of this treatment on the quantity of hydrogen present in the alloys is shown in Table 9.

It may be observed from these data that the initial hydrogen content of these alloys is in the range expected for good commercial practice. The hydrogen contents of the commercial titanium and the Ti-2.5Cr-2.5Mo alloy were not changed appreciably by the vacuum annealing treatment. The initial hydrogen level of the Ti-7.5Cr-7.5Mo alloy was somewhat higher, and the concentration of hydrogen was reduced by the vacuum anneal. The hydrogen concentrations of all three alloys were at about the same level after vacuum annealing.

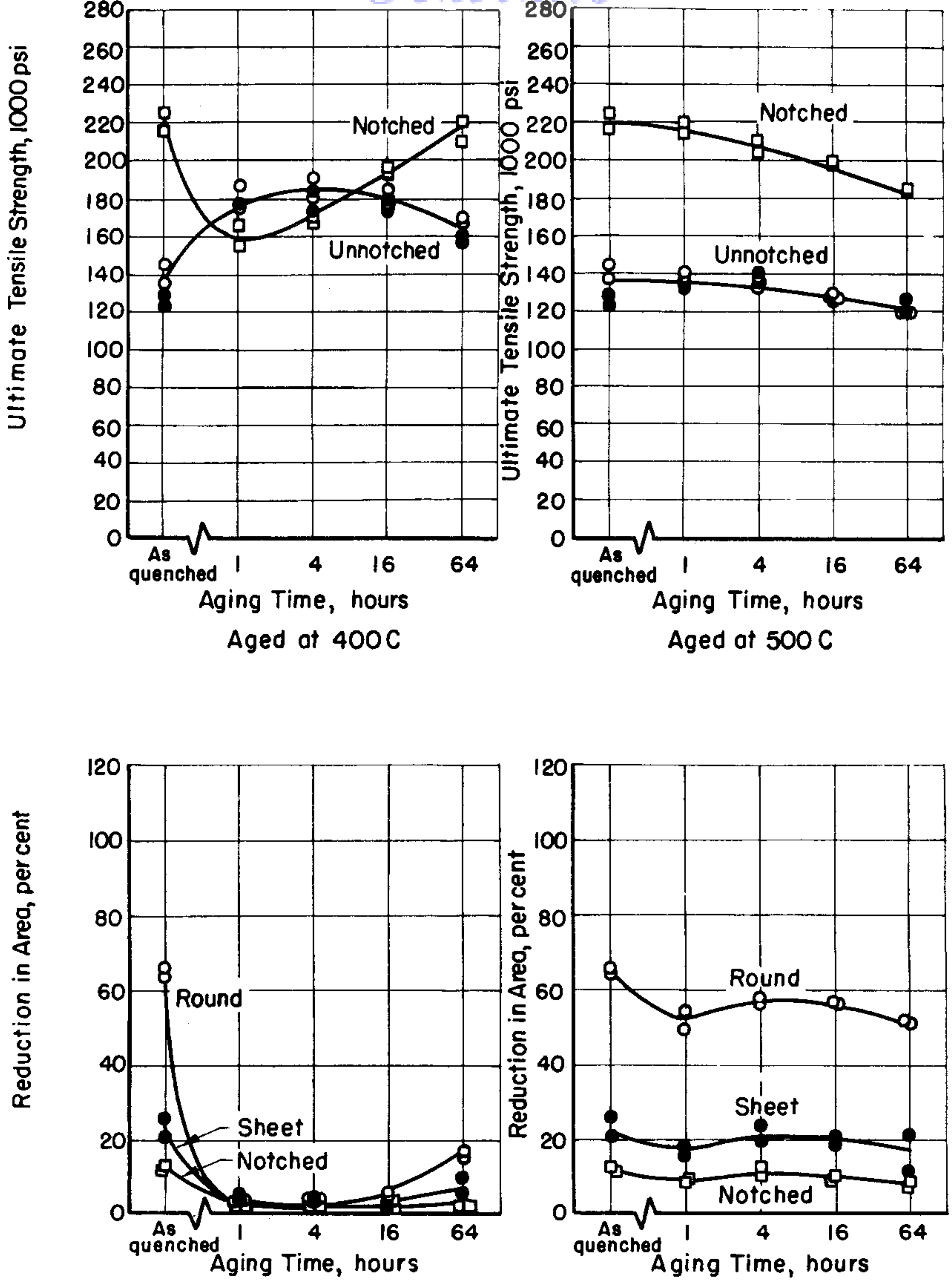
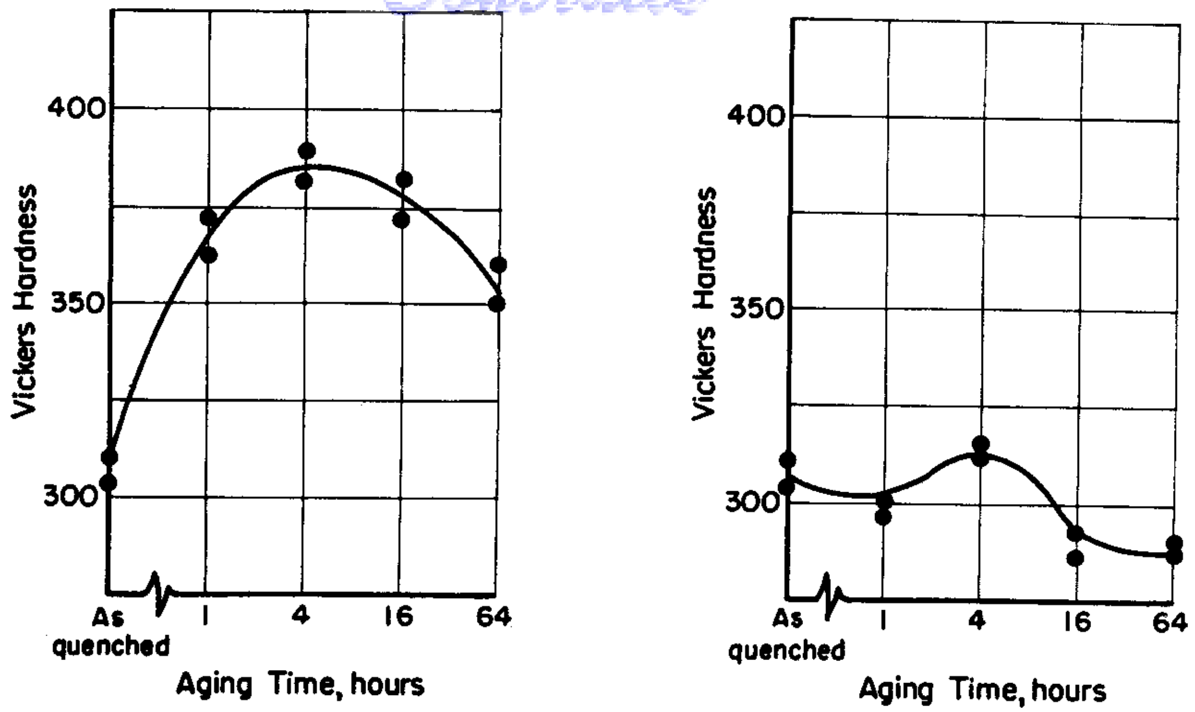


FIGURE 30. EFFECT OF AGING TIME ON THE TENSILE PROPERTIES OF A Ti-2.5 Cr-2.5 Mo ALLOY SOLUTION ANNEALED AT 750 C AND AGED AT 400 AND 500 C

A-12071



Aged at 400C

Aged at 500C

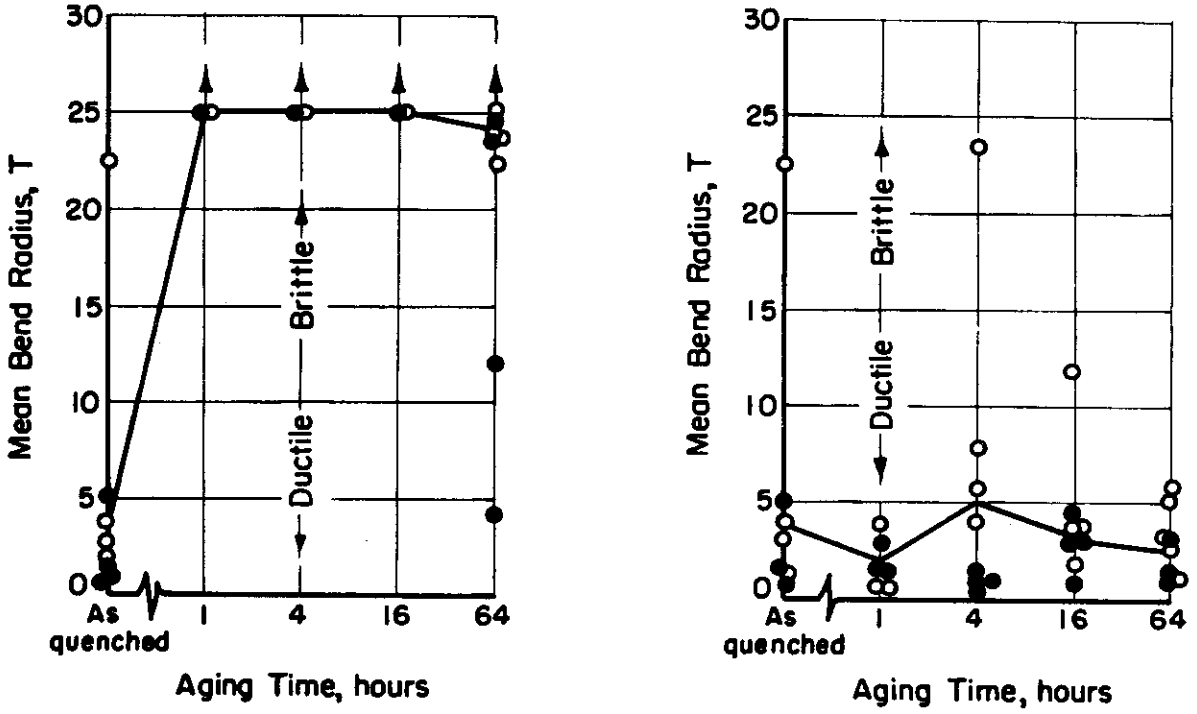


FIGURE 31. EFFECT OF AGING TIME ON HARDNESS AND BEND PROPERTIES OF A Ti-2.5Cr-2.5Mo ALLOY SOLUTION ANNEALED AT 75C AND AGED AT 400 AND 500C

A-12072

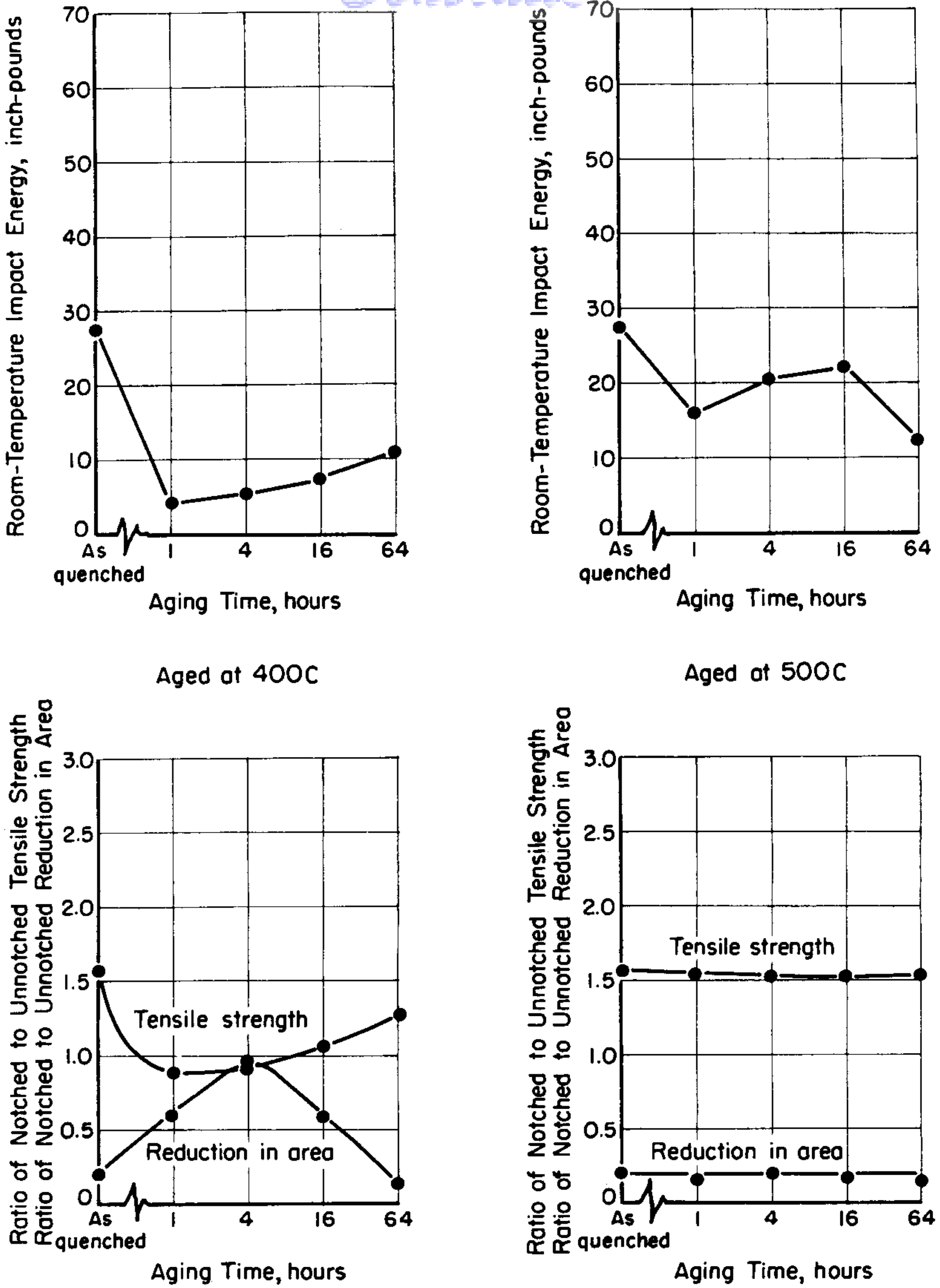


FIGURE 32. EFFECT OF AGING TIME ON MECHANICAL PROPERTIES OF A Ti-2.5Cr-2.5Mo ALLOY SOLUTION ANNEALED AT 750C AND AGED AT 400 AND 500C

A-12073

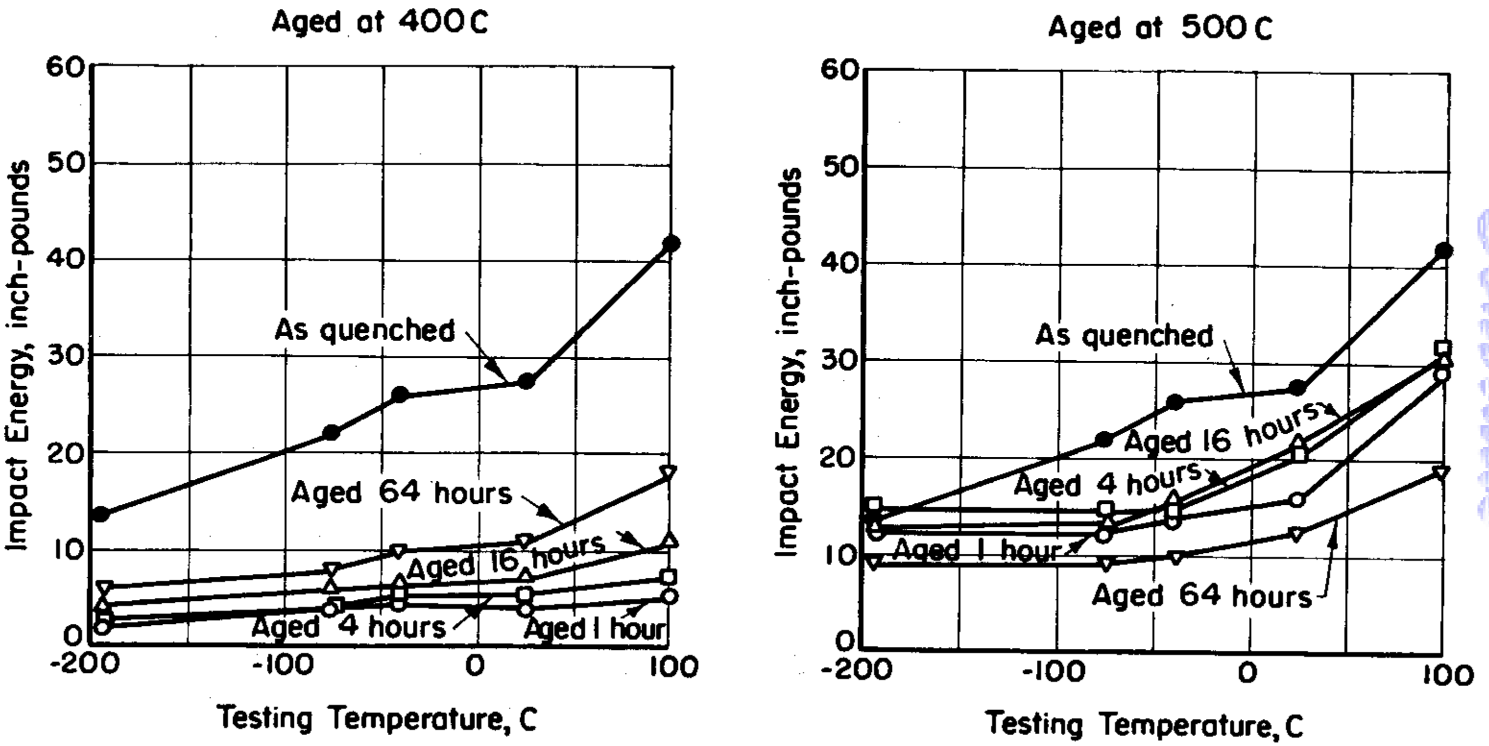


FIGURE 33. EFFECT OF TESTING TEMPERATURE ON IMPACT BEHAVIOR OF A Ti-2.5Cr-2.5Mo ALLOY SOLUTION ANNEALED AT 750C AND AGED AT 400 AND 500C

A-12074

TABLE 9. EFFECT OF VACUUM ANNEALING ON HYDROGEN CONCENTRATION

Alloy	Hydrogen Concentration, ppm Before Vacuum Annealing	Hydrogen Concentration, ppm After Vacuum Annealing
Commercial titanium	31	30
Ti-2.5Cr-2.5Mo alloy	44	41
Ti-7.5Cr-7.5Mo alloy	60	37

The mechanical properties of the vacuum-annealed specimens are included in Appendix A. Because the initial and final hydrogen concentrations were of the same order of magnitude, no great differences in mechanical properties could be expected. A very slight increase in impact-energy values was observed for the commercial titanium after vacuum annealing. The other properties were unaffected by vacuum annealing.

IMPACT-TEST CORRELATION

In order to conserve material, the impact behavior of these alloys was studied using a substandard round Izod specimen. In addition, impact-transition studies were made for one condition of each alloy using the standard V-notch Charpy impact specimen. Thus, a direct comparison may be made between the results of the two test specimens for each alloy type. The V-notch Charpy specimens were tested in an Amsler Universal impact-testing machine, in which the impact velocity and total available energy may be adjusted. When possible, the impact velocity was kept at 11.62 feet per second, which is the velocity closest to that of the micro impact test (11.37 feet per second). In some instances, however, the total available energy was insufficient at this setting, and higher velocities were employed. The results of these tests are presented in Figures 34, 35, and 36.

These data show that impact behavior can be determined adequately by either impact test. The scatter in impact-energy values is about the same for both tests, except for the Ti-2.5Cr-2.5Mo alloy, in which quite a large scatter is observed for the V-notch Charpy specimens. This is caused in part by the insufficient energy at the lower velocity settings.

The correlation between impact-energy values is affected by microstructure. For the commercial titanium, which is primarily alpha phase, the numerical values obtained for the micro impact test (in inch-pounds)

