FOREWORD

This report was prepared by Armour Research Foundation of Illinois Institute of Technology under USAF Contract No. AF 33(616)-7262. This contract was initiated under Project No. 7351, "Metallic Materials," Task No. 735105, "High Strength Metallic Materials." The work was administered under the direction of the Directorate of Materials and Processes, Deputy for Technology, Aeronautical Systems Division, with Mr. Paul L. Hendricks acting as project engineer.

This report covers the period from 1 August 1961 to 31 July 1962.

Personnel of Armour Research Foundation who made major contributions to this program were: C. R. Simcoe, supervisor; J. B. McAndrew, project engineer; and J. E. Anderson, technician. The data reported are recorded in ARF Logbooks C-1196, C-11914, C-12215, and C-12780. This report is identified internally as ARF-B201-27.

ABSTRACT

The primary screening of the Ti-Al-Cb system for high temperature alloys has been completed and data for the last 19 alloys are reported. Included are tensile tests at three strain rates at 1600°F and stress rupture results on eight alloys at elevated temperatures.

The alloys included in the investigation generally exhibited unusually high strain rate sensitivities, high creep rates, and questionable thermal stability. Prospects for commercial utilization of this family of alloys are not good, and continued broad alloy development of this series of alloys is considered inadvisable.

This technical documentary report has been reviewed and is approved.

T. D. Cooper

T. D. COOPER
Actg. Chief, Physical Metallurgy Branch
Metals and Ceramics Division
Air Force Materials Laboratory

TABLE OF CONTENTS

		Page
I	INTRODUCTION	1
II	EXPERIMENTAL PROCEDURES	1
	A. Materials	1
	B. Melting	1
	C. Forging	2
	D. Tensile Tests	2
	E. Stress Rupture Tests	2
	F. Oxidation Test	2
III.	EXPERIMENTAL RESULTS	3
	A. Tensile Tests	3
	B. Stress Rupture Tests	4
	C. Stress-Thermal Stability Tests	4
	D. Oxidation Test	5
IV.	DISCUSSION	5
V.	SUMMARY	6

LIST OF ILLUSTRATIONS

Figure		Page
1	Hounsfield Tensile Test Piece	17
2	Threaded Tensile Specimen	18
3	Ultimate Tensile Strength of Titanium Alloys at 1600°F	19
4	Ultimate Tensile Strength of Titanium Alloys at 1600°F	20
5	Ultimate Tensile Strength of Titanium Alloys at 1600°F	21
6	Yield Strength of Titanium Alloys at 1600°F	22
7	Yield Strength of Titanium Alloys at 1600°F	23
8	Yield Strength of Titanium Alloys at 1600°F	24
9	Stress Rupture Data for Ti-22.5Cb-15Al-1Sn	25
10	Stress Rupture Data for Ti-22.5Cb-15Al-0.5Zr	26
11	Stress Rupture Data for Ti-22.5Cb-12.5Al-1Zr	27
12	Stress Rupture Data for Ti-22.5Cb-12.5Al-1Hf	28
13	Stress Rupture Data for Ti-22.5Cb-12.5Al-5Sn	29
14	Stress Rupture Data for Ti-22.5Cb-12.5Al-5Hf	30
15	Stress Rupture Data for Ti-25Cb-13Al-1Zr-0.05B	31
16	Stress Rupture Data for Ti-25Cb-13Al-5Hf-0.1C	32
17	Ti-22.5Cb-12.5Al-1Hf. After 100 hr, 1000°C (1832°F) in Air	33
18	Ti-22.5Cb-12.5Al-2.5Hf. After 100 hr, 1000°C (1832°F) in Air	33
19	Ti-20Cb-17.5Al. After 100 hr, 1000°C (1832°F) in Air	34
20	Ti-22.5Cb-12.5Al-2Zr. After 100 hr, 1000°C (1832°F) in Air	35
21	Ti-22.5Cb-15Al-0.5Sn. After 100 hr, 1000°C (1832°F) in Air	35

LIST OF TABLES

Table		Page
I	Temperatures at which Various Alloys were Forged. .	7
II	Tensile Properties of Alloys Treated 6hr-1600°F-AC and Tested at Room Temperature with Crosshead Speed of 0.002 Inch Per Minute.	8
III	Tensile Properties of Alloys Treated 6hr-1600°F-AC and Tested at 1600°F with A Crosshead Speed of 0.2 Inch Per Minute.	9
IV	Tensile Properties of Alloys Treated 6hr-1600°F-AC and Tested at 1600°F with A Crosshead Speef of 0.02 Inch Per Minute.	10
V	Tensile Properties of Alloys Treated 6hr-1600°F-AC and Tested at 1600°F with A Crosshead Speed of 0.002 Inch Per Minute.	11
VI	Results of Stress Rupture Tests	12
VII	Tensile Data for Several Alloys Tested at Room Temperature with a Crosshead Speed of 0.02 Inch Per Minute	15
VIII	Oxidation of Titanium Alloys Exposed to Still Air at 1000°C(1832°F) for 100 hours	16

I. INTRODUCTION

The work reported here is a continuation of the research reported in WADD Technical Report 60-99 (April, 1960) and ASD TR 61-446 (August, 1961). The object of the investigation is to determine the potentialities of the Ti-Al-Cb system as a source of light-weight alloys for use at high temperatures.