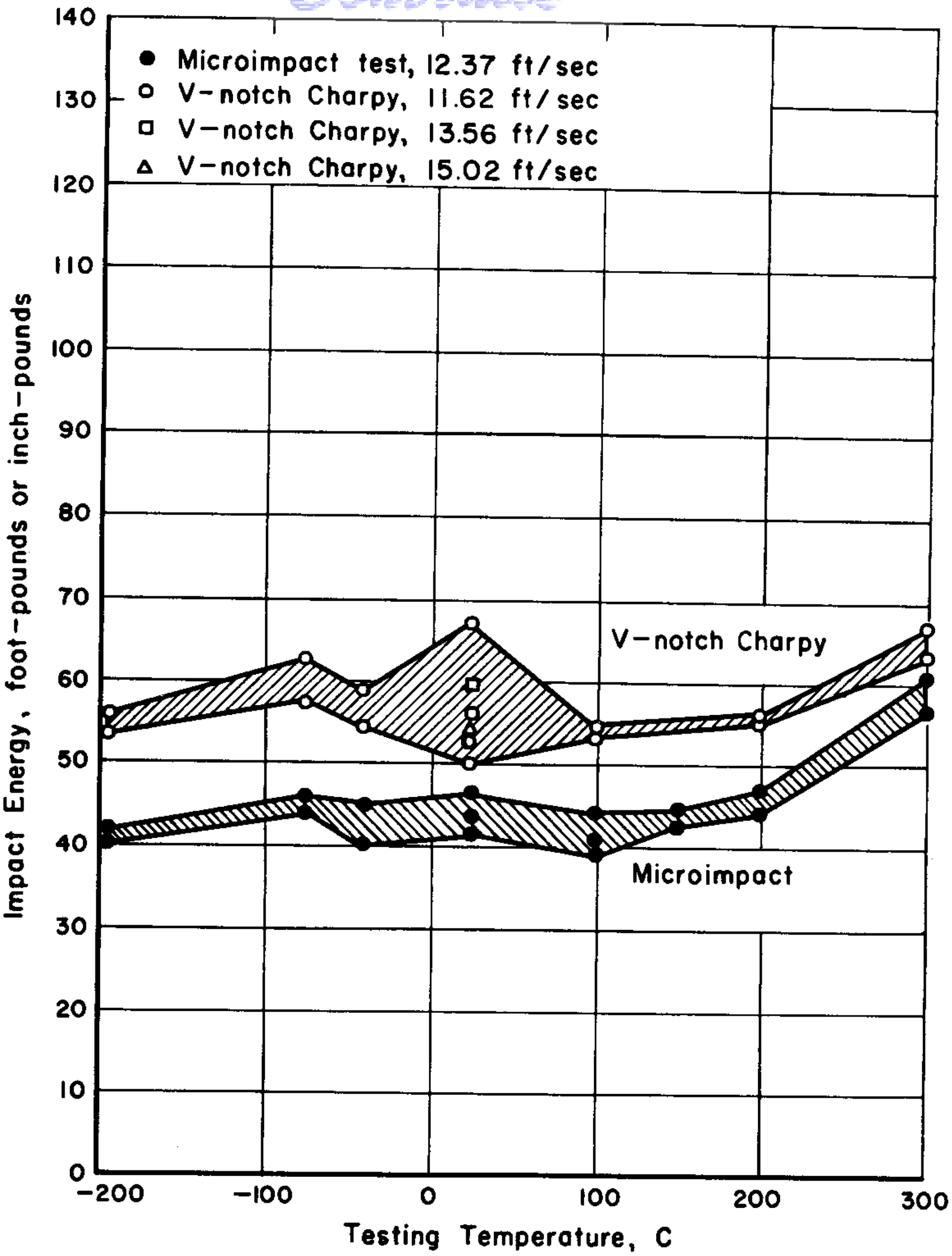


FIGURE 34. CORRELATION OF MICROIMPACT DATA WITH V-NOTCH CHARPY DATA FOR COMMERCIAL-PURITY TITANIUM

A-12075

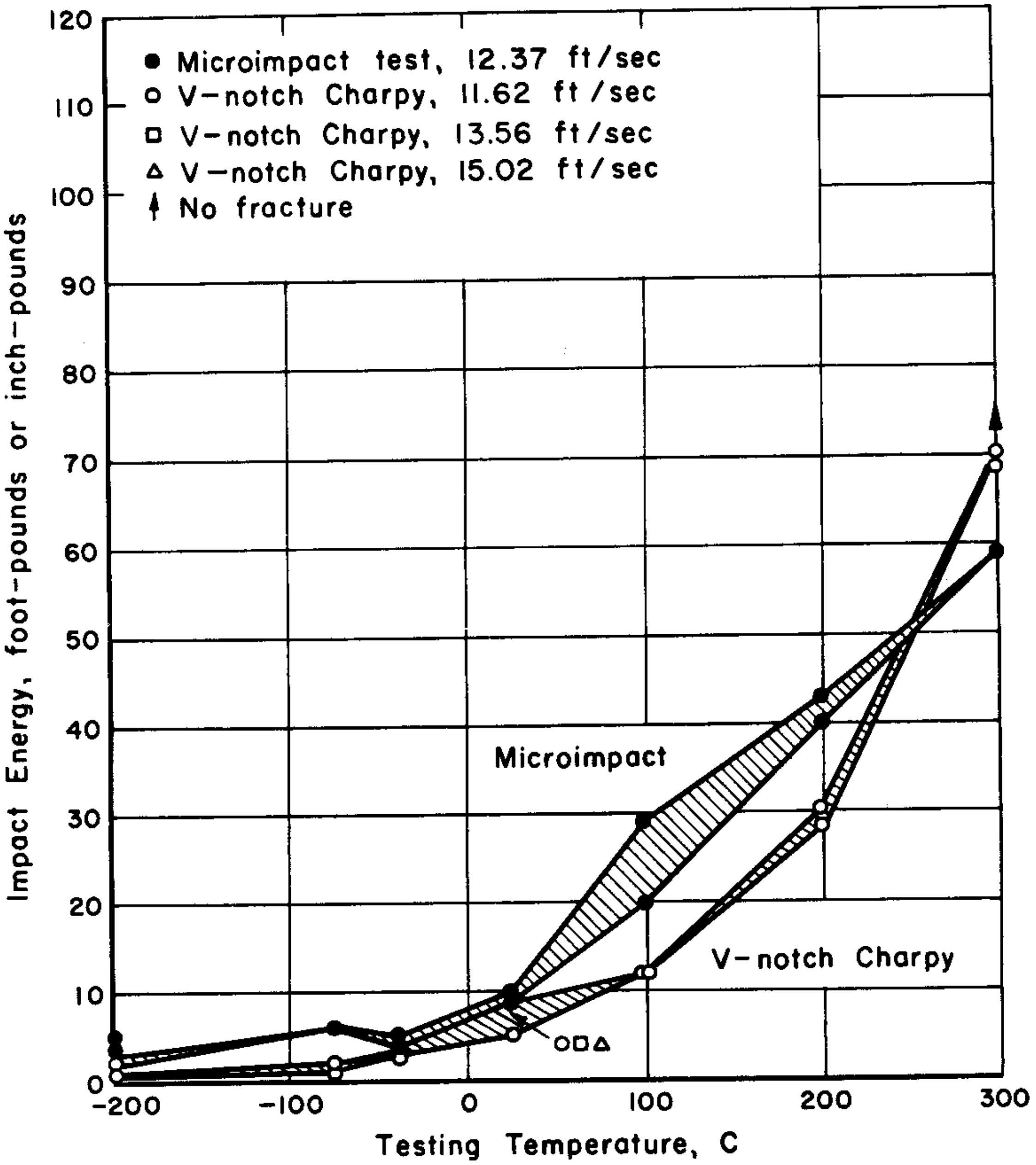


FIGURE 35. CORRELATION OF MICROIMPACT DATA WITH V-NOTCH CHARPY DATA FOR A Ti−7.5 Cr −7.5 Mo ALLOY

A-12076

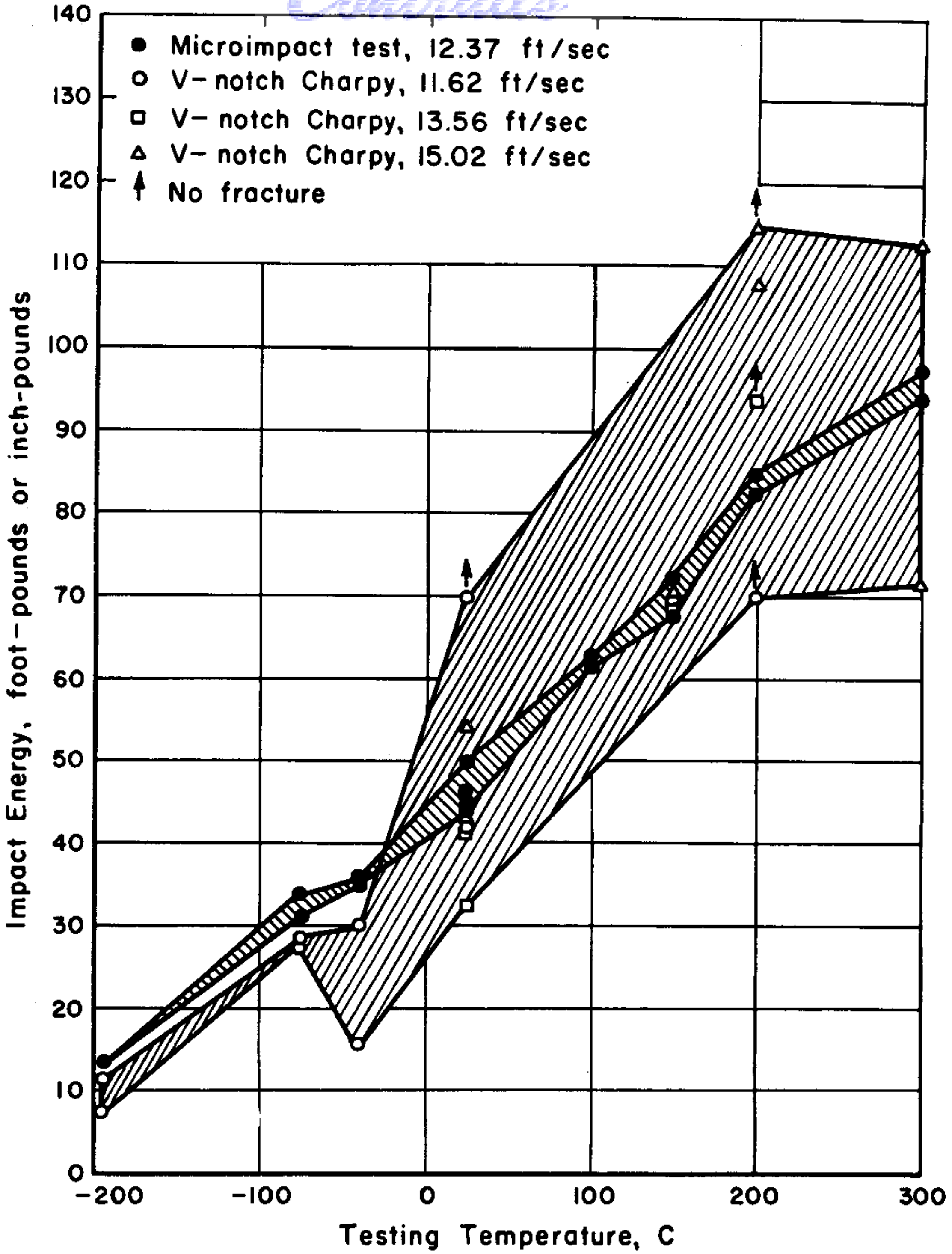


FIGURE 36. CORRELATION OF MICROIMPACT DATA WITH V-NOTCH CHARPY DATA FOR A Ti-2.5 Cr-2.5 Mo ALLOY

A-12078

are lower than those for the V-notch Charpy test (in foot-pounds). For the Ti-7.5Cr-7.5Mo alloy, which is predominantly beta phase, the reverse is the case. For the alpha-beta alloy (Ti-2.5Cr-2.5Mo), the numerical values are about the same. Transition temperatures appear to be about the same for both specimens.

The effect of impact velocity was investigated by using the V-notch Charpy specimens tested at room temperature. The results show considerable scatter, and do not indicate any consistent effect of impact velocity on impact energy absorbed. This is illustrated by the data tabulated below.

	Impact-Energy Values (V-Notch Charpy Specimens), foot-pounds		
Alloy	11.62 Feet Per Second	13.56 Feet Per Second	15.02 Feet Per Second
Commercial titanium	50.0; 50.5; 53.0; 56.5	59.5; 67.0	54.0; 67.0
Ti-2.5Cr-2.5Mo alloy	42.5; >70	32.5; 41.5	43.0; 54.5
Ti-7.5Cr-7.5Mo alloy	5.0; 7.0; 7.0; 8.0	8.0; 8.5	7.0; 7.5

From the data obtained in this and previous(4) work, it is concluded that the micro impact test provides an adequate measure of impact behavior. As a first approximation, a direct conversion from micro impact values in inch-pounds may be made to V-notch Charpy impact values in foot-pounds. The conversion is low for predominantly alpha structures, and high for predominantly beta structures. Transition temperatures, which occur primarily in beta alloys, tend to be lower for the micro impact than for the V-notch Charpy test.

The data reported here are recorded in BMI Laboratory Record Books No. 8101, pages 1 through 100, and No. 9050, pages 1 through 100.

LIST OF REFERENCES

(1) Romualdi, J. P., and D' Appolonia, E., "Research and Development of Effect of Range of Stress and Prestrain on the Fatigue Properties of Titanium and Its Alloys", Final Report for Office of Chief of

Ordnance, Research and Development Branch, October, 1952, Contract No. DA-36-061-ORD-68.

(2) Jaffee, R. I., Holden, F. C., and Ogden, H. R., "Mechanical Properties of Alpha Titanium as Affected by Structure and Composition", accepted by AIME for publication (TP 3858E).

(3) Ogden, H. R., Jaffee, R. I., and Holden, F. C., "Structure and Properties of Ti-C Alloys", accepted by AIME for publication (TP 3859E).

(4) Holden, F. C., Ogden, H. R., and Jaffee, R. I., "Microstructure and Mechanical Properties of Iodide Titanium", Trans. AIME, 197, 238-242 (1953).

(5) Ogden, H. R., Holden, F. C., and Jaffee, R. I., "Effect of Alpha Solutes on the Heat Treatment Response of Ti-Mn Alloys", accepted by AIME for publication (TP 3860E).

APPENDIX A

TABLE A-1. TENSILE PROPERTIES OF COMMERCIAL

Heat Treatment	Tensile Specimen	Reduction in Area, per cent	Elongation, per cent	Ultimate Tensile Strength, psi	Proportional Limit, psi
As hot worked	Sheet (E)	48	24	94,000	63,000
	Sheet (F)	32	15	91,000	60,000
	Round (A)	62	31	77,000	54,000
	Round (B)	64	43	72,000	48,000
	Notched (A)	32	--	129,000	--
	Notched (B)	30	--	124,000	--
Annealed for 1 hour at 600 C and air cooled	Sheet (C1)	42	27	73,000	41,000
	Sheet (C2)	50	38	74,000	39,000
	Round (A)	40	37	66,000	52,000
	Round (B)	49	35	62,000	42,000
	Notched (A)	24	--	107,000	--
	Notched (B)	25	--	109,000	--
Annealed for 2 hours at 700 C and air cooled	Sheet (B1)	48	31	70,000	36,000
	Sheet (B2)	46	32	67,000	43,000
	Round (A)	48*	36*	63,000*	46,000*
	Round (B)	69	58	64,000	47,000
	Notched (A)	27	--	102,000	--
	Notched (B)	22	--	106,000	--
Annealed for 4 hours at 825 C and air cooled	Sheet (E1)	50	33	66,000	37,000
	Sheet (E2)	52	28	65,000	39,000
	Round (A)	70	43	63,000	42,000
	Round (B)	69	46	63,000	38,000
	Notched (A)	31	--	103,000	--
	Notched (B)	26	--	103,000	--
Annealed for 16 hours at 875 C and air cooled	Sheet (G)	47	29	68,000	23,000
	Sheet (H)	51	18	66,000	30,000
	Round (A)	67	22	65,000	24,000
	Round (B)	70	38	64,000	33,000
	Notched (A)	35	--	108,000	--
	Notched (B)	28	--	103,000	--
Annealed for 1 hour at 900 C and air cooled	Sheet (F1)	52	25	68,000	29,000
	Sheet (F2)	40	27	67,000	31,000
	Round (A)	61	41	64,000	34,000
	Round (B)	69	40	65,000	34,000
	Notched (A)	30	--	104,000	--
	Notched (B)	27	--	102,000	--

0.01% Offset Yield Strength, psi	0.1% Offset Yield Strength, psi	0.2% Offset Yield Strength, psi	Flow Constants $\sigma = B\delta^n$			Vickers Hardness, 5-Kg Load
			B, psi	n	δ_{max}, in./in.	
66,000	74,000	77,000	126,000	0.083	0.071	236
65,000	72,000	75,000	127,000	0.094	0.077	220
59,000	68,000	70,000	105,000	0.087	0.065 - 0.110	203
53,000	64,000	66,000	90,000	0.058	0.065	205
--	--	--	--	--	--	--
--	--	--	--	--	--	--
45,000	--	53,000 (Y. P.)	111,000	0.170	0.153	177
45,000	--	54,000 (Y. P.)	119,000	0.145	0.137	180
54,000	--	55,000 (Y. P.)	89,000	0.088	0.116	175
46,000	--	50,000 (Y. P.)	86,000	0.101	0.119	182
--	--	--	--	--	--	--
--	--	--	--	--	--	--
40,000	--	50,000 (Y. P.)	103,000	0.127	0.162	177
46,000	--	49,000 (Y. P.)	95,000	0.113	0.144	178
49,000*	51,000*	51,000*	95,000	0.122	0.102	180
49,000	--	51,000 (Y. P.)	97,000	0.132	0.110	180
--	--	--	--	--	--	--
--	--	--	--	--	--	--
40,000	45,000	45,000	106,000	0.170	0.170	171
41,000	45,000	45,000	103,000	0.163	0.162	182
45,000	48,000	49,000	98,000	0.139	0.095	180
44,000	48,000	48,000	96,000	0.136	0.110	179
--	--	--	--	--	--	--
--	--	--	--	--	--	--
26,000	37,000	41,000	100,000	0.128	0.178	174
34,000	40,000	42,000	98,000	0.130	0.102	172
30,000	48,000	52,000	--	--	--	195
37,000	44,000	47,000	89,000	0.100	0.098	208
--	--	--	--	--	--	--
--	--	--	--	--	--	--
33,000	42,000	45,000	92,000	0.095	0.101	178
35,000	44,000	47,000	90,000	0.091	0.091	173
38,000	46,000	49,000	90,000	0.105	0.106 - 0.115	168
37,000	47,000	49,000	93,000	0.113	0.099 - 0.115	179
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TABLE A-1

Heat Treatment	Tensile Specimen	Reduction in Area, per cent	Elongation, per cent	Ultimate Tensile Strength, psi	Proportional Limit, psi
Annealed for 2 hours at 1000 C and air cooled	Sheet (D1)	39	31	65,000	33,000
	Sheet (D2)	41	33	66,000	33,000
	Round (A)	64	34	62,000	31,100
	Round (B)	67	38	63,000	37,000
	Notched (A)	26	--	103,000	--
	Notched (B)	30	--	99,000	--
Vacuum annealed 16 hours at 875 C and furnace cooled	Sheet (D1)	37	16	67,000	36,000
	Sheet (D2)	49	12	62,000	34,000
	Round (A)	73	42	62,000	33,000
	Round (B)	70	38	62,000	35,000
	Notched (A)	31	--	95,000	--
	Notched (B)	35	--	99,000	--

*Defect in reduced section of this specimen.

(Continued)

0.01% Offset Yield Strength, psi	0.1% Offset Yield Strength, psi	0.2% Offset Yield Strength, psi	Flow Constants $\sigma = B\delta^n$			Vickers Hardness, 5-Kg Load
			B, psi	n	δ_{max}, in./in.	
36,000	46,000	49,000	91,000	0.110	0.107	199
37,000	47,000	51,000	93,000	0.112	0.117	197
37,000	47,000	49,000	89,000	0.119	0.134	167
39,000	47,000	49,000	91,000	0.103	0.145	168
--	--	--	--	--	--	--
--	--	--	--	--	--	--
39,000	44,000	45,000	98,000	0.123	0.144	175
38,000	42,000	42,000	106,000	0.182	0.109	174
38,000	44,000	46,000	86,000	0.098	0.112	166
38,000	45,000	47,000	88,000	0.108	0.093	168
--	--	--	--	--	--	--
--	--	--	--	--	--	--

TABLE A-2. TENSILE PROPERTIES OF A

Heat Treatment	Tensile Specimen	Reduction in Area, per cent	Elongation, per cent	Ultimate Tensile Strength, psi	Proportional Limit, psi
As hot worked	Sheet (A)	29	7	147,000	120,000
	Sheet (B)	21	6	160,000	126,000
	Round (A)	28	13	148,000	130,000
	Round (B)	31	16	144,000	124,000
	Notched (A)	16	--	227,000	--
	Notched (B)	13	--	219,000	--
Annealed 1 hour at 700 C and quenched	Sheet (K)	31	8	139,000	112,000
	Sheet (L)	29	13	143,000	--
	Round (A)	38	22	145,000	126,000
	Round (B)	39	19	144,000	125,000
	Notched (A)	8	--	219,000	--
	Notched (B)	5	--	215,000	--
Annealed 2 hours at 850 C and quenched	Sheet (I)	30	12	137,000	114,000
	Sheet (J)	34	13	155,000	127,000
	Round (A)	58	22	142,000	116,000
	Round (B)	62	28	143,000	131,000
	Notched (A)	40	--	221,000	--
	Notched (B)	37	--	223,000	--
Annealed 4 hours at 1000 C and quenched	Sheet (G)	36	13	126,000	106,000
	Sheet (H)	20	10	139,000	108,000
	Round (A)	60	17	140,000	125,000
	Round (B)	48	22	142,000	127,000
	Notched (A)	31	--	221,000	--
	Notched (B)	32	--	224,000	--
Annealed 2 hours at 850 C; furnace cooled to 700 C, held 1 hour and quenched	Sheet (E1)	29	10	135,000	99,000
	Sheet (E2)	31	13	137,000	90,000
	Round (A)	49	20	137,000	120,000
	Round (B)	38	16	139,000	124,000
	Notched (A)	13	--	217,000	--
	Notched (B)	7	--	210,000	--
Annealed 4 hours at 1000 C; furnace cooled to 700 C, held 1 hour and quenched	Sheet (A1)	23	11	136,000	109,000
	Sheet (A2)	28	8	135,000	111,000
	Round (A)	36	18	138,000	125,000
	Round (B)	28	18	135,000	119,000
	Notched (A)	3	--	188,000	--
	Notched (B)	7	--	208,000	--

METASTABLE BETA ALLOY (Ti-7.5Cr-7.5Mo)

0.01% Offset Yield Strength, psi	0.1% Offset Yield Strength, psi	0.2% Offset Yield Strength, psi	Flow Constants, $\sigma = B\delta^n$			Vickers Hardness, 5-Kg Load
			B, psi	n	δ_{max}, in./in.	
126,000	139,000	142,000	--	--	--	336
130,000	145,000	150,000	--	--	--	331
134,000	138,000	140,000	191,000	0.068	0.064 - 0.074	334
129,000	137,000	138,000	194,000	0.080	0.095	345
--	--	--	--	--	--	--
--	--	--	--	--	--	--
118,000	132,000	134,000	160,000	0.029	0.039	342
--	--	--	--	--	--	332
130,000	135,000	136,000	196,000	0.085	0.087	333
129,000	135,000	137,000	199,000	0.095	0.094 - 0.102	331
--	--	--	--	--	--	--
--	--	--	--	--	--	--
120,000	132,000	135,000	166,000	0.045	0.049	324
133,000	148,000	151,000	162,000	0.042	0.048	349
126,000	137,000	138,000	149,000	0.015	0.043	326
134,000	139,000	140,000	--	--	--	336
--	--	--	--	--	--	--
--	--	--	--	--	--	--
110,000	120,000	123,000	143,000	0.022	0.057	336
117,000	129,000	132,000	159,000	0.026	0.038	354
128,000	135,000	137,000	--	--	--	322
131,000	138,000	139,000	--	--	--	342
--	--	--	--	--	--	--
--	--	--	--	--	--	--
107,000	125,000	129,000	154,000	0.030	0.029	342
96,000	126,000	131,000	155,000	0.027	0.029	339
125,000	133,000	134,000	153,000	0.025	0.029	320
127,000	134,000	135,000	155,000	0.023	0.035	310
--	--	--	--	--	--	--
--	--	--	--	--	--	--
114,000	130,000	132,000	165,000	0.046	0.048	--
114,000	129,000	132,000	162,000	0.045	0.038	342
128,000	134,000	135,000	--	--	--	338
123,000	130,000	132,000	--	--	--	345
--	--	--	--	--	--	--
--	--	--	--	--	--	--

TABLE A-2.

Heat Treatment	Tensile Specimen	Reduction in Area, per cent	Elongation, per cent	Ultimate Tensile Strength, psi	Proportional Limit, psi
Vacuum annealed; annealed 1 hour at 700 C and quenched	Round (A)	36	21	145,000	125,000
	Round (B)	21	13	147,000	109,000
	Notched (A)	12	--	221,000	--
	Notched (B)	10	--	219,000	--
Annealed 1 hour at 700 C and quenched; aged 100 hours at 300 C and quenched	Sheet (B1)	5	0	163,000	139,000
	Round (A)	0	1	111,000	--
	Round (B)	0	0	144,000	--
	Notched (A)	6	--	111,000	--
	Notched (B)	4	--	92,000	--

(Continued)

0.01% Offset Yield Strength, psi	0.1% Offset Yield Strength, psi	0.2% Offset Yield Strength, psi	Flow Constants, $\sigma = B\delta^n$			Vickers Hardness, 5-Kg Load
			B, psi	n	δ_{max}, in./in.	
130,000	135,000	136,000	--	--	--	314
122,000	137,000	138,000	--	--	--	321
--	--	--	--	--	--	--
--	--	--	--	--	--	--
148,000	--	--	--	--	--	502
--	--	--	--	--	--	475
--	--	--	--	--	--	476
--	--	--	--	--	--	--
--	--	--	--	--	--	--

TABLE A-3. TENSILE PROPERTIES OF A METASTABLE BETA

Heat Treatment	Tensile Specimen	Reduction in Area, per cent	Elongation, per cent	Ultimate Tensile Strength, psi
Annealed for 1 hour at 700 C and water quenched, and aged for 100 hours at 200 C and water quenched	Sheet (A1)	10	2	147,000
Annealed for 1 hour at 700 C and water quenched, and aged for 100 hours at 300 C and water quenched	Sheet (B1)	5	0	163,000
Annealed for 1 hour at 700 C and water quenched, and aged for 100 hours at 400 C and water quenched	Sheet (C1)	3	1	207,000
Annealed for 1 hour at 700 C and water quenched, and aged for 100 hours at 500 C and water quenched	Sheet (D1)	10	3	169,000
Annealed for 2 hours at 850 C and water quenched, and aged for 100 hours at 200 C and water quenched	Sheet (A2)	36	3	162,000
Annealed for 2 hours at 850 C and water quenched, and aged for 100 hours at 300 C and water quenched	Sheet (B2)	0	0	13,000
Annealed for 2 hours at 850 C and water quenched, and aged for 100 hours at 400 C and water quenched	Sheet (C2)	0	0	54,000
Annealed for 2 hours at 850 C and water quenched, and aged for 100 hours at 500 C and water quenched	Sheet (D2)	5	0	176,000
Annealed for 4 hours at 1000 C and water quenched, and aged for 100 hours at 200 C and water quenched	Sheet (A4)	1	1	112,000
Annealed for 4 hours at 1000 C and water quenched, and aged for 100 hours at 300 C and water quenched	Sheet (B4)	--	--	--
Annealed for 4 hours at 1000 C and water quenched, and aged for 100 hours at 400 C and water quenched	Sheet (C4)	1	0	71,000

ALLOY (Ti-7.5Cr-7.5Mo) AFTER AGING AT 100 to 500 C

Proportional Limit, psi	0.01% Offset Yield Strength, psi	0.1% Offset Yield Strength, psi	0.2% Offset Yield Strength, psi	Vickers Hardness, 5-Kg Load
126,000	136,000	147,000	147,000	356
139,000	148,000	--	--	502
168,000	178,000	193,000	207,000	515
137,000	144,000	159,000	162,000	388
134,000	145,000	161,000	161,000	333
--	--	--	--	566
--	--	--	--	549
156,000	164,000	176,000	--	417
--	--	--	--	358
--	--	--	--	--
--	--	--	--	568

TABLE A-3.

Heat Treatment	Tensile Specimen	Reduction in Area, per cent	Elongation, per cent	Ultimate Tensile Strength, psi
Annealed for 4 hours at 1000 C and water quenched, and aged for 100 hours at 500 C and water quenched	Sheet (D4)	1	1	178,000
Annealed for 2 hours at 850 C; furnace cooled to 700 C; held for 1 hour and water quenched, aged for 100 hours at 200 C and water quenched	Sheet (A3)	3	1	148,000
Annealed for 2 hours at 850 C; furnace cooled to 700 C; held for 1 hour and water quenched, aged for 100 hours at 300 C and water quenched	Sheet (B3)	0	0	55,000
Annealed for 2 hours at 850 C; furnace cooled to 700 C; held for 1 hour and water quenched, aged for 100 hours at 400 C and water quenched	Sheet (C3)	1	1	94,000
Annealed for 2 hours at 850 C; furnace cooled to 700 C; held for 1 hour and water quenched, aged for 100 hours at 500 C and water quenched	Sheet (D3)	18	1	179,000
Annealed for 4 hours at 1000 C; furnace cooled to 700 C; held for 1 hour and water quenched, aged for 100 hours at 200 C and water quenched	Sheet (A5)	13	2	154,000
Annealed for 4 hours at 1000 C; furnace cooled to 700 C; held for 1 hour and water quenched, aged for 100 hours at 300 C and water quenched	Sheet (B5)	0	0	52,000
Annealed for 4 hours at 1000 C; furnace cooled to 700 C; held for 1 hour and water quenched, aged for 100 hours at 400 C and water quenched	Sheet (C5)	1	1	92,000
Annealed for 4 hours at 1000 C; furnace cooled to 700 C; held for 1 hour and water quenched, aged for 100 hours at 500 C and water quenched	Sheet (D5)	2	1	165,000

(Continued)

Proportional Limit, psi	0.01% Offset Yield Strength, psi	0.1% Offset Yield Strength, psi	0.2% Offset Yield Strength, psi	Vickers Hardness, 5-Kg Load
150,000	158,000	176,000	--	425
124,000	134,000	148,000	--	373
--	--	--	--	524
--	-	--	--	549
133,000	146,000	163,000	166,000	389
117,000	129,000	145,000	145,000	362
--	--	--	--	516
--	--	--	--	570
140,000	147,000	162,000	--	508

TABLE A-4. TENSILE PROPERTIES OF AN

Heat Treatment	Tensile Specimen	Reduction in Area, per cent	Elongation, per cent	Ultimate Tensile Strength, psi	Proportional Limit, psi
As hot worked	Sheet (C)	16	11	152,000	72,000
	Sheet (D)	16	8	155,000	59,000
	Round (A)	60	16	151,000	95,000
	Round (B)	56	20	143,000	86,000
	Notched (A)	17	--	202,000	--
	Notched (B)	19	--	203,000	--
Annealed for 1 hour at 750 C; furnace cooled to 650 C and air cooled	Sheet (E)	34	20	106,000	59,000
	Sheet (SS)	37	19	109,000	72,000
	Round (A)	65	32	104,000	95,000
	Round (B)	55	32	103,000	94,000
	Notched (A)	18	--	157,000	--
	Notched (B)	20	--	162,000	--
Vacuum annealed; annealed 1 hour at 750 C; furnace cooled to 650 C and air cooled	Round (A)	65	32	108,000	72,000
	Round (B)	52	31	110,000	80,000
	Notched (A)	18	--	166,000	--
	Notched (B)	20	--	167,000	--
Annealed 64 hours at 750 C; furnace cooled to 650 C and air cooled	Sheet (WO)	37	12	107,000	71,000
	Sheet (WX)	31	12	109,000	56,000
	Round (A)	56	30	102,000	74,000
	Round (B)	57	27	103,000	77,000
	Notched (A)	16	--	156,000	--
	Notched (B)	16	--	159,000	--
Annealed 1/2 hour at 900 C; furnace cooled to 750 C, and held for 1 hour; furnace cooled to 650 C and air cooled	Sheet (VV)	27	28	110,000	47,000
	Sheet (UU)	30	19	107,000	67,000
	Round (A)	48	24	104,000	65,000
	Round (B)	45	27	107,000	70,000
	Notched (A)	18	--	156,000	--
	Notched (B)	22	--	160,000	--
Annealed for 1 hour at 1000 C; furnace cooled to 750 C, and held for 1 hour; furnace cooled to 650 C and air cooled	Sheet (D)	26	20	107,000	67,000
	Sheet (XX)	25	14	107,000	66,000
	Round (A)	39	26	107,000	66,000
	Round (B)	36	25	108,000	66,000
	Notched (A)	19	--	161,000	--
	Notched (B)	13	--	162,000	--
Annealed for 1 hour at 750 C and water quenched	Sheet (AA)	21	9	129,000	86,000
	Sheet (BB)	27	15	122,000	85,000
	Round (A)	64	13	145,000	92,000
	Round (B)	66	13	136,000	90,000
	Notched (A)	13	--	216,000	--
	Notched (B)	13	--	224,000	--

0.01% Offset Yield Strength, psi	0.1% Offset Yield Strength, psi	0.2% Offset Yield Strength, psi	Flow Constants, $\sigma = B\delta^n$			Vickers Hardness, 5-Kg Load
			B, psi	n	δ_{max}, in./in.	
83,000	112,000	126,000	--	--	--	353
71,000	113,000	127,000	--	--	--	343
99,000	114,000	124,000	167,000	0.050	0.058	311
90,000	104,000	115,000	171,000	0.042	0.042 -0.062	310
--	--	--	--	--	--	--
--	--	--	--	--	--	--
71,000	90,000	94,000	156,000	0.124	0.118	281
82,000	--	101,000 (Y. P.)	164,000	0.133	0.095	270
96,000	--	96,000 (Y. P.)	157,000	0.131	0.160	241
95,000	--	95,000 (Y. P.)	150,000	0.120	0.146	280
--	--	--	--	--	--	--
--	--	--	--	--	--	--
79,000	--	97,000 (Y. P.)	156,000	0.116	0.114	285
85,000	--	99,000 (Y. P.)	163,000	0.124	0.124	297
--	--	--	--	--	--	--
--	--	--	--	--	--	--
74,000	83,000	86,000	161,000	0.130	0.085	261
67,000	84,000	89,000	162,000	0.123	0.103	263
79,000	85,000	85,000	149,000	0.120	0.118	258
80,000	86,000	87,000	145,000	0.099	0.088	259
--	--	--	--	--	--	--
--	--	--	--	--	--	--
60,000	84,000	91,000	175,000	0.160	0.130	259
74,000	87,000	91,000	160,000	0.130	0.112	254
69,000	82,000	86,000	155,000	0.126	0.112	283
73,000	83,000	87,000	159,000	0.120	0.126	293
--	--	--	--	--	--	--
--	--	--	--	--	--	--
73,000	86,000	90,000	159,000	0.132	0.117	288
73,000	86,000	90,000	158,000	0.115	0.104	273
71,000	82,000	85,000	97,000	0.115	0.128	259
72,000	83,000	86,000	125,000	0.119	0.149	262
--	--	--	--	--	--	--
--	--	--	--	--	--	--
95,000	--	128,000 (Y. P.)	--	--	--	303
93,000	--	122,000 (Y. P.)	175,000	0.115	0.130	311
98,000	127,000	137,000	--	--	--	348
97,000	121,000	129,000	--	--	--	417
--	--	--	--	--	--	--
--	--	--	--	--	--	--

TABLE A-4.

Heat Treatment	Tensile Specimen	Reduction in Area, per cent	Elongation, per cent	Ultimate Tensile Strength, psi	Proportional Limit, psi
Annealed for 1 hour at 750 C and water quenched; aged for 1 hour at 400 C and water quenched	Sheet (CC)	2	0	176,000	111,000
	Sheet (DD)	6	2	178,000	109,000
	Round (A)	2	0	186,000	108,000
	Round (B)	2	0	175,000	112,000
	Notched (A)	1	--	166,000	--
	Notched (B)	1	--	154,000	--
Annealed for 1 hour at 750 C and water quenched; aged for 4 hours at 400 C and water quenched	Sheet (EE)	4	1	172,000	113,000
	Sheet (FF)	4	1	184,000	120,000
	Round (A)	2	0	191,000	109,000
	Round (B)	3	0	178,000	103,000
	Notched (A)	1	--	173,000	--
	Notched (B)	3	--	168,000	--
Annealed for 1 hour at 750 C and water quenched; aged for 16 hours at 400 C and water quenched	Sheet (GG)	2	1	179,000	116,000
	Sheet (HH)	2	1	174,000	106,000
	Round (A)	7	3	177,000	104,000
	Round (B)	4	3	185,000	112,000
	Notched (A)	3	--	196,000	--
	Notched (B)	3	--	192,000	--
Annealed for 1 hour at 750 C and water quenched; aged for 64 hours at 400 C and water quenched	Sheet (II)	10	5	158,000	102,000
	Sheet (JJ)	5	2	161,000	111,000
	Round (A)	17	5	169,000	--
	Round (B)	16	4	170,000	111,000
	Notched (A)	2	--	213,000	--
	Notched (B)	2	--	221,000	--
Annealed for 1 hour at 750 C and water quenched; aged for 1 hour at 500 C and water quenched	Sheet (KK)	16	10	135,000	89,000
	Sheet (LL)	19	10	136,000	90,000
	Round (A)	50	20	139,000	90,000
	Round (B)	56	20	140,000	91,000
	Notched (A)	9	--	218,000	--
	Notched (B)	8	--	215,000	--
Annealed for 1 hour at 750 C and water quenched; aged for 4 hours at 500 C and water quenched	Sheet (MM)	24	15	139,000	90,000
	Sheet (NN)	20	10	135,000	92,000
	Round (A)	57	20	136,000	96,000
	Round (B)	58	25	135,000	90,000
	Notched (A)	10	--	210,000	--
	Notched (B)	12	--	204,000	--

0.01% Offset Yield Strength, psi	0.1% Offset Yield Strength, psi	0.2% Offset Yield Strength, psi	Flow Constants, $\sigma = B\delta^n$			Vickers Hardness, 5-Kg Load
			B, psi	n	δ_{max}, in./in.	
119,000	147,000	156,000	--	--	--	363
116,000	145,000	156,000	--	--	--	372
119,000	147,000	161,000	--	--	--	427
121,000	150,000	162,000	--	--	--	464
--	--	--	--	--	--	--
--	--	--	--	--	--	--
121,000	146,000	157,000	--	--	--	390
127,000	155,000	166,000	--	--	--	382
118,000	149,000	164,000	--	--	--	442
111,000	135,000	145,000	--	--	--	344
--	--	--	--	--	--	--
--	--	--	--	--	--	--
123,000	150,000	158,000	--	--	--	382
116,000	143,000	152,000	--	--	--	372
112,000	135,000	143,000	--	--	--	413
122,000	146,000	159,000	--	--	--	397
--	--	--	--	--	--	--
--	--	--	--	--	--	--
109,000	132,000	137,000	--	--	--	351
119,000	135,000	140,000	--	--	--	361
--	--	--	--	--	--	397
119,000	133,000	138,000	--	--	--	435
--	--	--	--	--	--	--
--	--	--	--	--	--	--
96,000	113,000	117,000	172,000	0.069	0.088	301
97,000	111,000	116,000	190,000	0.101	0.077	297
96,000	112,000	116,000	185,000	0.077	0.089	321
100,000	113,000	117,000	178,000	0.068	0.076	320
--	--	--	--	--	--	--
--	--	--	--	--	--	--
100,000	117,000	123,000	190,000	0.093	0.095	316
97,000	114,000	117,000	184,000	0.090	0.086	313
105,000	116,000	118,000	173,000	0.076	0.085	312
102,000	114,000	117,000	187,000	0.089	0.084	308
--	--	--	--	--	--	--
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TABLE A-4.

Heat Treatment	Tensile Specimen	Reduction in Area, per cent	Elongation, per cent	Ultimate Tensile Strength, psi	Proportional Limit, psi
Annealed for 1 hour at 750 C and water quenched; aged for 16 hours at 500 C and water quenched	Sheet (OO)	21	13	125,000	78,000
	Sheet (PP)	19	15	126,000	82,000
	Round (A)	57	22	128,000	97,000
	Round (B)	57	22	129,000	100,000
	Notched (A)	10	--	196,000	--
	Notched (B)	10	--	198,000	--
Annealed for 1 hour at 750 C and water quenched; aged for 64 hours at 500 C and water quenched	Sheet (QQ)	12	11	125,000	83,000
	Sheet (RR)	21	8	120,000	83,000
	Round (A)	52	22	120,000	91,000
	Round (B)	52	22	120,000	--
	Notched (A)	9	--	183,000	--
	Notched (B)	7	--	183,000	--

(Continued)

0.01% Offset Yield Strength, psi	0.1% Offset Yield Strength, psi	0.2% Offset Yield Strength, psi	Flow Constants, $\sigma = B\delta^n$			Vickers Hardness, 5-Kg Load
			B, psi	n	δ_{max}, in./in.	
86,000	110,000	113,000	165,000	0.078	0.085	287
95,000	111,000	114,000	167,000	0.078	0.117	293
101,000	111,000	112,000	--	--	--	303
109,000	114,000	117,000	171,000	0.087	0.070	317
--	--	--	--	--	--	--
--	--	--	--	--	--	--
94,000	108,000	112,000	172,000	0.093	0.085	289
91,000	105,000	108,000	159,000	0.072	0.043	290
99,000	107,000	107,000	157,000	0.097	0.090	293
--	--	--	162,000	0.093	0.103	297
--	--	--	--	--	--	--
--	--	--	--	--	--	--

TABLE A-5. BEND TEST DATA FOR COMMERCIAL TITANIUM

Heat Treatment	Minimum Bend Radius, T							
	Longitudinal				Transverse			
	1	2	3	4	1	2	3	4
As Worked	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Annealed for 1 hour at 600 C and air cooled	0	0	0	0	0	0	0	0
Annealed for 2 hours at 700 C and air cooled	0	0	0	0	0	0	0	0
Annealed for 4 hours at 825 C and air cooled	0	0	0.2	0.2	0	0	0	0
Annealed for 16 hours at 875 C and air cooled	0	0	0	--	0	0	0	0.7
Annealed for 1 hour at 900 C and air cooled	0	0	0	0	0	0	0	0
Annealed for 2 hours at 1000 C and air cooled	0	0	0	0	0	0	0	0
Vacuum annealed for 16 hours at 875 C and furnace cooled	0	0	0.3	0.3	0	0	0.2	0

TABLE A-6. BEND-TEST DATA FOR A METASTABLE BETA ALLOY (Ti-7.5Cr-7.5Mo)

Heat Treatment	Minimum Bend Radius, T							
	Longitudinal				Transverse			
	1	2	3	4	1	2	3	4
As hot worked	0.8	1.5	0.8	1.0	4.0	4.2	6.2	6.0
Annealed for 1 hour at 700 C and water quenched	1.0	6.3	3.1	4.5	2.0	2.9	1.1	4.3
Annealed for 2 hours at 850 C and water quenched	2.9	0	0.6	0	0	0	2.7	0.5
Annealed for 4 hours at 1000 C and water quenched	0	0	0.3	0	0.8	0.8	0	0
Annealed for 2 hours at 850 C; furnace cooled to 700 C, held for 1 hour and water quenched	1.5	23.8	>26.0	3.2	1.7	2.8	2.9	6.2
Annealed for 4 hours at 1000 C; furnace cooled to 700 C; held for 1 hour and water quenched	3.1	3.2	>26.0	3.1; >26	3.2	35	33	--
Annealed for 1 hour at 700 C and water quenched, and annealed for 100 hours at 200 C and water quenched	1.9	--	--	--	--	--	--	--
Annealed for 1 hour at 700 C and water quenched, and annealed for 100 hours at 300 C and water quenched	>23.8	--	--	--	--	--	--	--
Annealed for 1 hour at 700 C and water quenched, and annealed for 100 hours at 400 C and water quenched	>23.4	--	--	--	--	--	--	--
Annealed for 1 hour at 700 C and water quenched, and annealed for 100 hours at 500 C and water quenched	24.2	24.6	24.2	24.2	24.6	24.6	24.6	>23.8
Annealed for 2 hours at 850 C and water quenched, and annealed for 100 hours at 200 C and water quenched	1.9	--	--	--	--	--	--	--

TABLE A-6. (Continued)

Heat Treatment	Minimum Bend Radius, T							
	Longitudinal				Transverse			
	1	2	3	4	1	2	3	4
Annealed for 2 hours at 850 C and water quenched, and annealed for 100 hours at 300 C and water quenched	>22.3	--	--	--	--	--	--	--
Annealed for 2 hours at 850 C and water quenched, and annealed for 100 hours at 400 C and water quenched	>24.2	--	--	--	--	--	--	--
Annealed for 2 hours at 850 C and water quenched, and annealed for 100 hours at 500 C and water quenched	>25.2	--	--	--	--	--	--	--
Annealed for 4 hours at 1000 C and water quenched, and annealed for 100 hours at 200 C and water quenched	>26.3	--	--	--	--	--	--	--
Annealed for 4 hours at 1000 C and water quenched, and annealed for 100 hours at 300 C and water quenched	>24.2	--	--	--	--	--	--	--
Annealed for 4 hours at 1000 C and water quenched, and annealed for 100 hours at 400 C and water quenched	>25.0	--	--	--	--	--	--	--
Annealed for 4 hours at 1000 C and water quenched, and annealed for 100 hours at 500 C and water quenched	>26.3	--	--	--	--	--	--	--
Annealed for 2 hours at 850 C; furnace cooled to 700 C; held for 1 hour and water quenched; annealed for 100 hours at 200 C and water quenched	4.1	--	--	--	--	--	--	--
Annealed for 2 hours at 850 C; furnace cooled to 700 C; held for 1 hour and water quenched; annealed for 100 hours at 300 C and water quenched	>23.3	--	--	--	--	--	--	--

TABLE A-6. (Continued)

Heat Treatment	Minimum Bend Radius, T							
	Longitudinal				Transverse			
	1	2	3	4	1	2	3	4
Annealed for 2 hours at 850 C; furnace cooled to 700 C; held for 1 hour and water quenched; annealed for 100 hours at 400 C and water quenched	>24.2	--	--	--	--	--	--	--
Annealed for 2 hours at 850 C; furnace cooled to 700 C; held for 1 hour and water quenched; annealed for 100 hours at 500 C and water quenched.	>23.3	--	--	--	--	--	--	--
Annealed for 4 hours at 1000 C; furnace cooled to 700 C; held for 1 hour and water quenched; annealed for 100 hours at 200 C and water quenched	23.8	--	--	--	--	--	--	--
Annealed for 4 hours at 1000 C; furnace cooled to 700 C; held for 1 hour and water quenched; annealed for 100 hours at 300 C and water quenched	23.8	--	--	--	--	--	--	--
Annealed for 4 hours at 1000 C; furnace cooled to 700 C; held for 1 hour and water quenched; annealed for 100 hours at 400 C and water quenched	>25.0	--	--	--	--	--	--	--
Annealed for 4 hours at 1000 C; furnace cooled to 700 C; held for 1 hour and water quenched; annealed for 100 hours at 500 C and water quenched	>25.0	--	--	--	--	--	--	--

TABLE A-7. BEND-TEST DATA FOR AN ALPHA-BETA ALLOY (Ti-2.5Cr-2.5Mo)

Heat Treatment	Minimum Bend Radius, T							
	Longitudinal				Transverse			
	1	2	3	4	1	2	3	4
As hot worked	3.7	5.7	2.8	5.5	11.3	11.4	11.4	22.0
Annealed for 1 hour at 750 C, and furnace cooled to 650 C and air cooled	0.9	--	--	--	0.5	--	--	--
Annealed for 64 hours at 750 C, and furnace cooled to 650 C and air cooled	0.5	0.2	0.7	0.7	0.5	0.5	0.7	3.9
Annealed for 1/2 hour at 900 C and furnace cooled to 750 C; annealed at 750 C for 1 hour, and furnace cooled to 650 C and air cooled	0.7	0.7	0.7	1.0	0.9	1.5	1.0	1.0
Annealed for 1 hour at 1000 C and furnace cooled to 750 C; and annealed for 1 hour, and furnace cooled to 650 C and air cooled	0.3	0.7	0.7	1.5	1.0	1.5	1.4	1.5
Annealed for 1 hour at 750 C and water quenched	1.0	1.5	5.0	1.0	22.4	3.0	1.9	2.9
Annealed for 1 hour at 750 C and water quenched, and aged for 1 hour at 400 C and water quenched	23.0	>23.3	>25.2	>23.0	>24.2	>23.3	>23.4	>23.4
Annealed for 1 hour at 750 C and water quenched, and aged for 4 hours at 400 C and water quenched	23.0	>22.9	>24.6	>23.3	>23.3	>23.4	>23.3	>23.8
Annealed for 1 hour at 750 C and water quenched, and aged for 16 hours at 400 C and water quenched	24.2	>23.3	23.8	23.8	>23.4	22.9	23.2	>23.3
Annealed for 1 hour at 750 C and water quenched, and aged for 64 hours at 400 C and water quenched	12.1	23.3	4.3	24.6	>23.4	23.8	23.4	22.4
Annealed for 1 hour at 750 C and water quenched, and aged for 1 hour at 500 C and water quenched	1.5	2.9	2.9	1.5	3.7	0.5	0.5	3.8

TABLE A-7. (Continued)

Heat Treatment	Minimum Bend Radius, T							
	Longitudinal				Transverse			
	1	2	3	4	1	2	3	4
Annealed for 1 hour at 750 C and water quenched, and aged for 4 hours at 500 C and water quenched	0.46	0.9	1.5	1.0	23.4	7.7	3.9	5.7
Annealed for 1 hour at 750 C and water quenched, and aged for 16 hours at 500 C and water quenched	0.9	2.9	4.5	2.9	1.7	3.8	11.9	3.9
Annealed for 1 hour at 750 C and water quenched, and aged for 64 hours at 500 C and water quenched	1.0	1.5	3.1	2.9	1.0	5.8	5.5	2.9
Annealed for 2 hours at 750 C, and furnace cooled to 650 C and air cooled	0.5	--	--	--	0.9	--	--	--
Annealed for 4 hours at 750 C, and furnace cooled to 650 C and air cooled	0.7	--	--	--	1.4	--	--	--
Annealed for 2 hours at 750 C and furnace cooled to 700 C; and annealed for 1 hour at 750 C and furnace cooled to 650 C, and annealed at 650 C for 2 hours and air cooled	0.5	--	--	--	0.2	--	--	--
Annealed for 1 hour at 1000 C, and furnace cooled to 650 C and air cooled	1.0	--	--	--	1.0	--	--	--
Annealed for 1 hour at 1000 C and furnace cooled to 750 C; and annealed for 2 hours at 750 C, and furnace cooled to 650 C and air cooled	0.7	--	--	--	1.0	--	--	--
Annealed for 1 hour at 1000 C and furnace cooled to 750 C; and annealed for 4 hours at 750 C, and furnace cooled to 650 C and air cooled	0.7	--	--	--	1.0	--	--	--

TABLE A-7. (Continued)

Heat Treatment	Minimum Bend Radius, T							
	Longitudinal				Transverse			
	1	2	3	4	1	2	3	4
Annealed for 1 hour at 1000 C and furnace cooled to 750 C; and annealed for 2 hours at 750 C and furnace cooled to 700 C; and annealed for 1 hour at 700 C and furnace cooled to 650 C, and annealed for 2 hours at 650 C and air cooled	0.5	--	--	--	0.8	--	--	--

TABLE A-8. IMPACT TEST DATA FOR COMMERCIAL TITANIUM

Heat Treatment	Impact Energy Values, inch-pounds, at Indicated Temperatures, Micro-Impact Test								
	-196 C	-75 C	-40 C	25 C	100 C	150 C	200 C	300 C	400 C
As fabricated	42; 42	47; 44	44; 45	43; 43; 43; 47	50; 47	--	52; 62	62; 72	--
Annealed 1 hour at 600 C and air cooled	38; 40	46; 42; 41	38; 43; 40	42; 42	41; 40	46; 45	52; 47	68; 58	91; 87
Annealed 2 hours at 700 C and air cooled	42; 41	46; 44	45; 40	47; 44; 42	41; 39; 44	45; 43	44; 47	61; 57	57; >136
Annealed 4 hours at 825 C and air cooled	33; 37	35; 32	33; 32	31; 32; 32; 32	38; 39	42; 43	44; 44	55; 49	102; 60
Annealed 16 hours at 875 C and air cooled	30; 32	36; 32	34; 32	38; 38; 34; 34	42; 45	--	41; 43	48; 54	--
Annealed 1 hour at 900 C and air cooled	29; 32	34; 30	28; 28	32; 39; 31; 33	39; 36	--	40; 42	38; 42	--
Annealed 2 hours at 1000 C and air cooled	28; 31	28; 29	30; 28	31; 30; 32; 29	36; 38	49; 52	46; 42	40; 46	36; 41
Vacuum annealed 16 hours at 875 C and furnace cooled	43; 42	44; 39	41; 46	44; 44; 37; 36	47; 49	--	44; 42	45; 48	--

Heat Treatment	Impact Energy Values, foot-pounds, at Indicated Temperatures, V-Notch Charpy Impact Test						
	-196 C	-75 C	-40 C	25 C	100 C	200 C	300 C
Annealed 2 hours at 700 C and air cooled	56; 54	63; 58	55; 59	51; 57; 50; 53 67*; 60*; 67**; 54**	55; 54	56; 56	67; 64

Note: Impact velocity for the micro-impact test is 11.37 ft/sec. Impact velocity for the V-notch Charpy impact test is 11.62 ft/sec unless otherwise indicated.

*Tested at 13.56 ft/sec.

**Tested at 15.02 ft/sec.

TABLE A-9. IMPACT-TEST DATA FOR A Ti-7.5Cr-7.5Mo ALLOY

Heat Treatment	Impact Energy Values, inch-pounds, at Indicated Temperatures, Micro-Impact Test										
	-196 C	-75 C	-40 C	0 C	25 C	75 C	100 C	150 C	200 C	300 C	400 C
As fabricated	2; 2	6; 4	6; 7	--	12; 10; 9	--	25; 27	--	47; 40	41; 60	--
Annealed 1 hour at 700 C and quenched	3; 2	6; 6	4; 5	--	9; 10	--	29; 20	--	40; 43	59	--
Annealed 2 hours at 850 C and quenched	4; 3	8; 12	14; 12	28; 12	39; 38	--	47; 47	--	71; 78	68; 75	--
Annealed 4 hours at 1000 C and quenched	4; 4	8; 6	8; 9	14; 21	36; 36	--	42; 44	--	60; 93	82; 53	--
Annealed 2 hours at 850 C; furnace cooled to 700 C, held 1 hour, and quenched	2; 4	4; 7	4; 6	9; 6	7; 10	--	10; 17	--	32; 33	46; 38	--
Annealed 4 hours at 1000 C; furnace cooled to 700 C, held 1 hour, and quenched	2; 3	3; 4	4; 4	--	5; 8	--	9; 8	13;11	25; 21	29; 30	--
Vacuum annealed; annealed 1 hour at 700 C and quenched	4; 3	6; 4	5; 5	--	9; 10	13; 14	28; 29	34; 38	46; 46	59; 66	69; 75
Annealed 1 hour at 700 C and quenched; aged 100 hours at 300 C and quenched	3; 2	2; 2	1; 2	--	1; 1; 2; 4	--	2; 2	1; 2	2; 3	4; 4	38; 41

TABLE A-9. (Continued)

	Impact Energy Values, inch-pounds, at Indicated Temperatures, V-Notch Charpy Impact Test										
Heat Treatment	-196 C	-75 C	-40 C	0 C	25 C	75 C	100 C	150 C	200 C	300 C	400 C
Annealed 1 hour at 700 C and quenched	1; 1	2; 2	3; 4	--	7; 7; 8; 5 9*; 8*; 8**; 7**	--	12; 12	--	29; 31	>70; 69	--

Note: Impact velocity for the micro-impact test is 11.37 ft/sec. Impact velocity for the V-notch Charpy impact test is 11.62 ft/sec unless otherwise indicated.
*Tested at 13.56 ft/sec.
**Tested at 15.02 ft/sec.

TABLE A-10. IMPACT-TEST DATA FOR Ti-2.5Cr-2.5Mo ALLOY

Heat Treatment	Impact Energy Values, inch-pounds, at Indicated Temperatures, Micro-Impact Test									
	-196 C	-75 C	-40 C	0 C	25 C	100 C	150 C	200 C	300 C	400 C
As fabricated	8; 8	17; 12	12; 12	--	19; 44; 29	65; 56	--	94; 72; 83	99; 88	--
Annealed 1 hour at 750 C; furnace cooled to 650 C and air cooled	14; 14	31; 34	35; 36	--	47; 50 44; 45	62; 63	68; 73	83; 85	98; 94	92; 87
Vacuum annealed; annealed 1 hour at 750 C; furnace cooled to 650 C and air cooled	12; 13	30; 22	34; 35	--	45; 52 48; 53	68; 72	73; 80	91; 90	92; 94	85; 85
Annealed 64 hours at 750 C; furnace cooled to 650 C and air cooled	8; 5	22; 20	28; 25	--	37; 42 39; 35	45; 54	62	72; 70	75; 76	60; 62
Annealed 1/2 hour at 900 C; furnace cooled to 750 C and held for 1 hour; furnace cooled to 650 C and air cooled	9; 10	28; 28	29; 28	33; 39	36; 37 35; 37	40; 45	--	44; 44	48; 49	40; 44
Annealed 1 hour at 1000 C; furnace cooled to 750 C and held for 1 hour; furnace cooled to 650 C and air cooled	9; 9	28; 29	31; 28	32; 38	34; 37 36; 34	41; 43	--	45; 45	45; 48	40; 39
Annealed 1 hour at 750 C and quenched	14; 13	23; 21	26; 27	--	24; 31	42; 42	--	--	--	--
Annealed 1 hour at 750 C and quenched; aged 1 hour at 400 C and quenched	2; 3	4; 4	5; 5	--	5; 4	6	--	--	--	--

TABLE A-10. (Continued)

Heat Treatment	Impact Energy Values, inch-pounds, at Indicated Temperatures, Micro-Impact Test									
	-196 C	-75 C	-40 C	0 C	25 C	100 C	150 C	200 C	300 C	400 C
Annealed 1 hour at 750 C and quenched; aged 4 hours at 400 C and quenched	3; 3	5; 4	6; 6	--	6; 6	7; 8	--	--	--	--
Annealed 1 hour at 750 C and quenched; aged 16 hours at 400 C and quenched	6; 4	6; 6	7; 6	--	8; 7	10; 12	--	--	--	--
Annealed 1 hour at 750 C and quenched; aged 64 hours at 400 C and quenched	7; 6	8; 8	11; 9	--	12; 10	14; 22	--	--	--	--
Annealed 1 hour at 750 C and quenched; aged 1 hour at 500 C and quenched	12; 13	12; 13	13; 15	--	16; 16	30; 29	--	--	--	--
Annealed 1 hour at 750 C and quenched; aged 4 hours at 500 C and quenched	15; 15	15; 15	15; 15	--	21; 20	32; 31	--	--	--	--
Annealed 1 hour at 750 C and quenched; aged 16 hours at 500 C and quenched	13; 13	13; 14	15; 16	--	22; 22	31; 32	--	--	--	--
Annealed 1 hour at 750 C and quenched; aged 64 hours at 500 C and quenched	9; 9	10; 9	9; 11	--	12; 13	20; 18	--	--	--	--

Heat Treatment	Impact Energy Values, foot-pounds, at Indicated Temperatures, V-Notch Charpy Impact Test						
	-196 C	-75 C	-40 C	25 C	100 C	200 C	300 C
Annealed 1 hour at 750 C; furnace cooled to 650 C and air cooled	8; 12	29; 28	16; 30	33**; >70; 43; 42*; 55**; 43**	>70; 71*	>94*; >70; 108**; >115**	113**; 72**

Footnotes appear on the following page.

Note: Impact velocity for the micro-impact test is 11.37 ft/sec. Impact velocity for the V-notch Charpy impact test is 11.62 ft/sec unless otherwise indicated.

*Tested at 13.56 ft/sec.
**Tested at 15.02 ft/sec.

APPENDIX B

FLOW CURVES

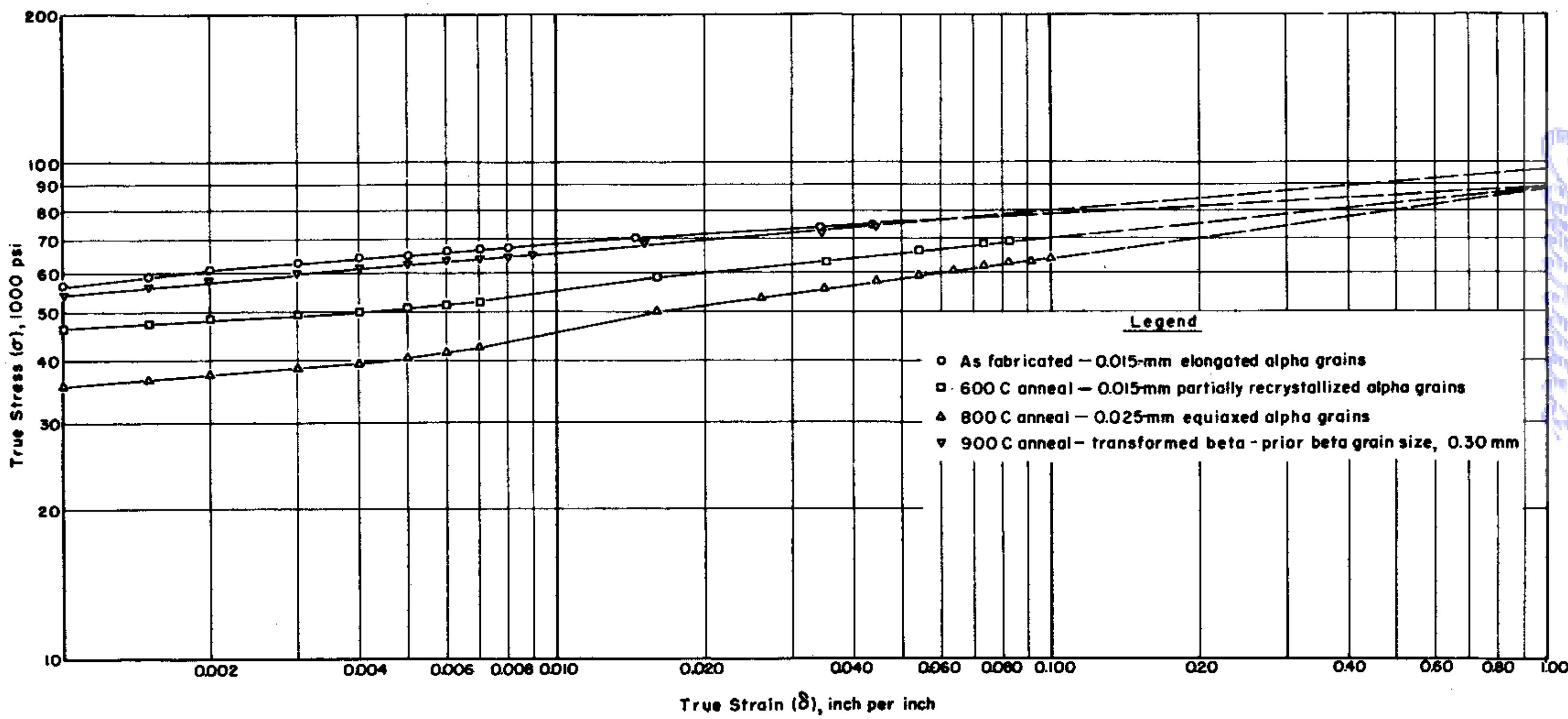

FIGURE B-1. FLOW CURVES FOR COMMERCIAL TITANIUM ANNEALED 1 HOUR IN AIR AND AIR COOLED
Flow Constants Reported in Table 1, Third Quarterly Progress Report

C-9112

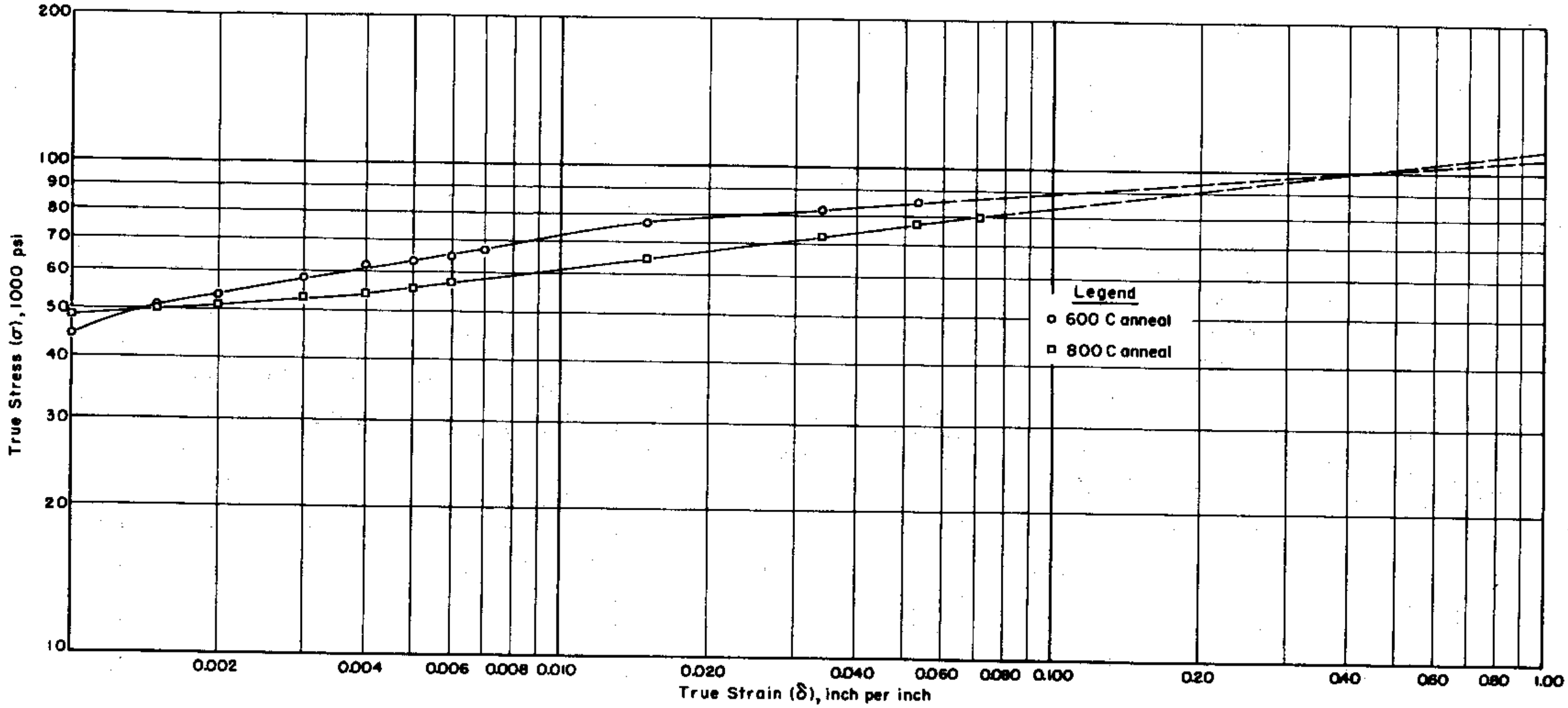

FIGURE B-2. FLOW CURVES FOR COMMERCIAL TITANIUM VACUUM ANNEALED 6 HOURS AT 900C, AIR ANNEALED I HOUR AT INDICATED TEMPERATURE AND AIR COOLED
Flow Constants Reported in Table I, Third Quarterly Progress Report

C-9113

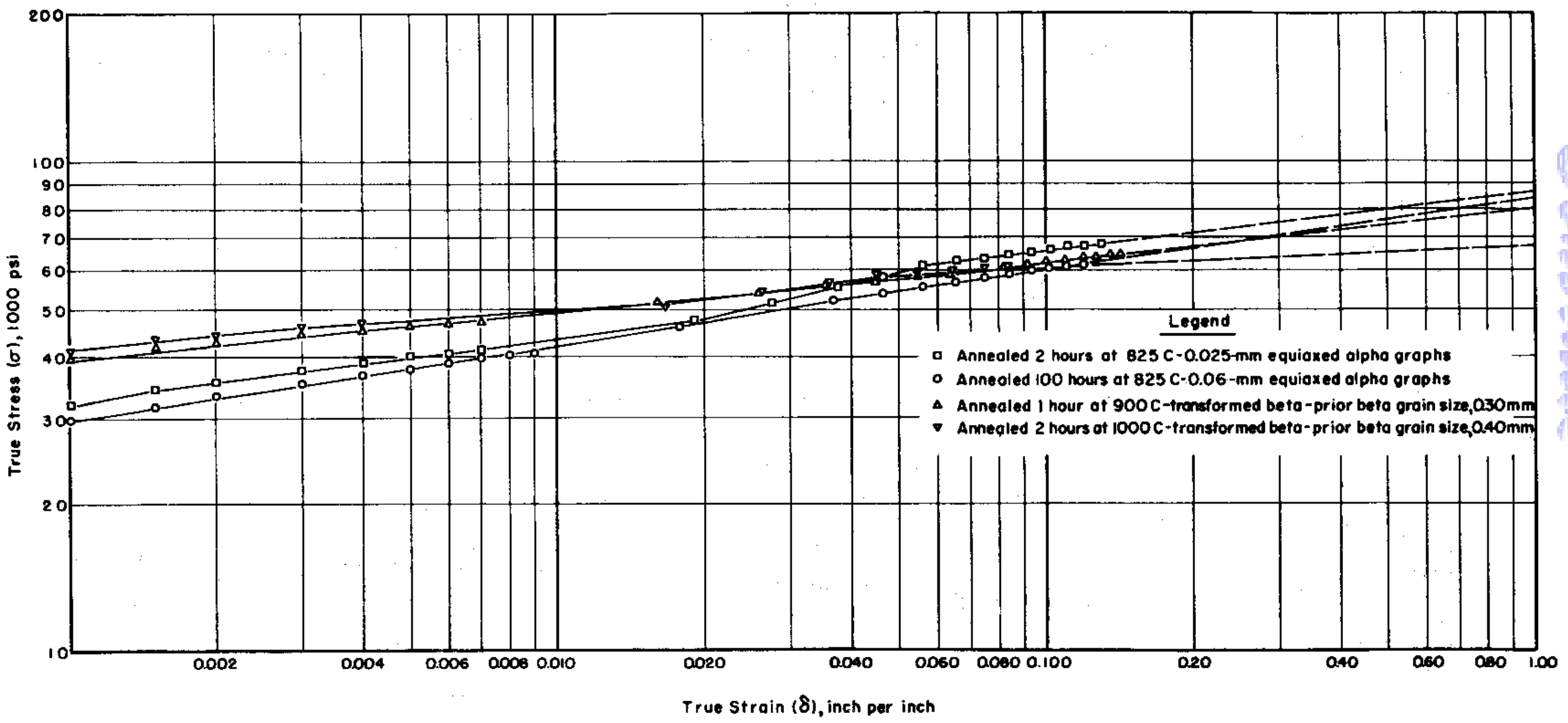

FIGURE B-3. FLOW CURVES FOR COMMERCIAL TITANIUM ANNEALED UNDER ARGON AND ARGON COOLED
Flow Constants Reported in Table I.

C-9114

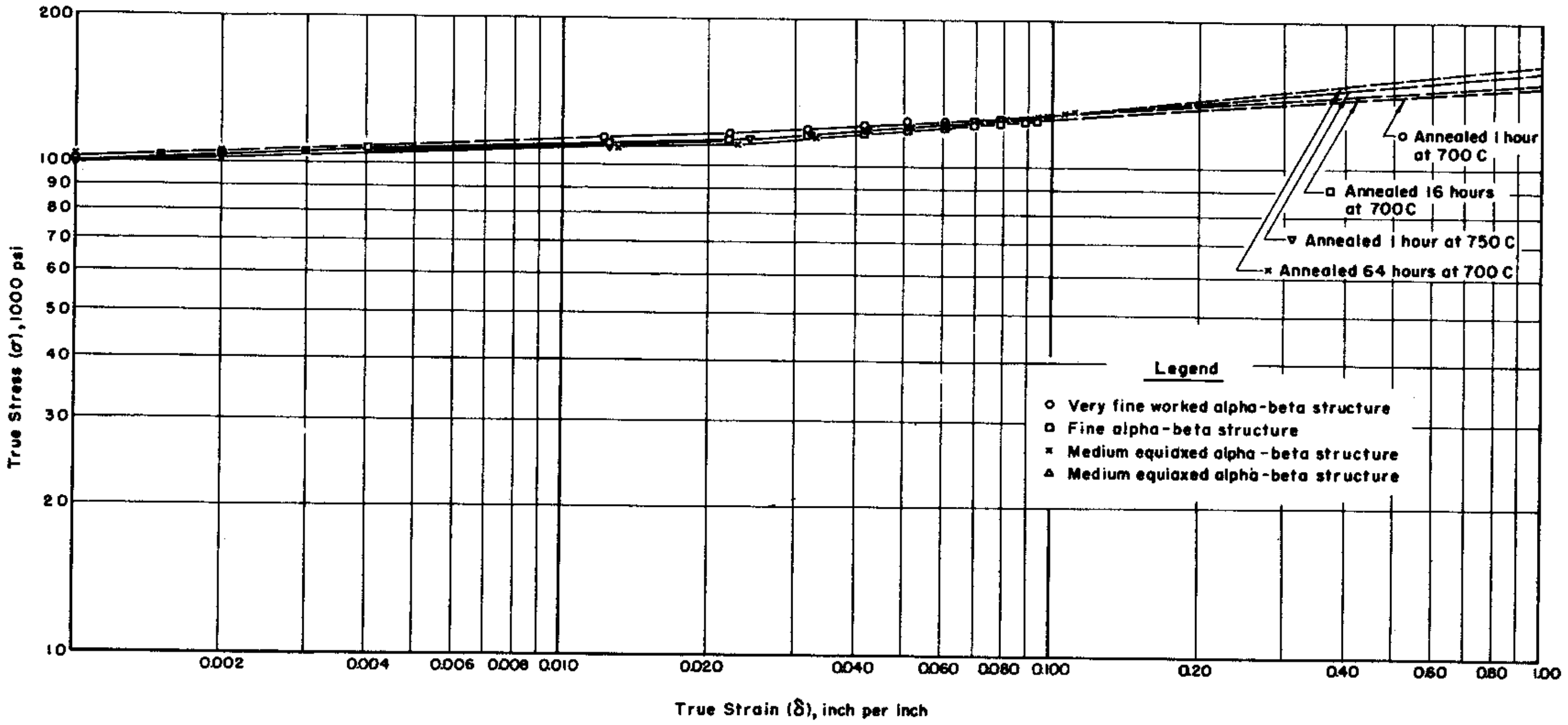

FIGURE B-4. FLOW CURVES FOR A Ti-5.0 Cr-5.0 Mo ALLOY ANNEALED UNDER ARGON, FURNACE COOLED TO 550 C, AND ARGON COOLED
Flow Coefficients Reported in Table I.

C-9115

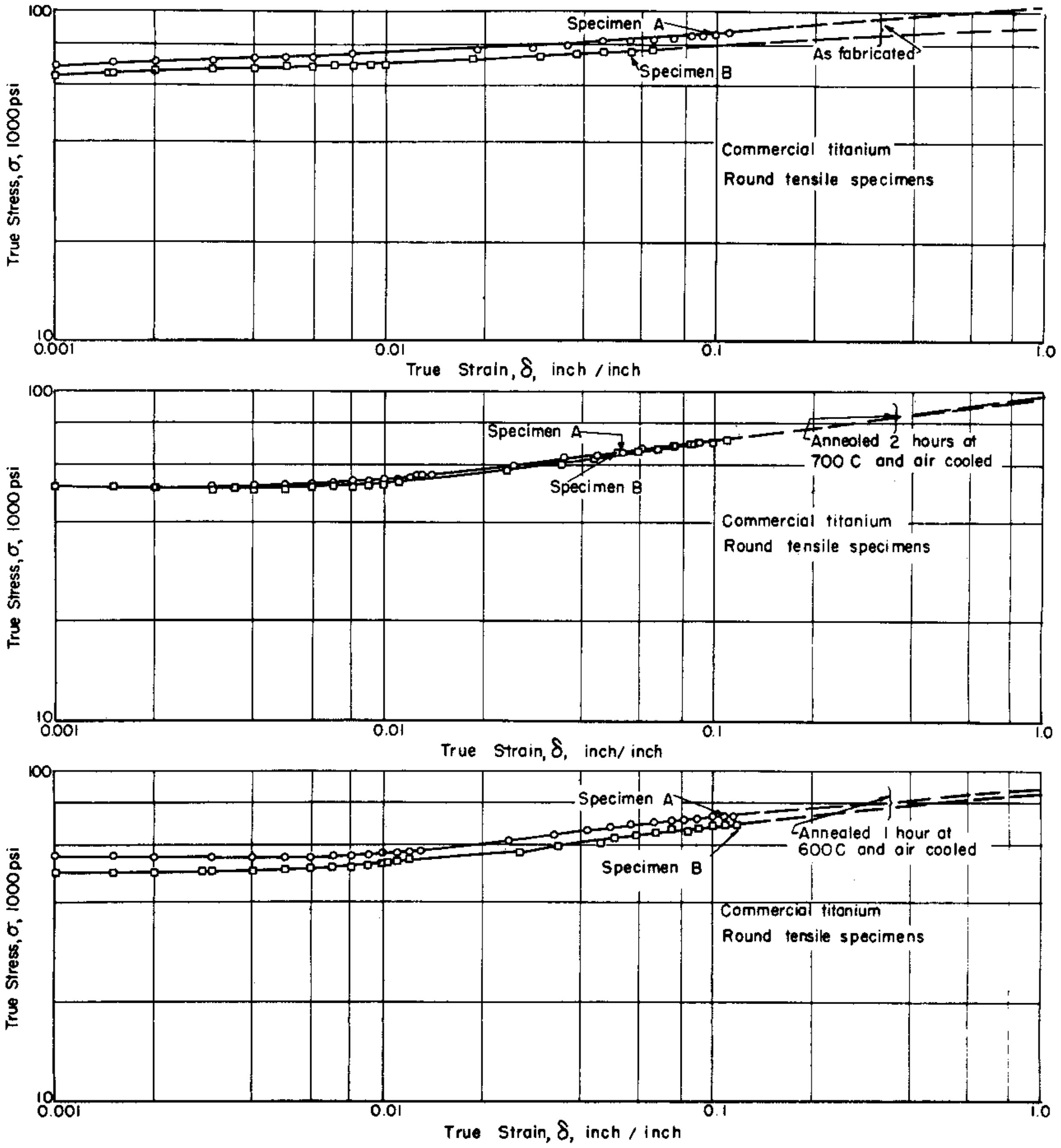

FIGURE B-5. FLOW CURVES FOR COMMERCIAL TITANIUM (ROUND SPECIMENS)

B-12079

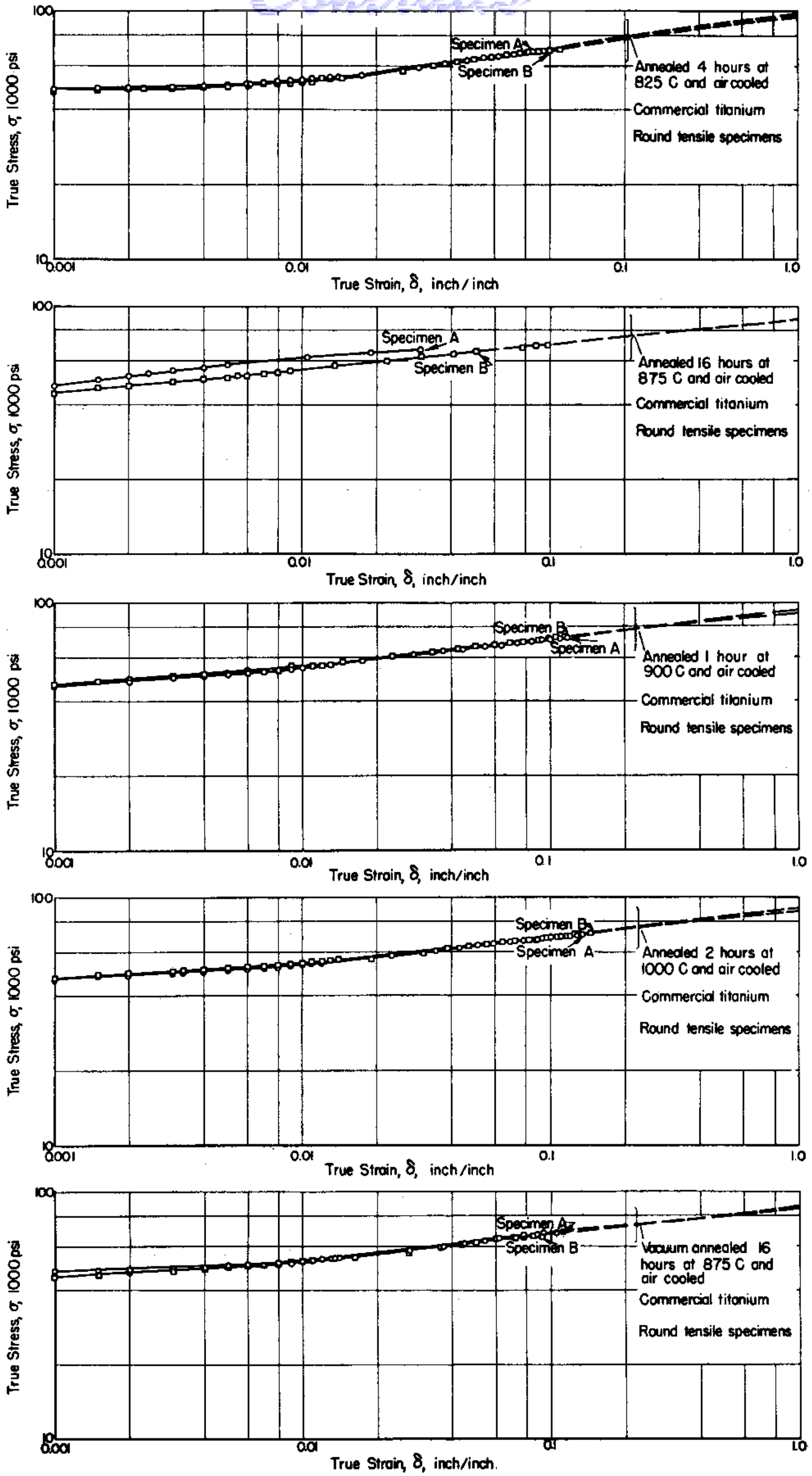

FIGURE B-6. FLOW CURVES FOR COMMERCIAL TITANIUM (ROUND SPECIMENS)

B-12080

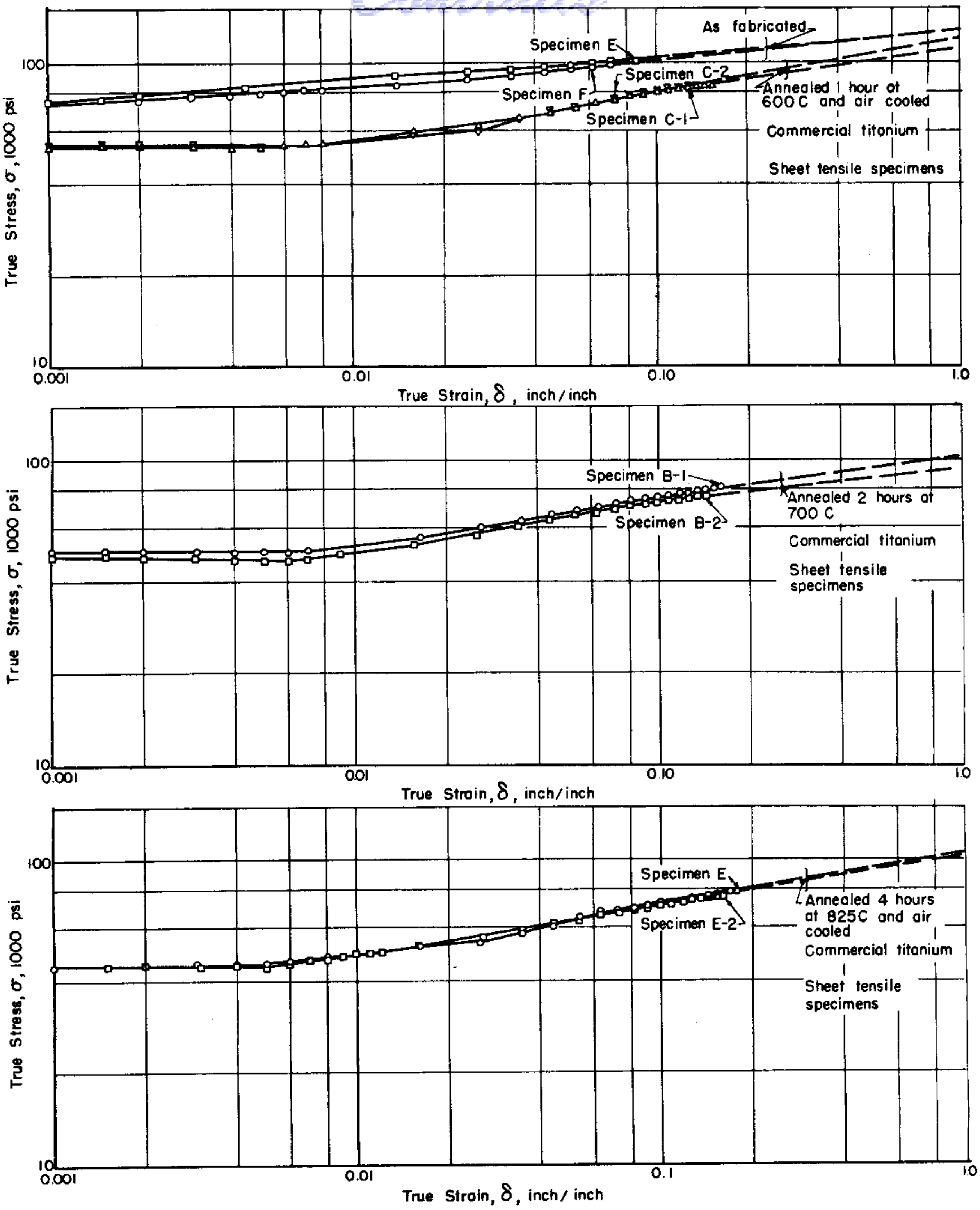

FIGURE B-7. FLOW CURVES FOR COMMERCIAL TITANIUM (SHEET SPECIMENS)

B-12081

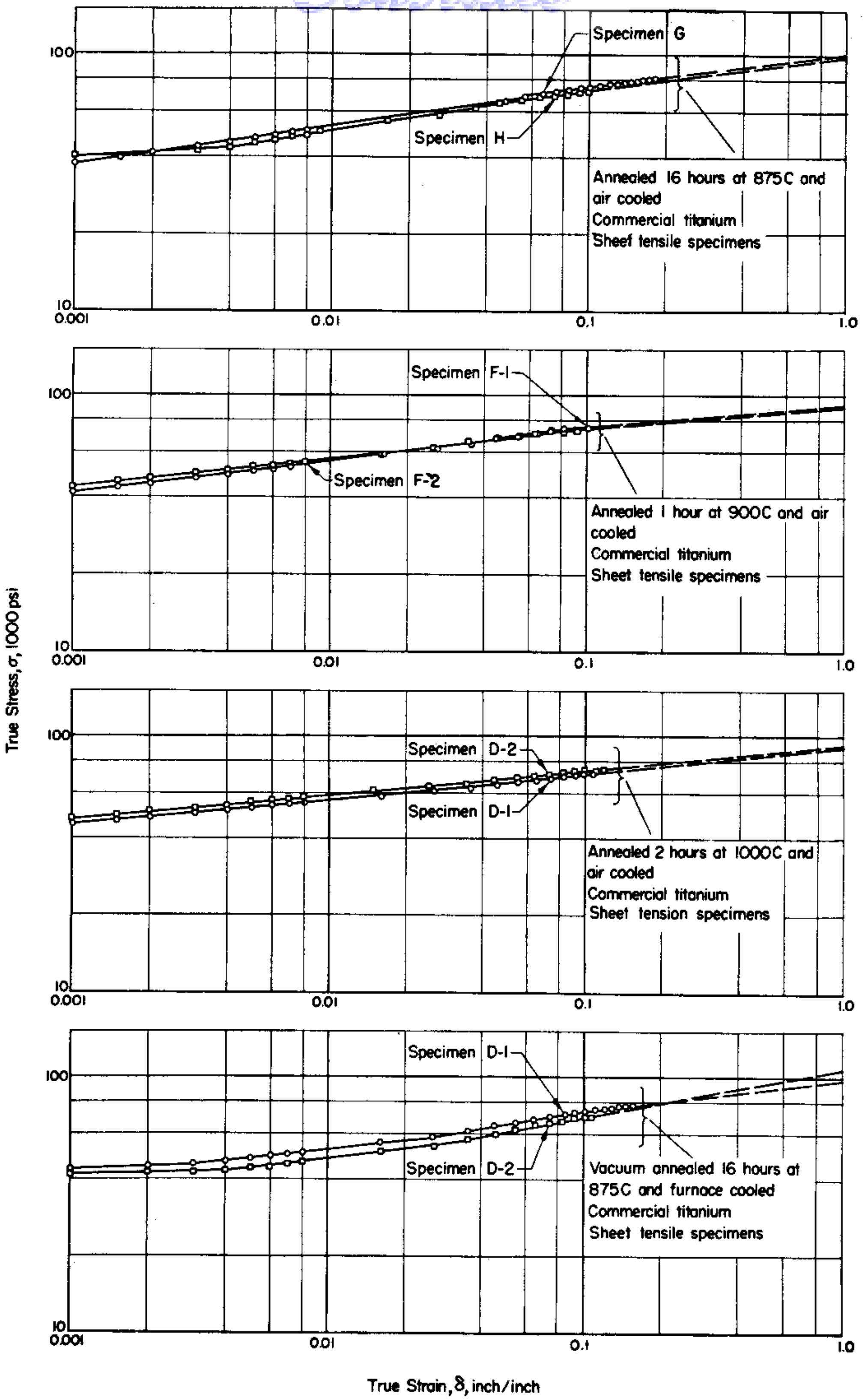

FIGURE B-8. FLOW CURVES FOR COMMERCIAL TITANIUM (SHEET SPECIMENS)

B-12082

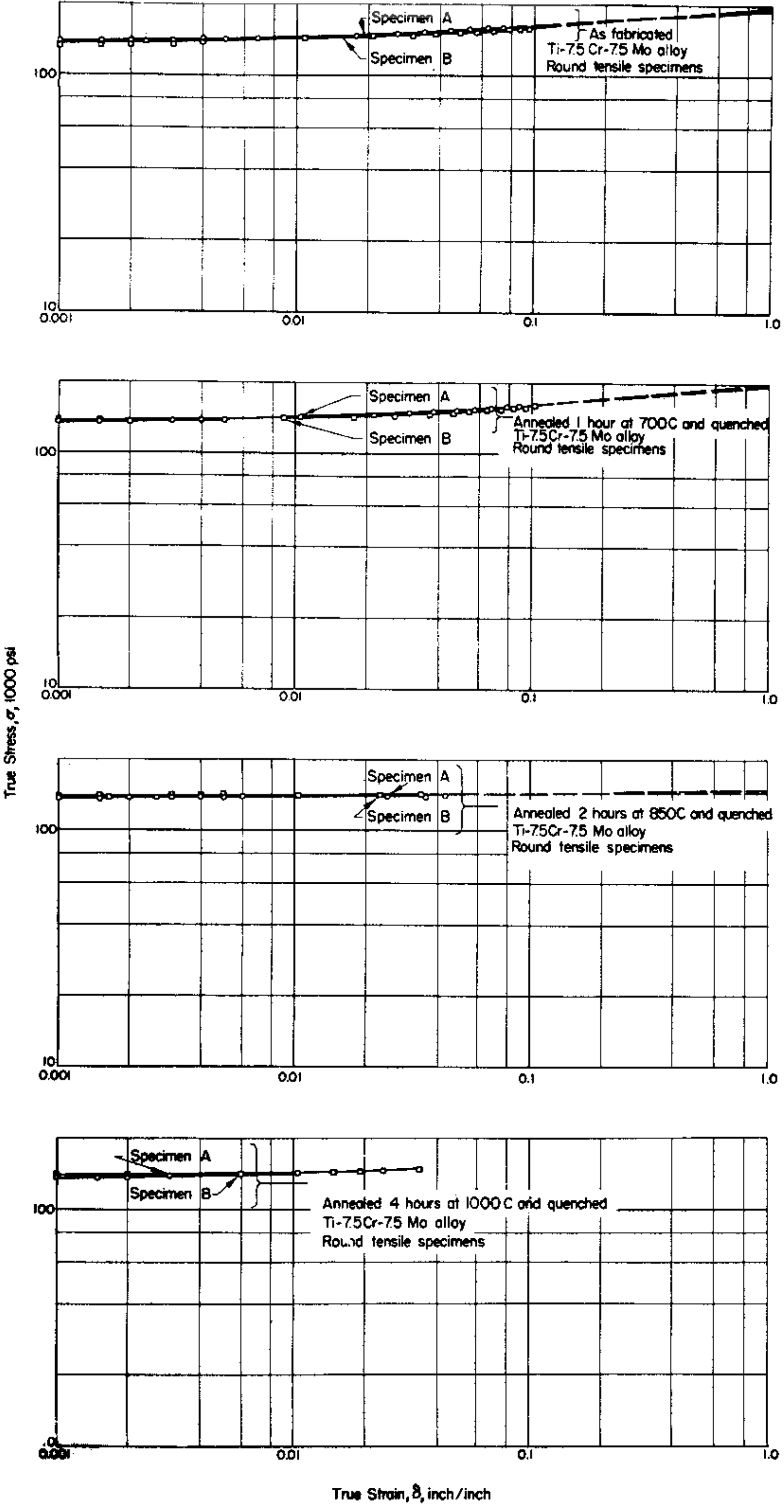

FIGURE B-9. FLOW CURVES FOR A Ti-7.5Cr-7.5 Mo ALLOY (ROUND SPECIMENS)

B-12083

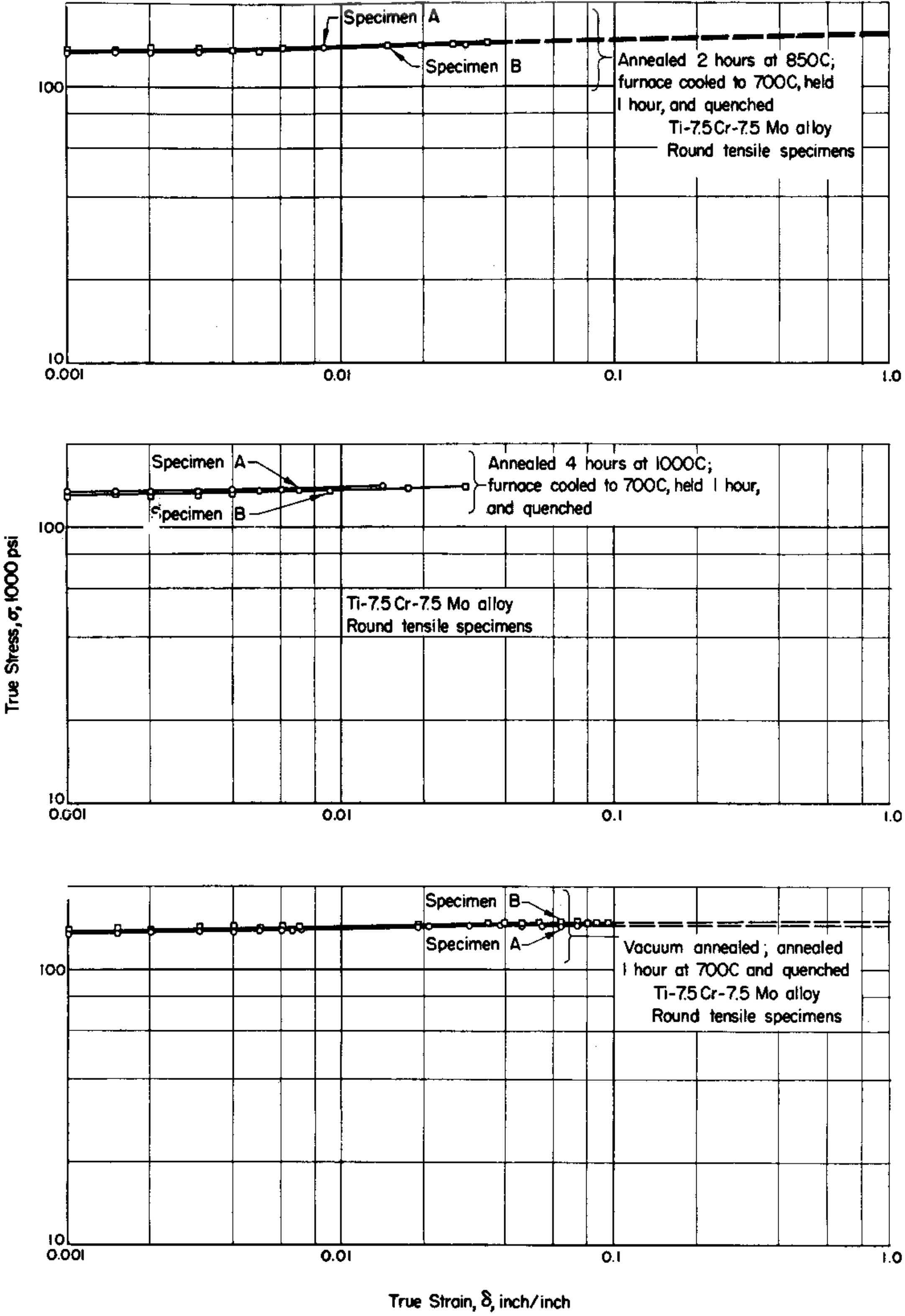

FIGURE B-10. FLOW CURVES FOR A Ti-7.5Cr-7.5 Mo ALLOY (ROUND SPECIMENS)

B-12084

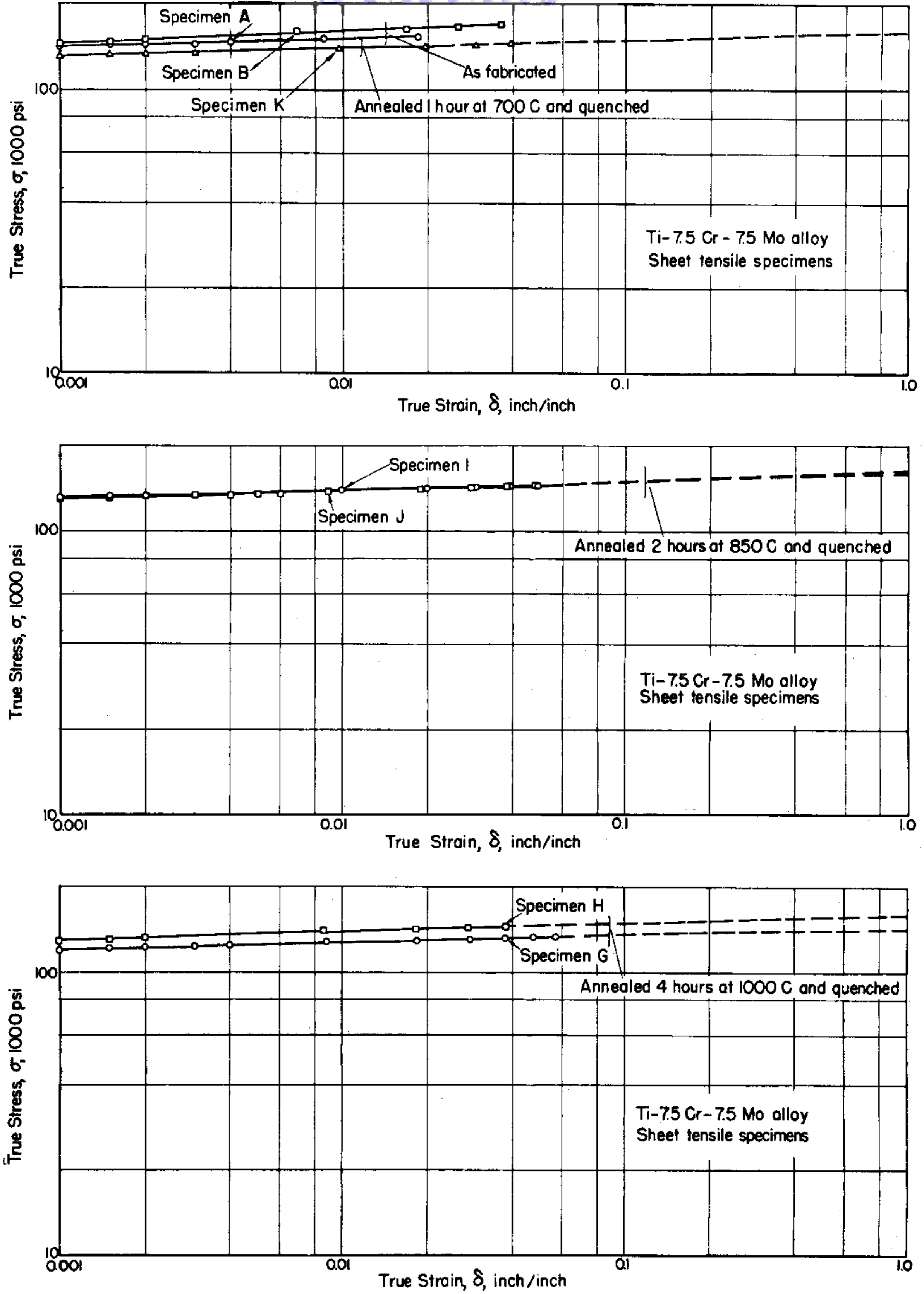

FIGURE B-11. FLOW CURVES FOR A Ti-7.5 Cr-7.5 Mo ALLOY (SHEET SPECIMENS)

B-12085

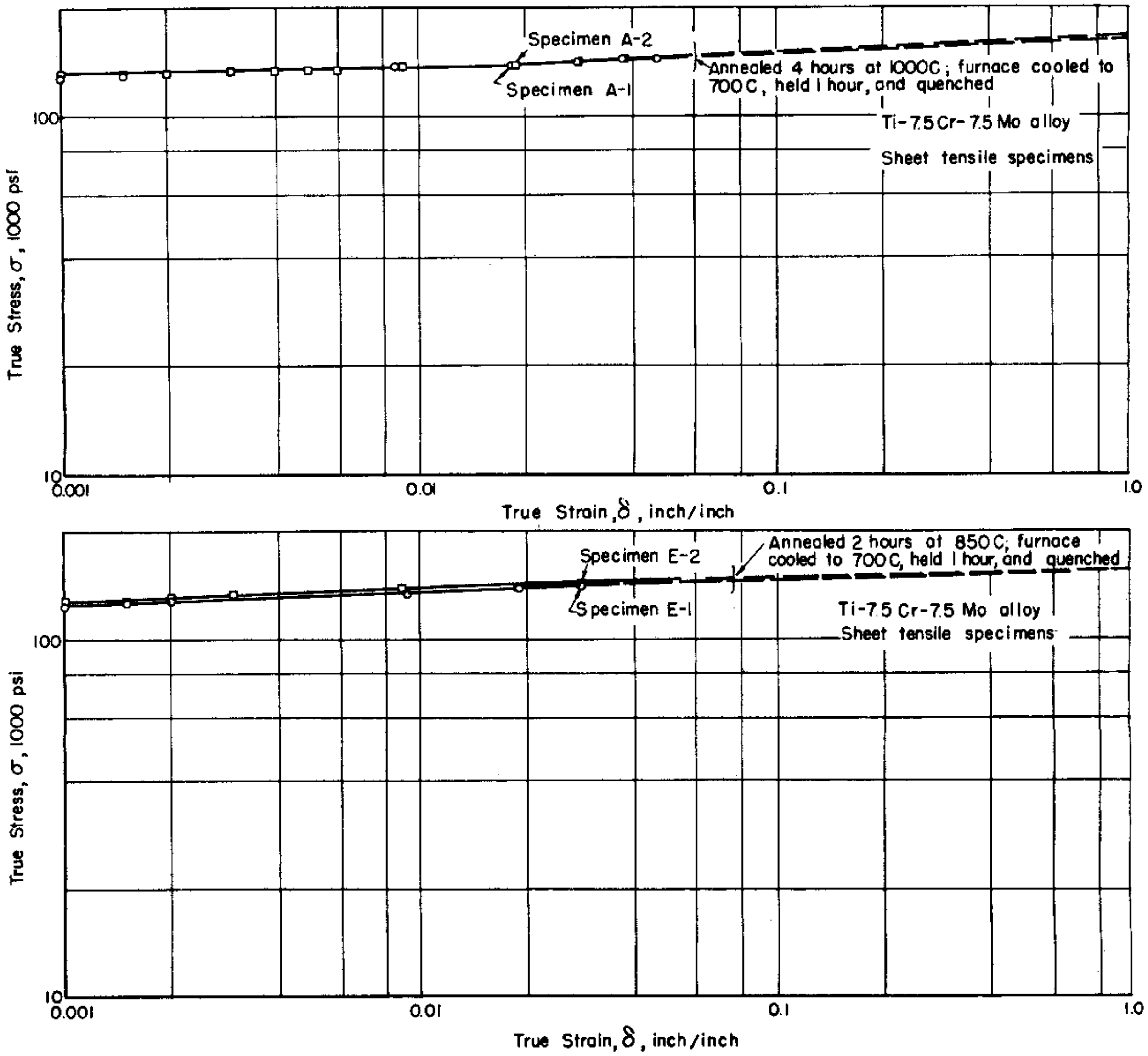

FIGURE B-12. FLOW CURVES FOR A Ti–7.5 Cr–7.5 Mo ALLOY
(SHEET SPECIMENS)

B-12086

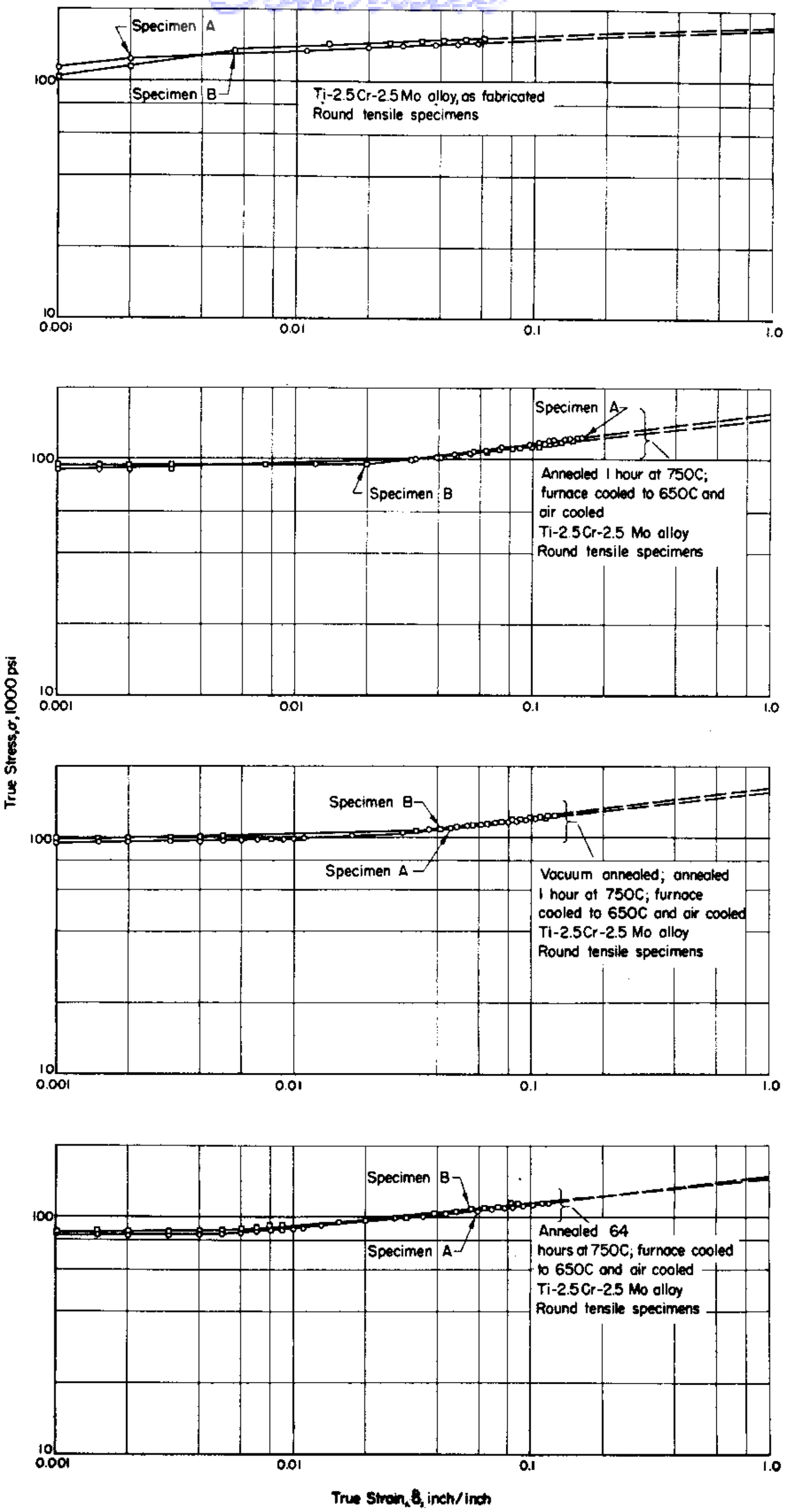

FIGURE B-13. FLOW CURVES FOR Ti-2.5Cr-2.5 Mo ALLOY (ROUND SPECIMENS)

B-12087

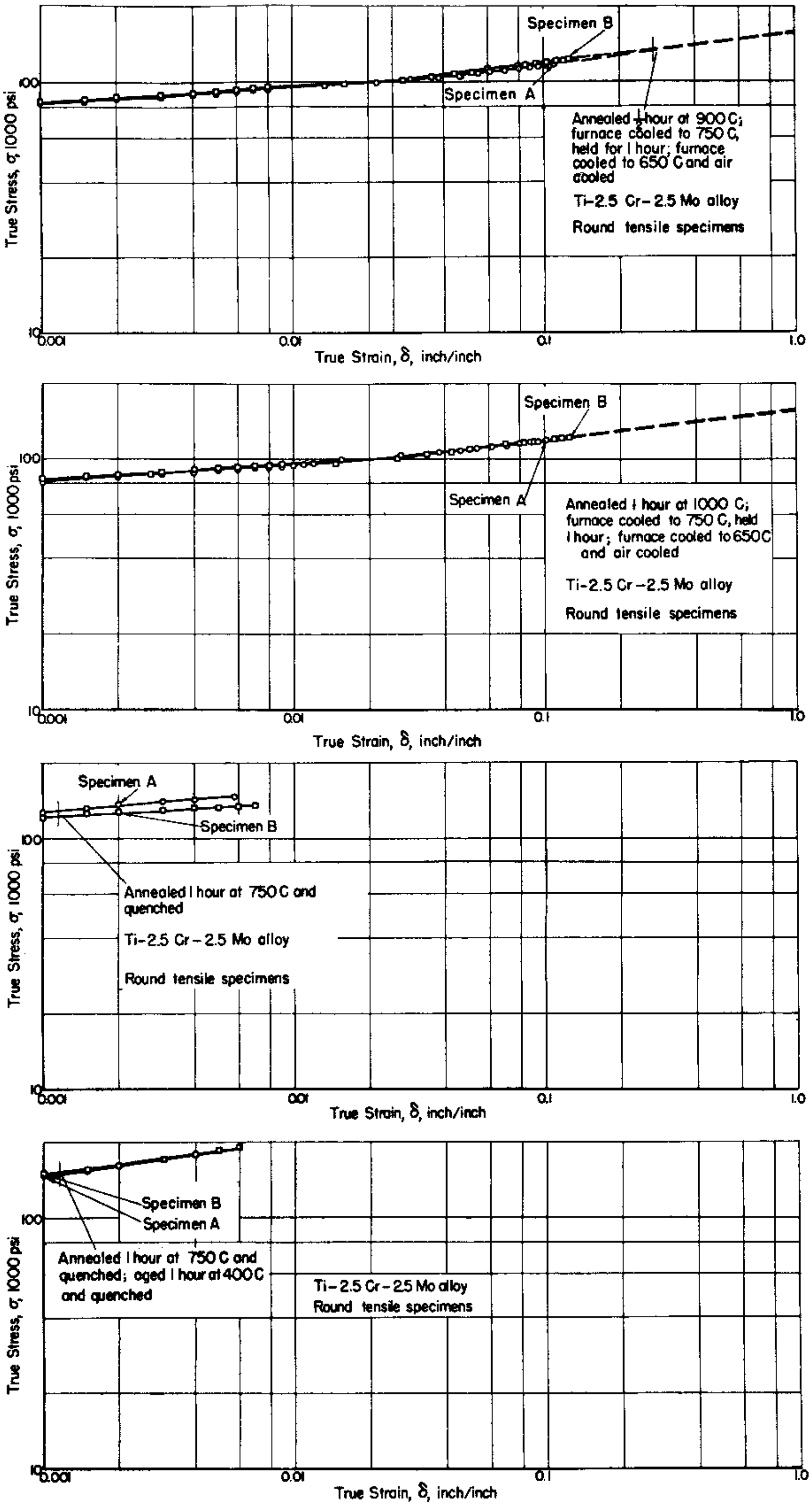

FIGURE B-14. FLOW CURVE FOR A Ti-2.5 Cr-2.5 Mo ALLOY (ROUND SPECIMENS)

B-12088

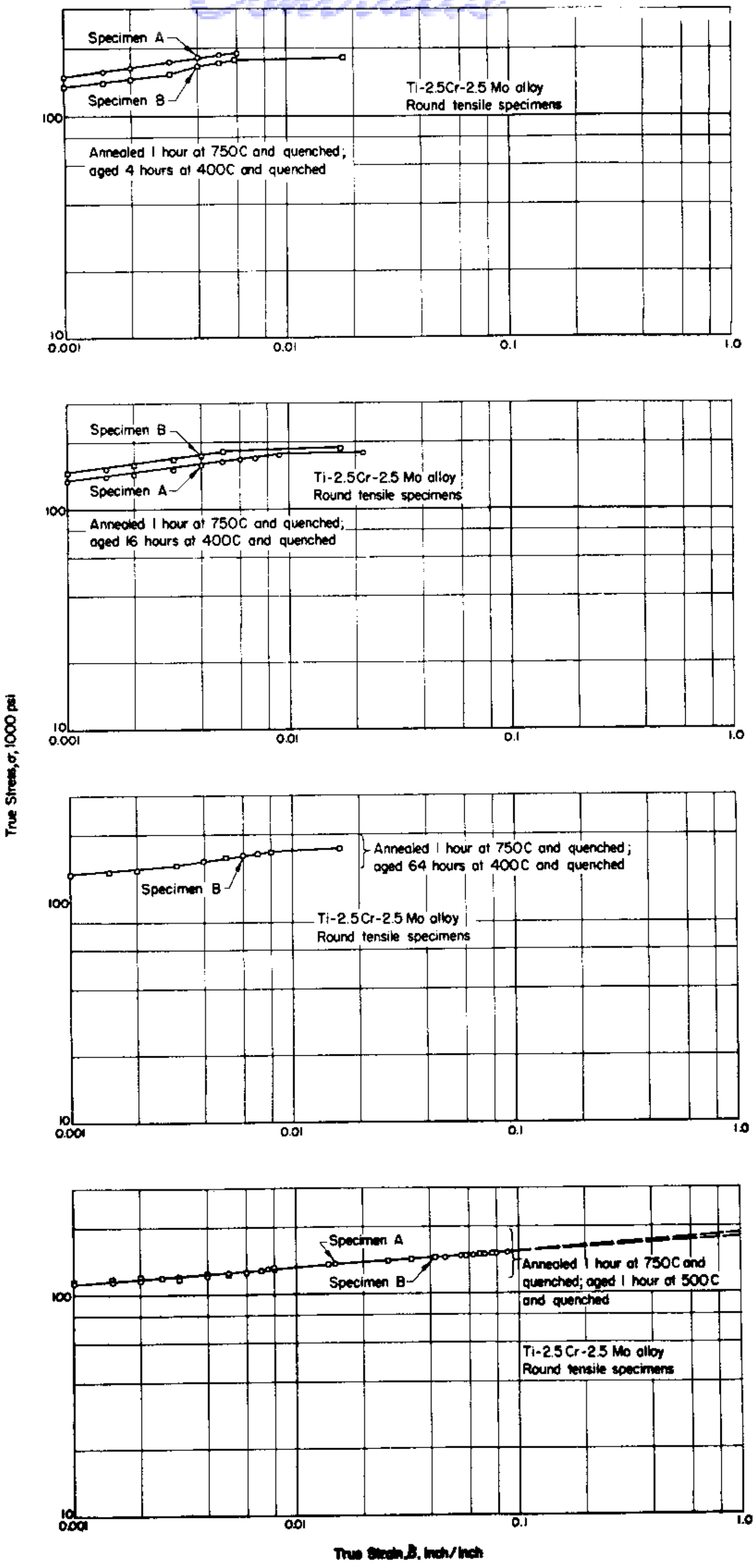

FIGURE B-15. FLOW CURVES FOR Ti-2.5Cr-2.5 Mo ALLOY(ROUND SPECIMENS)

B-12089

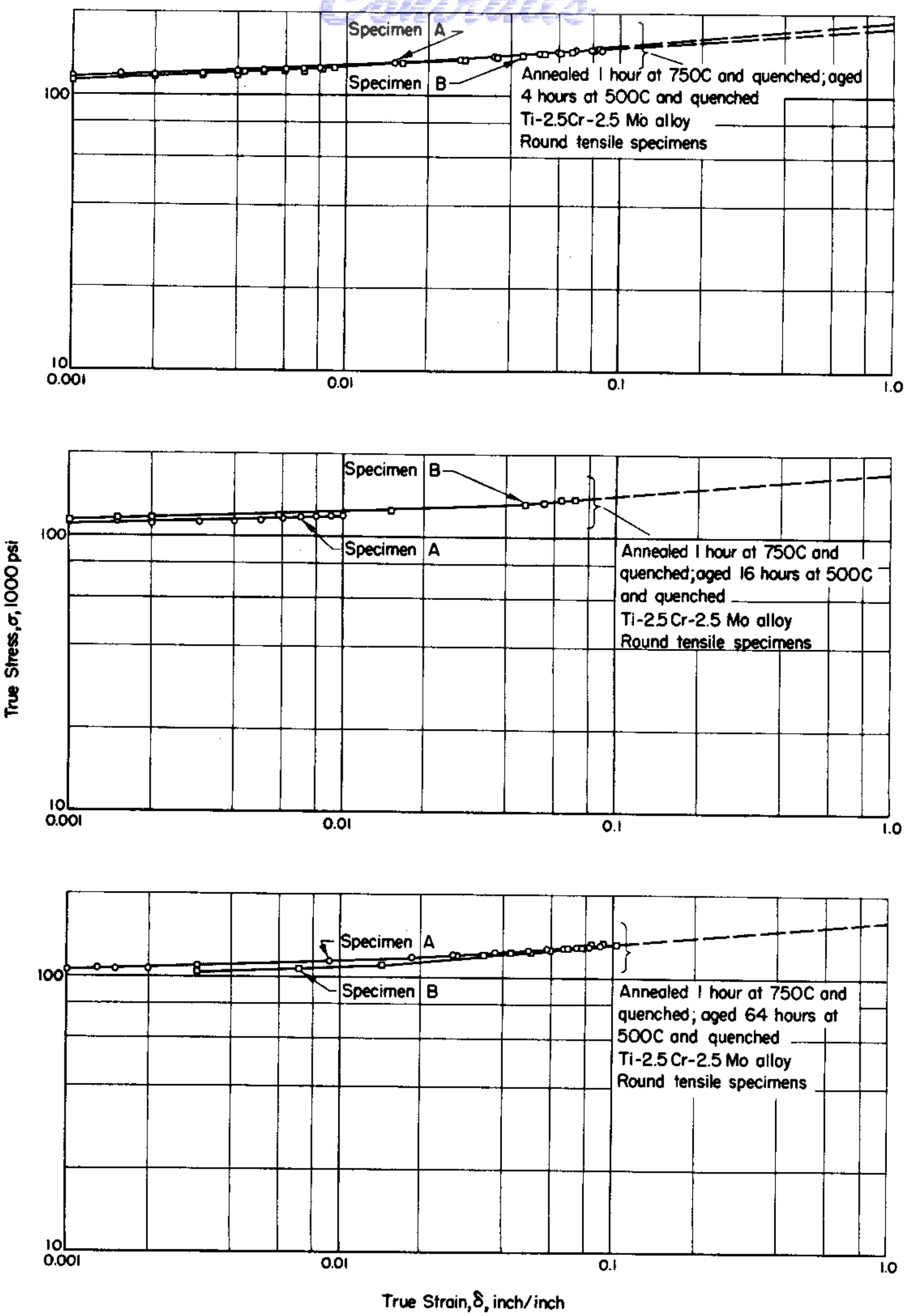

FIGURE B-16. FLOW CURVES FOR A Ti-2.5 Cr-2.5 Mo ALLOY (ROUND SPECIMENS)

B-12090

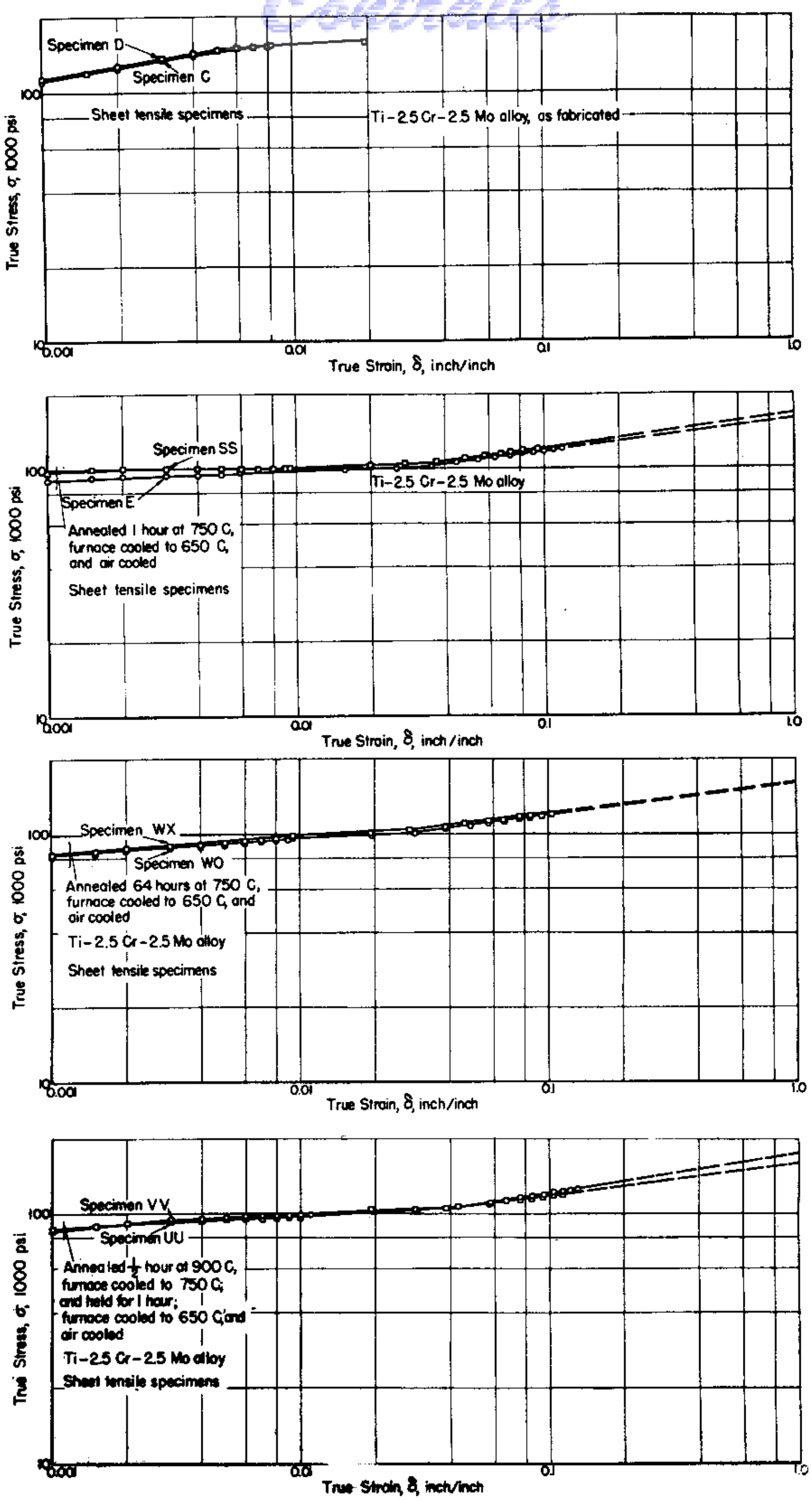

FIGURE B-17. FLOW CURVES FOR A Ti-2.5 Cr-2.5 Mo ALLOY (SHEET SPECIMENS)

B-12091

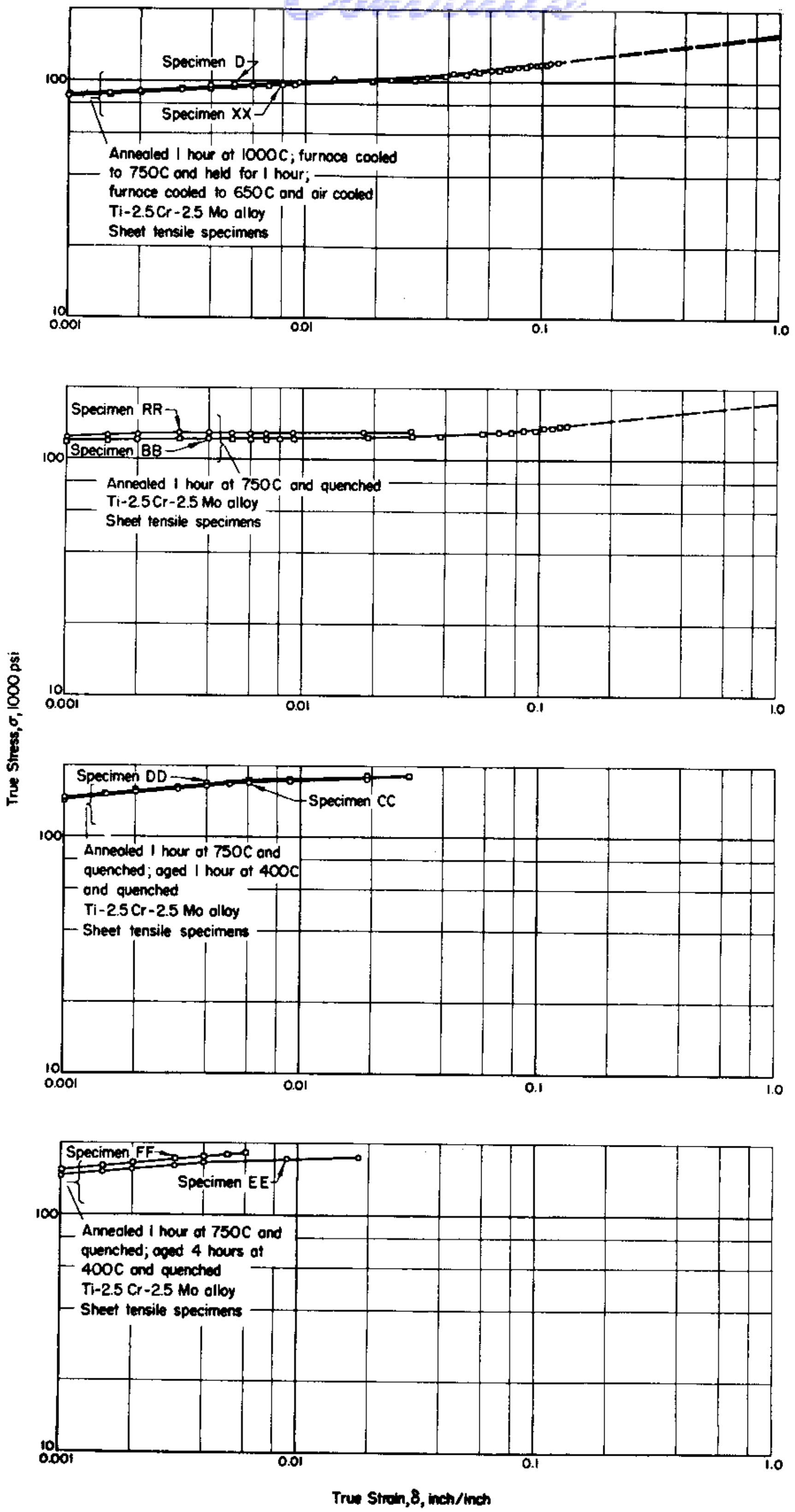

FIGURE B-18. FLOW CURVES FOR Ti-2.5Cr-2.5 Mo ALLOY(SHEET SPECIMENS)

B-12092

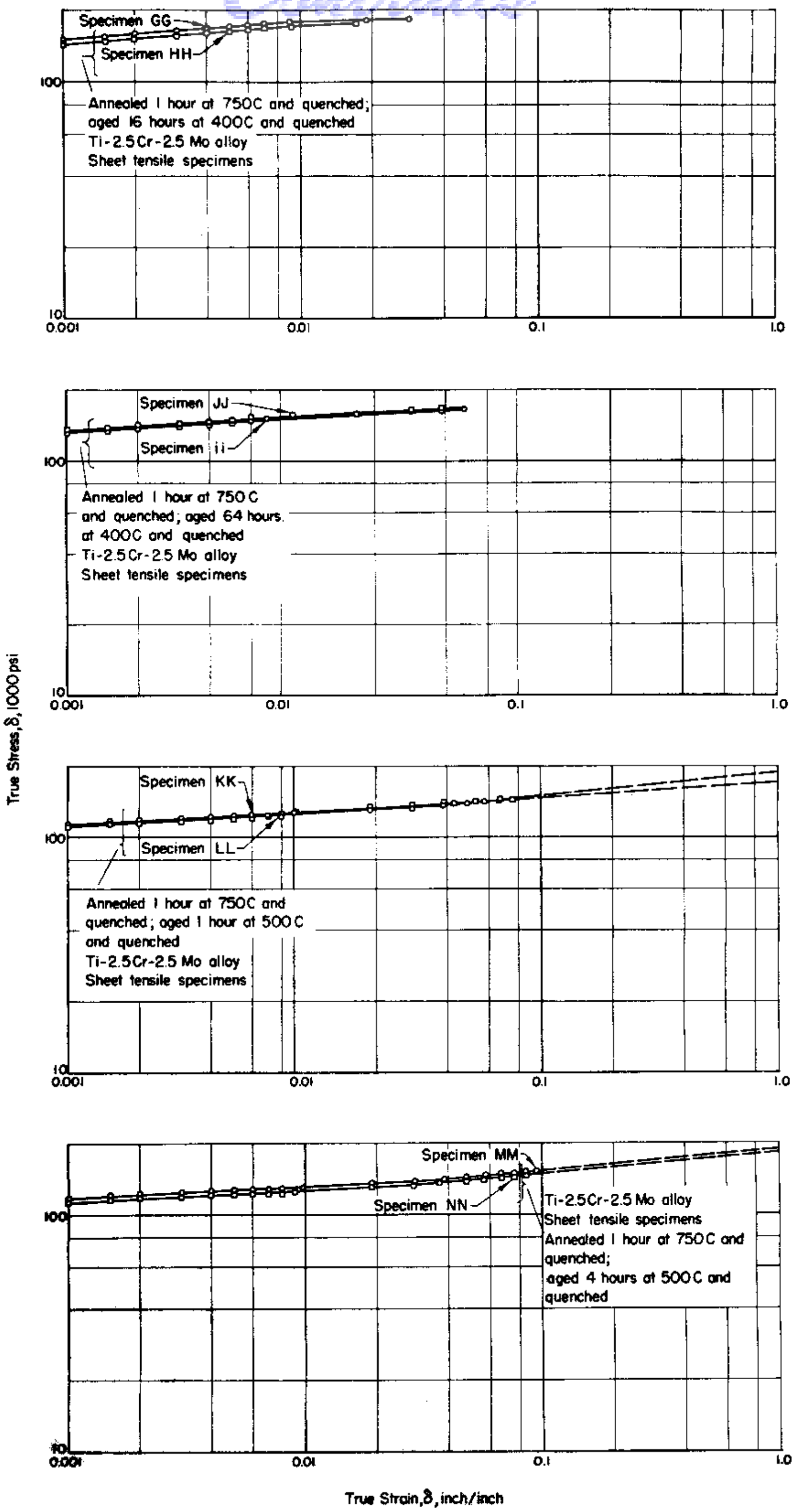

FIGURE B-19. FLOW CURVES FOR Ti-2.5Cr-2.5 Mo ALLOY (SHEET SPECIMENS)

B-12093

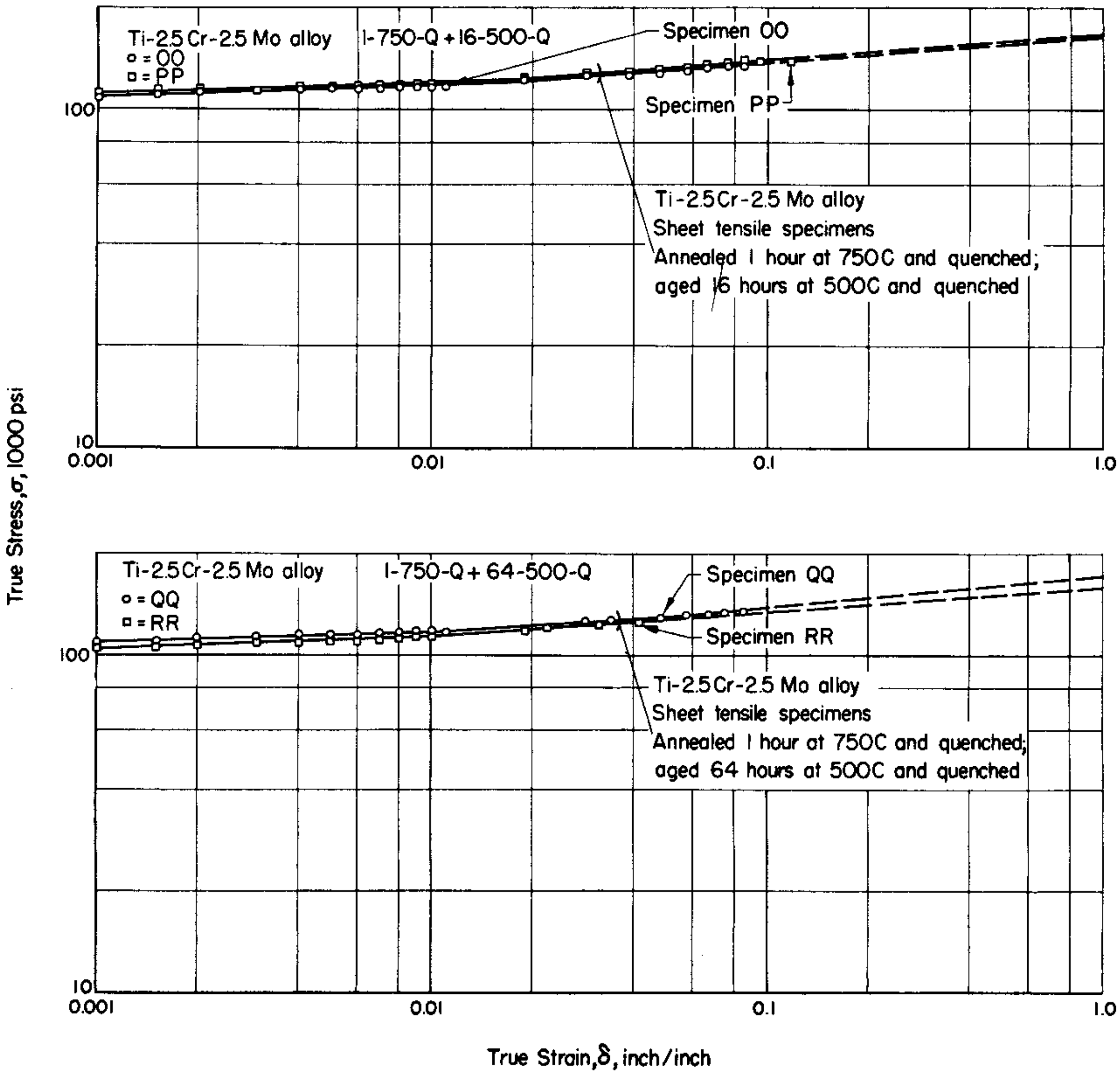

FIGURE B-20. FLOW CURVES FOR Ti-2.5Cr-2.5 Mo ALLOYS (SHEET SPECIMENS)

B-12094

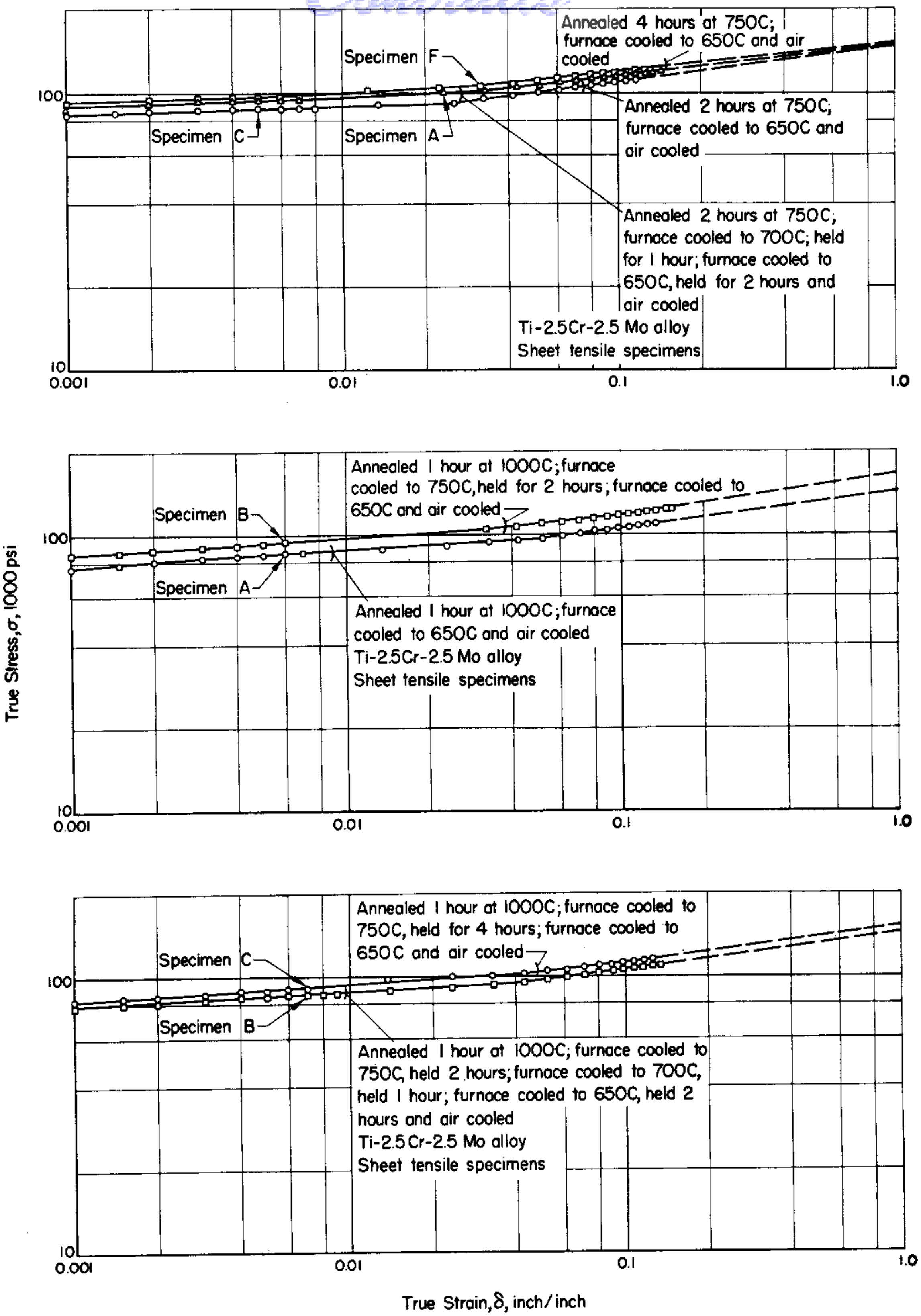

FIGURE B-21. FLOW CURVES FOR Ti-2.5 Cr-2.5 Mo ALLOY (SHEET SPECIMENS)

8-12095

S-N CURVES

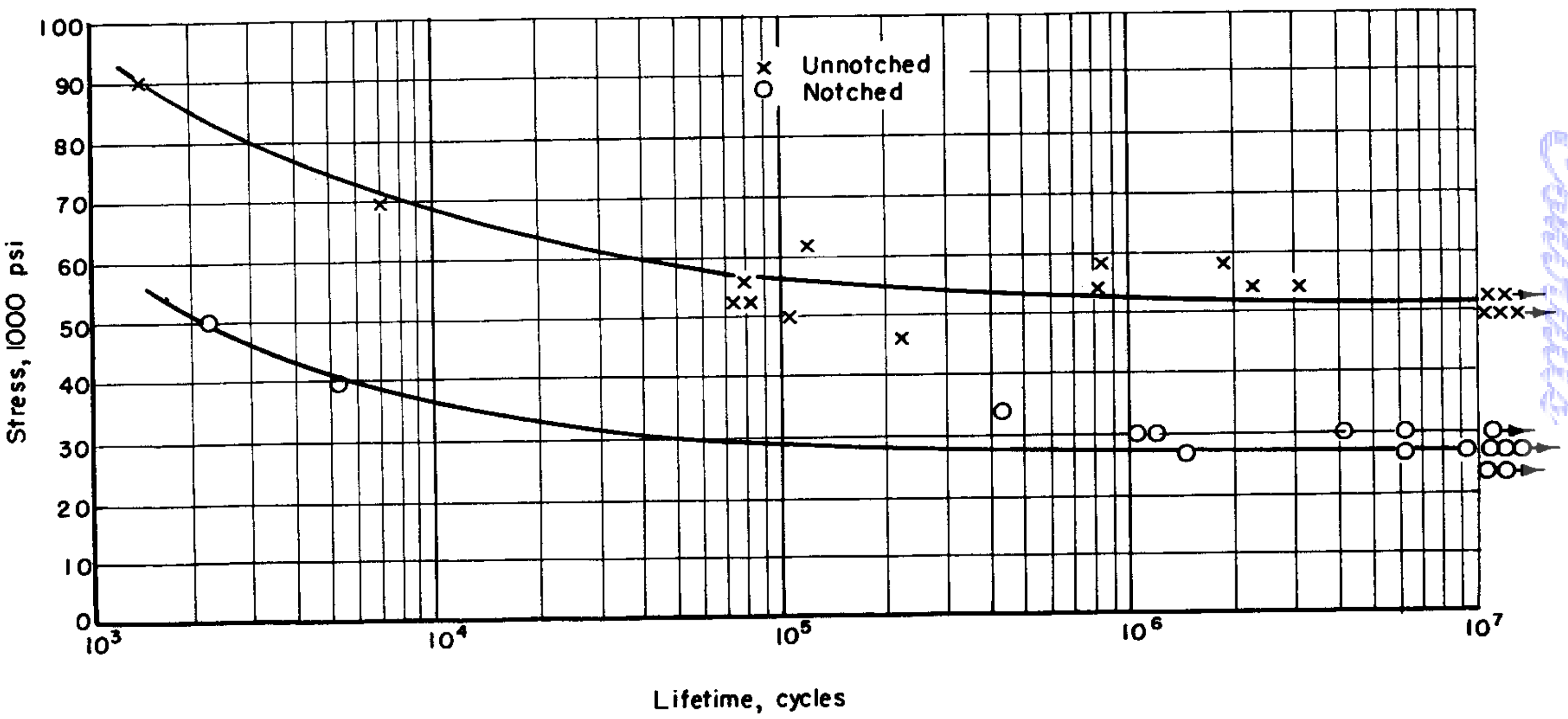

FIGURE C-I. COMMERCIAL TITANIUM ANNEALED TWO HOURS AT 700 C AND AIR COOLED

A-12096

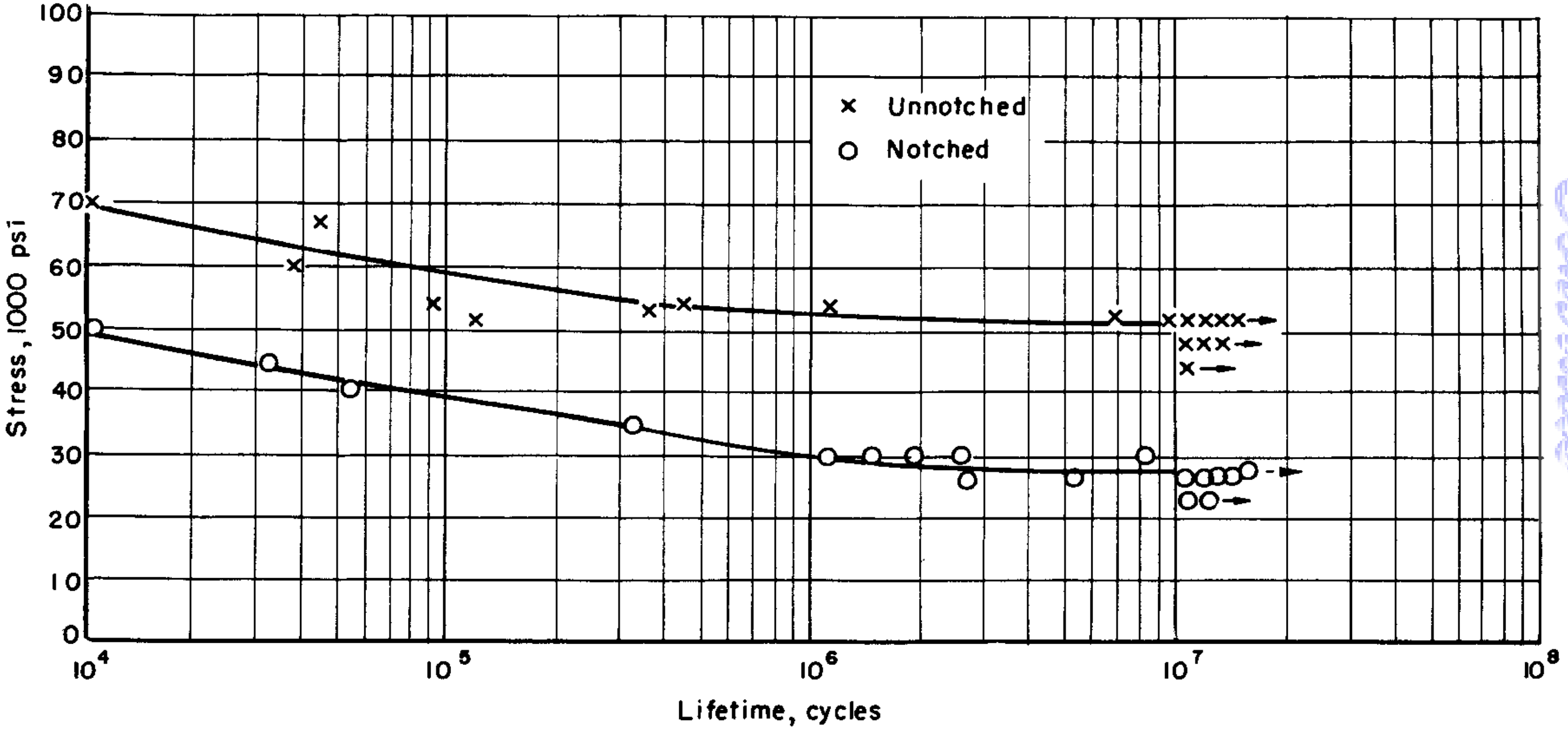

FIGURE C-2. COMMERCIAL TITANIUM ANNEALED 16 HOURS AT 875 C AND AIR COOLED

A-12097

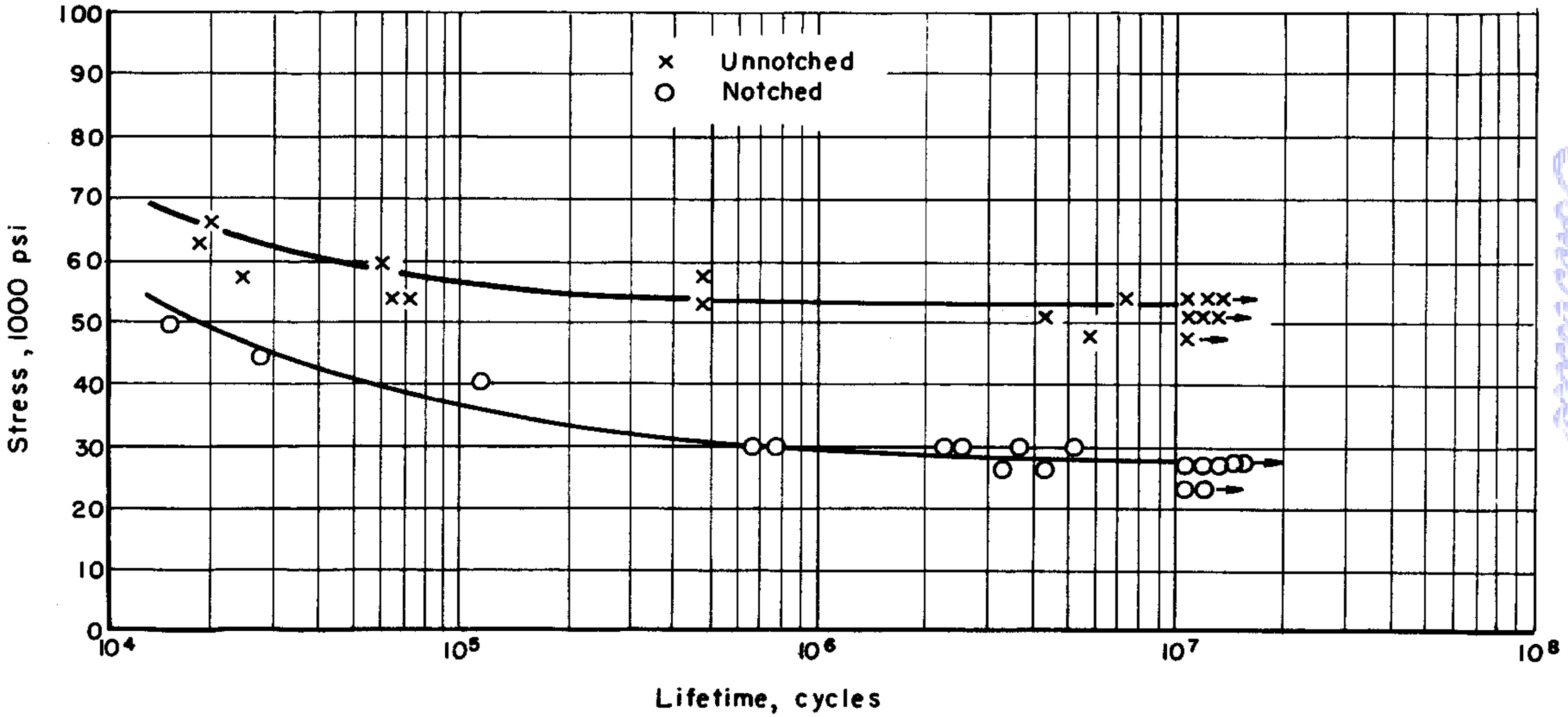

FIGURE C-3. COMMERCIAL TITANIUM ANNEALED 1 HOUR AT 900 C AND AIR COOLED

A-12098

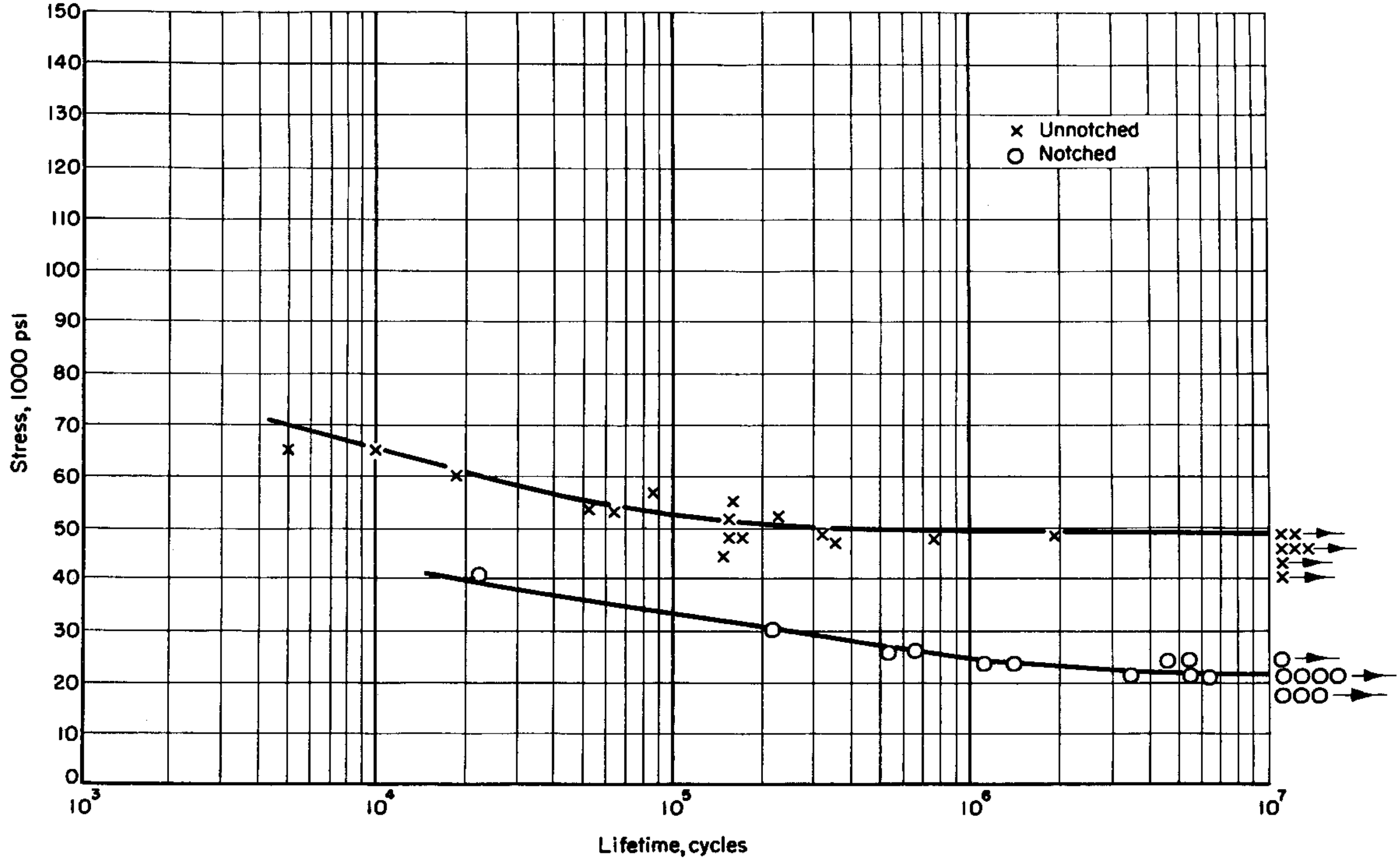

FIGURE C-4. COMMERCIAL TITANIUM VACUUM ANNEALED 16 HOURS AT 875C AND FURNACE COOLED

A-12099

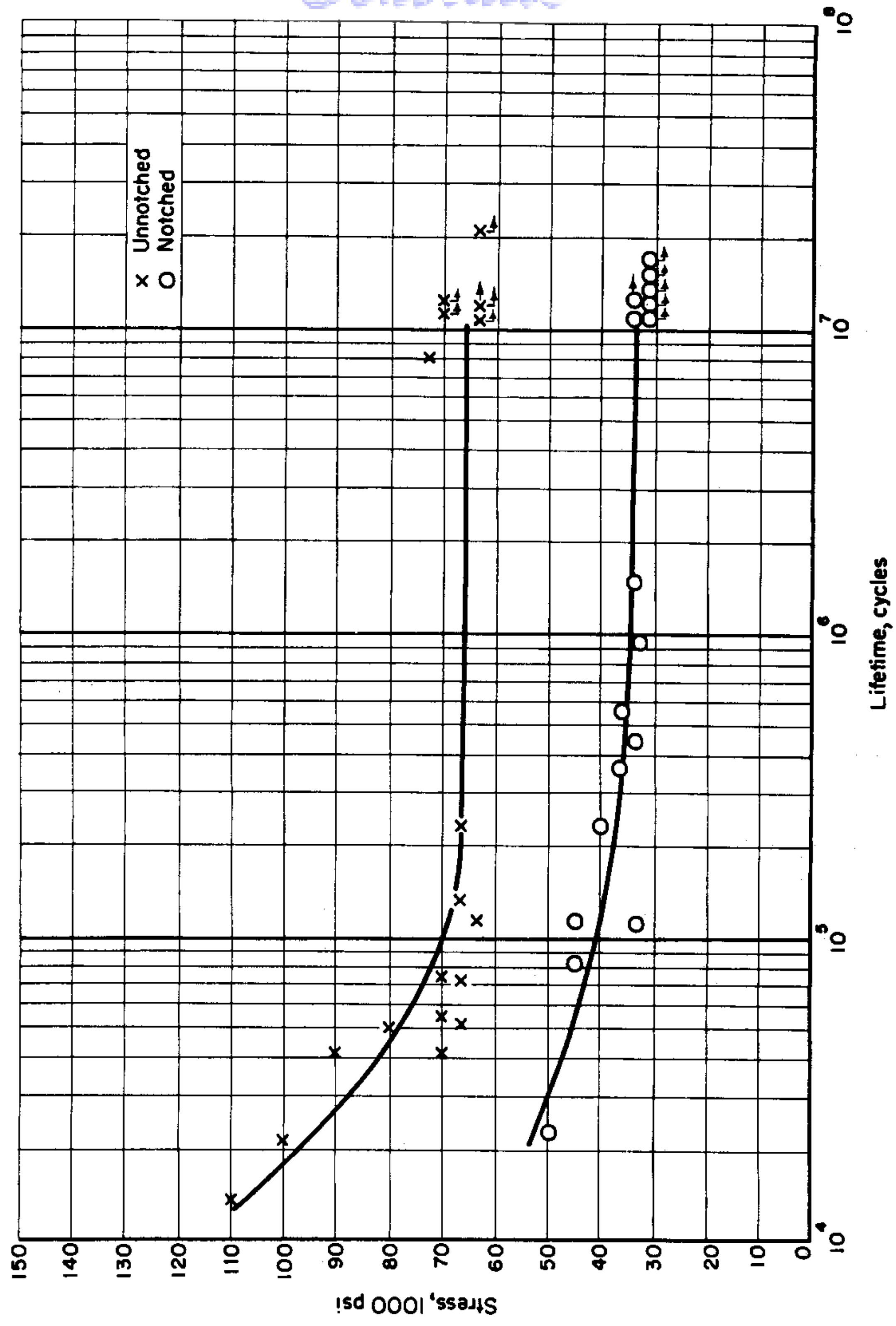

FIGURE C-5. Ti-7.5Cr-7.5 Mo ALLOY ANNEALED 1 HOUR AT 700C AND QUENCHED

A-12100

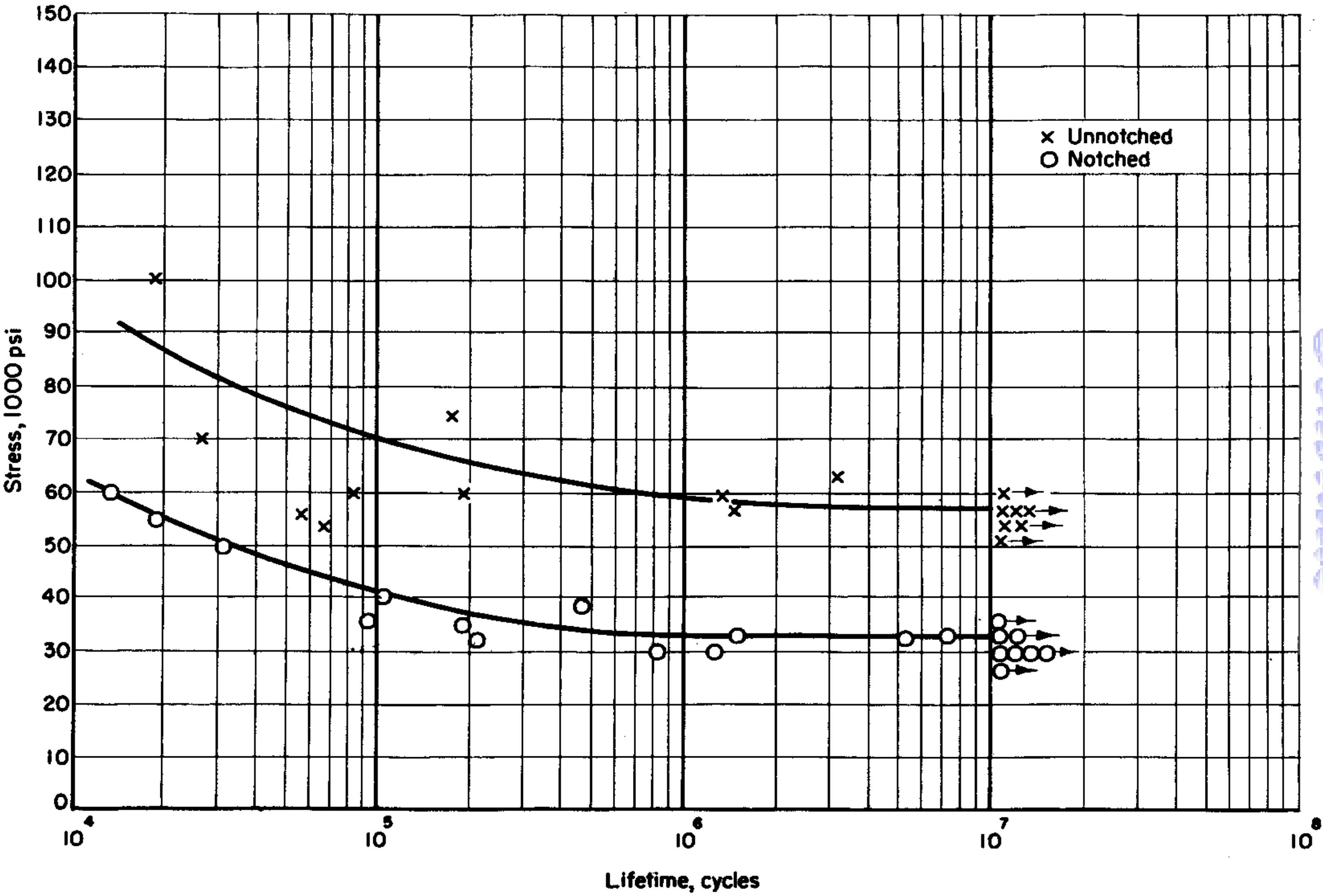

FIGURE C-6. Ti-7.5Cr-7.5 Mo ALLOY ANNEALED 4 HOURS AT 1000C AND QUENCHED

A-12101

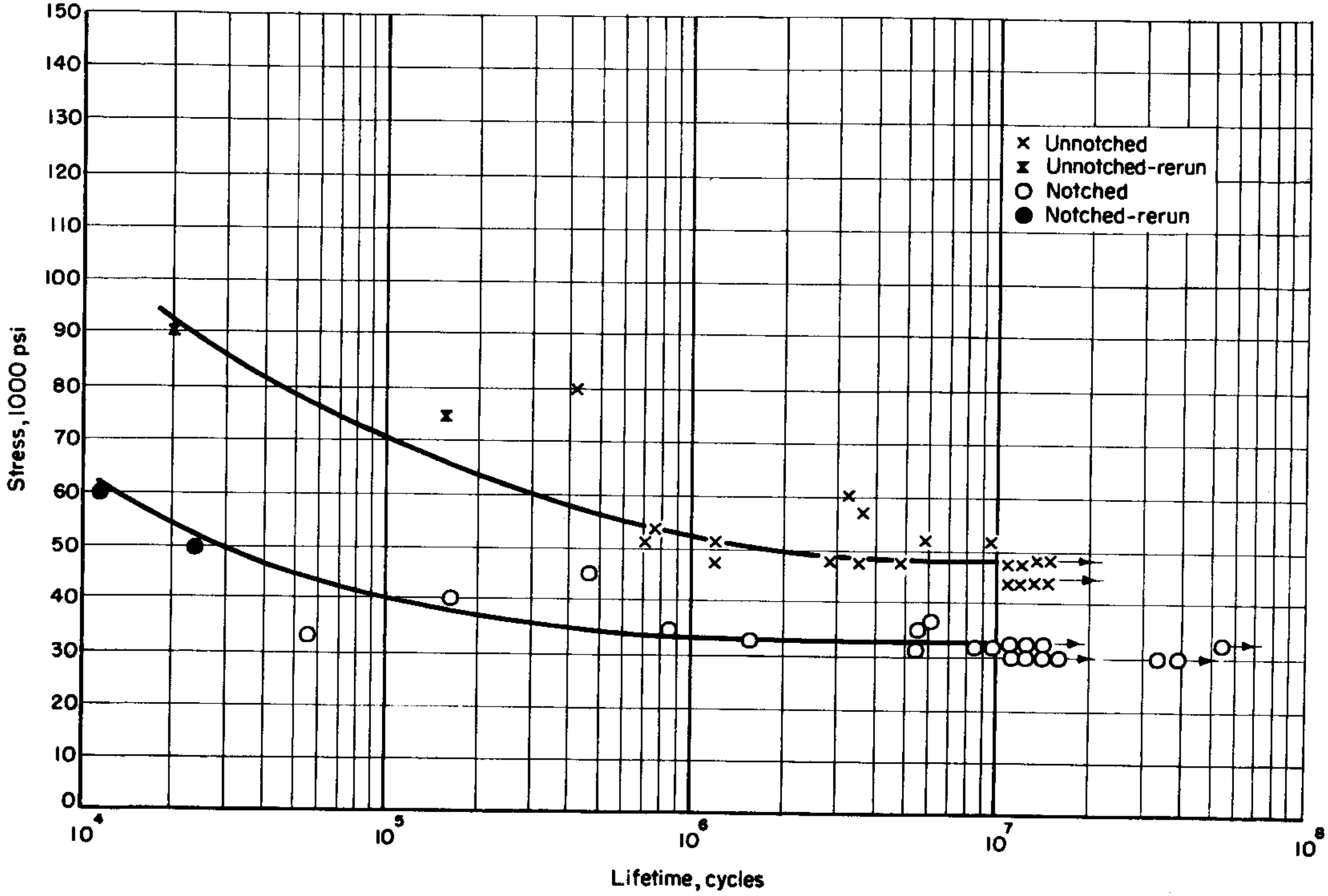

FIGURE C-7. Ti-7.5Cr-7.5 Mo ALLOY ANNEALED 4 HOURS AT 1000C; FURNACE COOLED TO 700C, HELD 1 HOUR, AND QUENCHED

A-12102

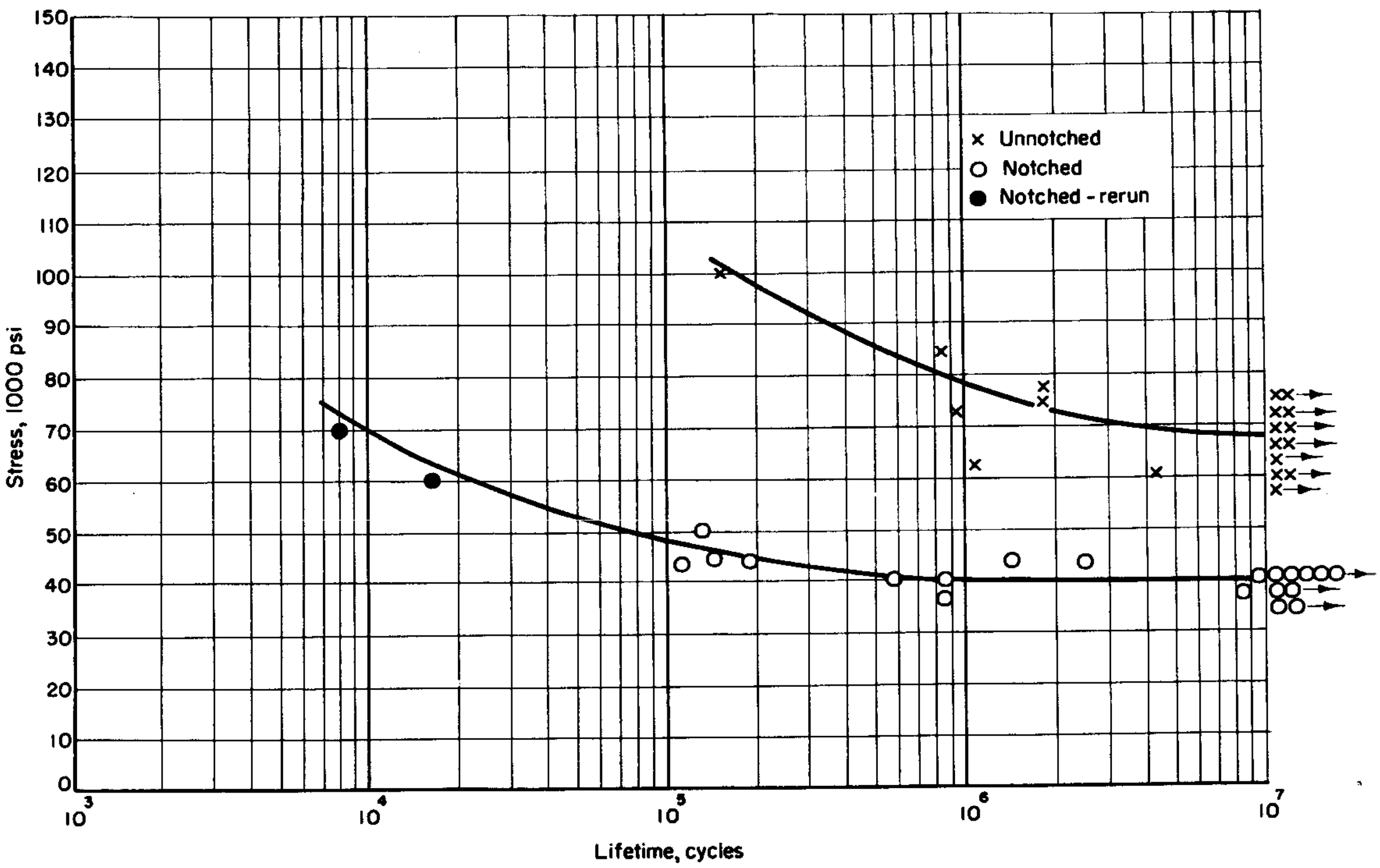

FIGURE C-8. Ti-7.5Cr-7.5 Mo ALLOY ANNEALED 1 HOUR AT 700C AND QUENCHED; REHEATED TO 300C FOR 100 HOURS AND QUENCHED

A-12103

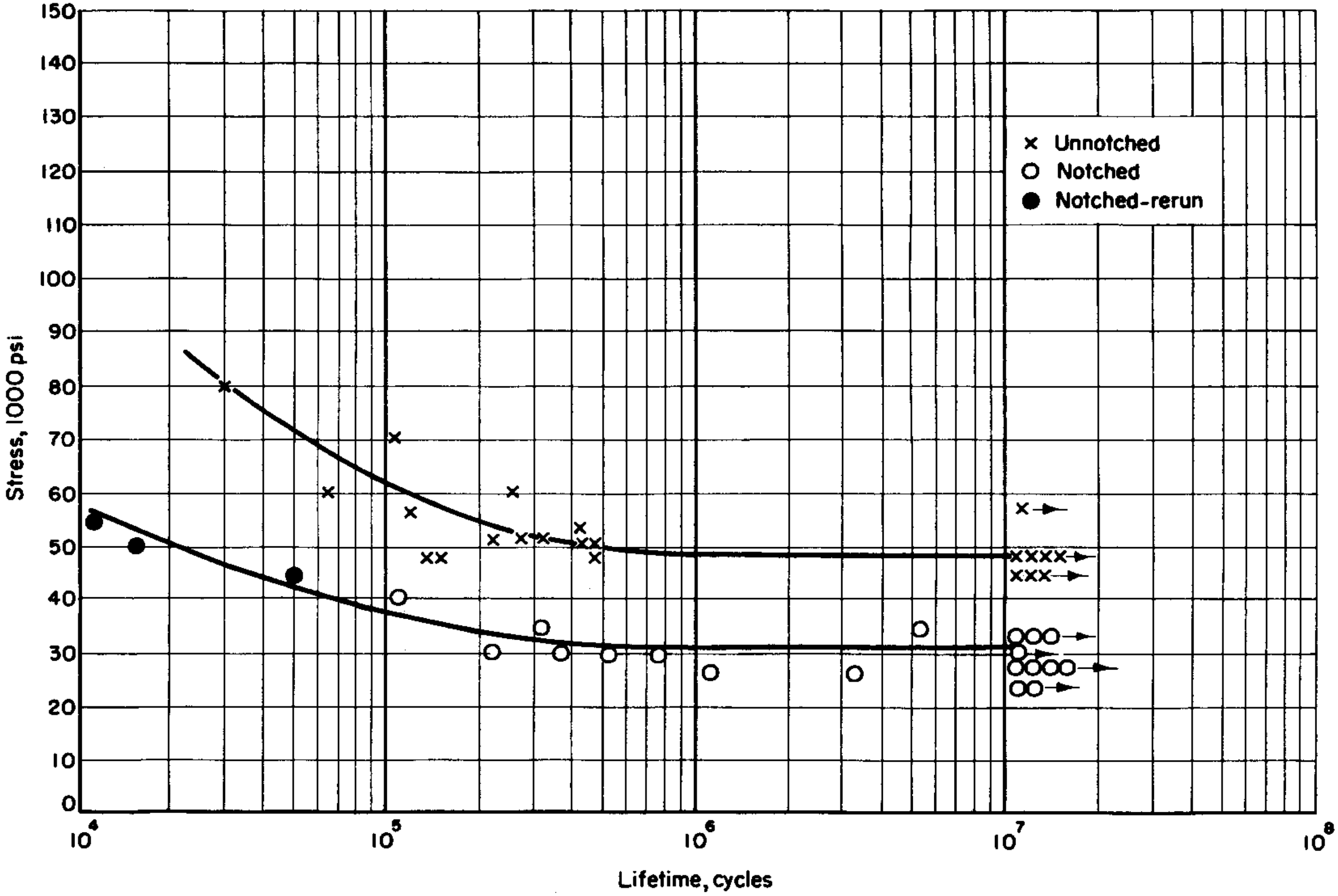

FIGURE C-9. Ti-2.5Cr-2.5Mo ALLOY ANNEALED I HOUR AT 750C, FURNACE COOLED TO 650C, AND AIR COOLED

A-12104

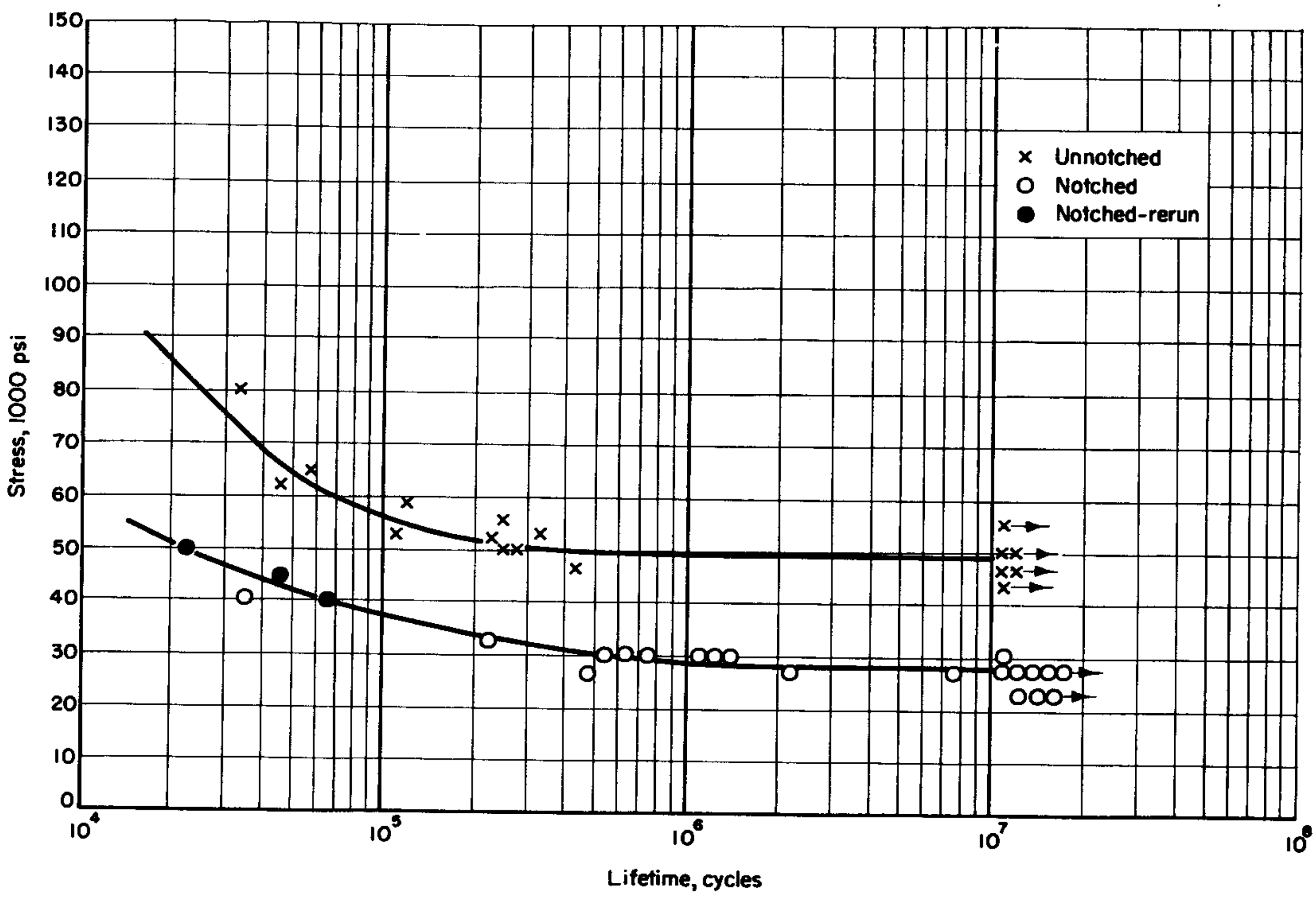

FIGURE C-10. Ti-2.5Cr-2.5Mo ALLOY ANNEALED 64 HOURS AT 750C, FURNACE COOLED TO 650C, AND AIR COOLED

A-12105

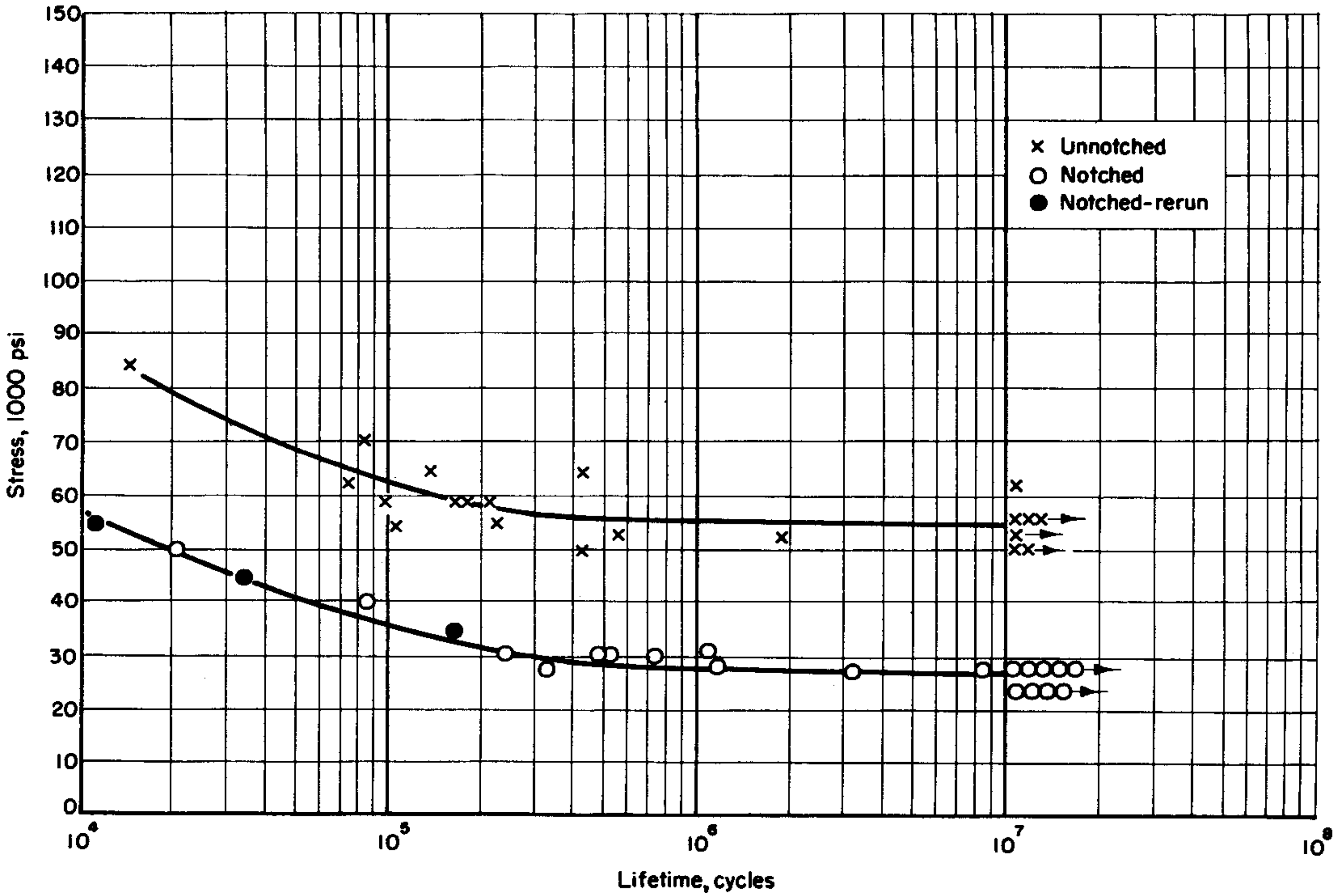

FIGURE C-11. Ti-2.5 Cr-2.5 Mo ALLOY ANNEALED $\frac{1}{2}$ HOUR AT 900C; FURNACE COOLED TO 750C; HELD 1 HOUR, FURNACE COOLED TO 650C, AND AIR COOLED

A-12106

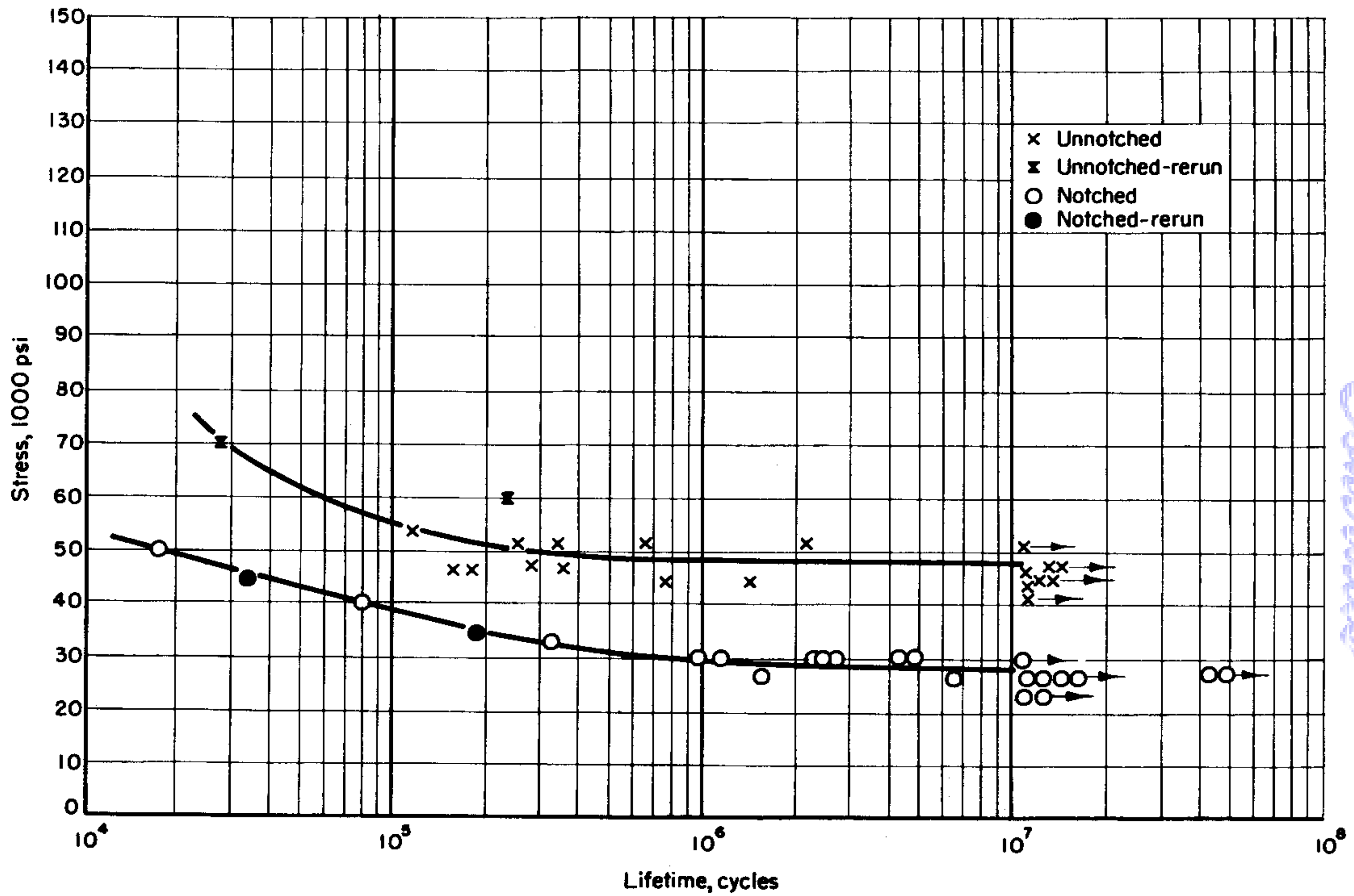

FIGURE C-12. Ti-2.5Cr -2.5 Mo ALLOY ANNEALED I HOUR AT 1000C; FURNACE COOLED TO 750C; HELD I HOUR; FURNACE COOLED TO 650C AND AIR COOLED

A-12107

Statistical Analysis of Fatigue Tests

The fatigue limits were determined according to a statistical method of analysis developed by Dixon and Mood*; the method for establishing fatigue limits was suggested by Ransom and Mehl**.

The fatigue limit is a statistical quantity, and therefore a large number of specimens is required for determination of the mean-fatigue limit by the usual statistical means. Since the testing of a large number of fatigue specimens is often impractical from the standpoints of economy and time, it is useful to resort to an approximate statistical procedure. In interpreting the results of this investigation, it is necessary to realize that these experimental values are approximations of the mean-fatigue limits, since they are based on a very small sample of the total population.

The method of testing is as follows. A rough estimate of the mean-fatigue limit for the material is made, and a specimen is tested at this estimated stress value. If this specimen lasts to 10^7 cycles, it is considered to be a "runout" or, in other words, to have infinite life at that stress. Then the stress level of the next specimen is raised a fixed amount — in this case, 3000 psi. This procedure is continued until a specimen fails. When a failure is obtained, the stress level of the next test specimen is lowered 3000 psi. Thus, the stress to be applied to a specimen depends upon what happened to the previous specimen. The effect of this procedure is to concentrate the testing around the mean-fatigue limit of the group.

The 3000-psi interval between test levels is an estimate based on the amount of scatter expected, and, for best results, should be in the range of 0.5 to 2.0 times the standard deviation of the group being tested. This method affords the best estimate of the true mean that can be obtained with only a few specimens. Approximately a 30 per cent saving in the number of specimens required to give the same accuracy as obtained by other methods is said to be obtained by this method.

A sample calculation is included to afford an example of the procedure followed for each group.

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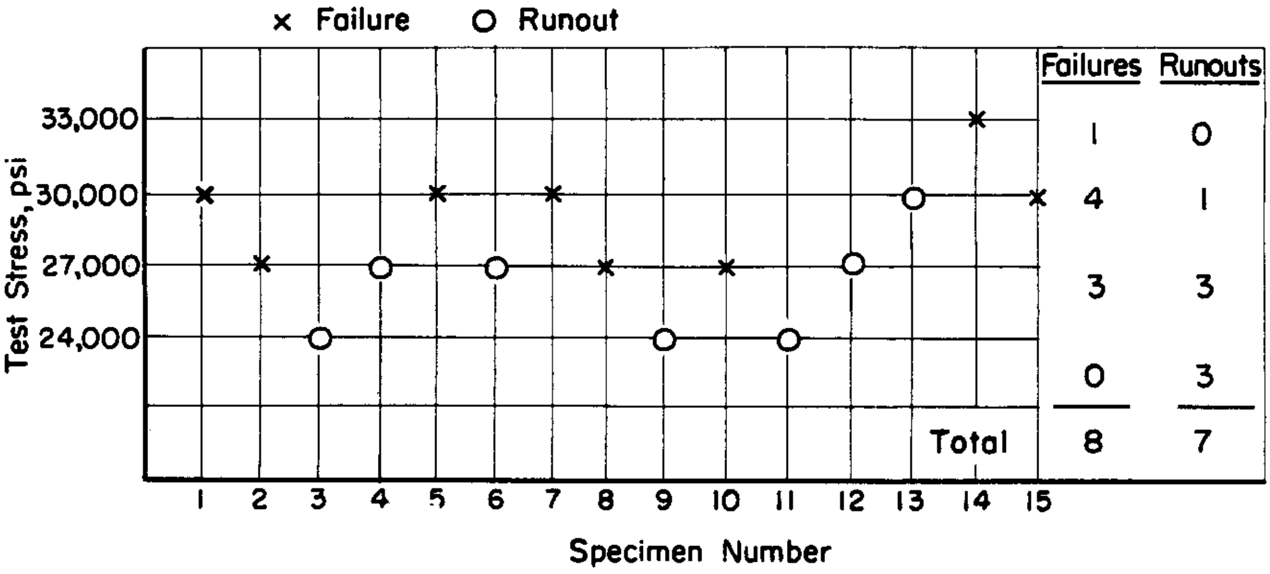
* "A Method for Obtaining and Analyzing Sensitivity Data", J. Am. Statis. Assoc., 109 (March, 1948).

** ASTM Spec. Tech. Pub. No. 137 (June 24, 1952).

Sample Calculation for Commercial Titanium Annealed 2 Hours at 700 C and Air Cooled; Notched Specimens

The specimens reacted to the test procedure as shown below:



This analysis uses the data from whichever condition (failure or runout) gave the least number of specimens, in this example, runouts. This is called the least condition.

$\dot{I}$	N_i	$\dot{I}N_i$	$\dot{I}^2N_i$
2	1	2	4
1	3	3	3
0	3	0	0
	$N = 7$	$A = 5$	$B = 7$

$\dot{I}$ is the numbered test interval for the least condition, starting with the lowest stress, i.e., $\dot{I} = 0$ at 24,000 psi; $\dot{I} = 1$ at 27,000 psi.

N_i is the number of specimens of the least condition at each interval.

The equation for the mean fatigue $\bar{x}$ is:

$$\bar{x} = y' + d\left(\frac{A}{N} \pm \frac{1}{2}\right),$$

where

y' is the lowest stress at which the least condition occurred (in this case, 24,000 psi)

d is the stress interval between test specimens (in this case, 3000 psi)

A is the value determination as shown in the tabulation (sum of values in Column IN_i)

N is the total number of specimens subjected to the least condition (in this case, 7 runouts).

The use of (+) or (-) 1/2 depends upon whether the analysis is based on failures or on runouts. The (-) is used in the case of failures and the (+) in the case of runouts. For this example,

$$\bar{x} = 24,000 + 3000\left(\frac{5}{7} + \frac{1}{2}\right) = 27,645 \text{ psi.}$$

The standard deviation is determined from the equation:

$$s = 1.62\, d\left(\frac{NB - A^2}{N^2} + 0.029\right),$$

where all terms are defined as before, and, in addition, the B term is found as shown in the tabulation (the sum of values in the Column I^2N_i).

$$s = 1.62 \times 3000\left(\frac{7 \times 7 - 5^2}{7^2} + 0.029\right) = 2,520 \text{ psi}.$$