Alloys ranging widely in composition were studied in a systematic program that was essentially exploratory in nature. Forgeability, oxidation resistance, density, and short time tensile properties at room temperature and elevated temperatures were determined in screening tests for comparison of the relative merits of different alloys within the Ti-Al-Cb system. On the basis of that information, several alloys were selected as most worthy of further investigation and development. In addition to completion of this earlier work, the present phase included stress rupture tests of eight alloys.

II. EXPERIMENTAL PROCEDURES

A. Materials

Alloys were prepared from sponge titanium of about 103 Vickers hardness, electron-beam-melted columbium and hafnium, iodide zirconium, 99.99% pure aluminum, spectrographic carbon, high-purity tin, and commercial TiB_2 powder.

Ti-B, Ti-C, Ti-Hf, and Cb-Al master alloys were prepared in order to promote solution of boron, carbon, hafnium, and columbium in the melts.

B. Melting

Two melting procedures were employed. In the first method, 150-g charges were melted in a nonconsumable-electrode arc furnace in inert atmosphere. The buttons were inverted and remelted seven times. In order to achieve homogeneity, it was found necessary to use a high arc current and a holding time of at least two minutes for each melting operation. As a check for homogeneity, the forged bars from these melts were X-rayed, and bars showing inhomogeneity were discarded.

The second melting method was to prepare 4.5-kg ingots by non-consumable arc melting. These ingots were then cut into quarters lengthwise, and welded end-to-end to form a consumable electrode for the second

---

Manuscript released by the authors March 1963 for publication as an ASD Technical Documentary Report.

melting operation. The alloys prepared by this method were Ti-22.5Cb-12.5Al-1Zr, Ti-22.5Cb-12.5Al-1Hf, Ti-22.5Cb-12.5Al-5Hf, Ti-22.5Cb-12.5Al-5Sn, Ti-22.5Cb-15Al-0.5Zr, and Ti-22.5Cb-15Al-1Sn. During testing of these six alloys there was evidence that at least two, and probably three, of the ingots were not completely homogeneous.

C. Forging

All of the alloys were hammer forged to bar stock, and any compositions that did not forge successfully were discarded. The forging temperatures are shown in Table I.

D. Tensile Tests

Two types of tensile specimen were employed, as shown in Figs. 1 and 2. Although some specimens were prepared by machining, grinding was more satisfactory, and all of the threaded specimens were ground. Tensile tests were performed on an Instron machine with a 10,000-lb load cell. The rates of crosshead travel used in various tests are given in the headings of the appropriate tables. The tests were recorded with chart speeds of 20, 1, or 0.5 in./min depending on the rate of crosshead travel. Specimens for elevated temperature tests were heated by an electric tube furnace with three zones individually controlled with autotransformers, with final control obtained electronically. Temperatures were checked with a potentiometer and a thermocouple placed with the junction near the center of the specimen.

E. Stress Rupture Tests

All stress rupture specimens were of the type shown in Fig. 2. It will be noted that this is a standard tensile specimen, in which the center portion is very slightly smaller in diameter than the rest of the gage length. A single thermocouple was wired to the specimen at the center of the reduced section. This procedure does not ensure the ultimate in accuracy, but it does ensure that any errors due to nonuniformity of the hot zone will give rupture lives that are shorter than they should be, rather than longer. The temperature indicated by the thermocouple was carefully adjusted before loading the specimen, and was checked daily, except on weekends, throughout the tests. For most tests, a record of this temperature was also obtained with an electronic recorder.

The test machines had 20-to-1 lever arms, and all of the machines and weights were calibrated before the series of tests was started. Rupture times were registered on digital electric timers which were turned off by a microswitch at specimen failure.

F. Oxidation Test

Oxidation specimens were cleaned, etched lightly, and placed in unglazed porcelain crucibles. These were heated in an electric muffle furnace, in still air, continuously for a period of 100 hr. Weight gains were measured, and also the thickness of metal converted to oxide. This test is used to obtain a preliminary evaluation of the relative oxidation resistance of various alloys and to screen out any compositions that might exhibit a catastrophic type of oxidation.

III. EXPERIMENTAL RESULTS

A. Tensile Tests

The results of tensile tests on a number of alloys at room temperature and 1600°F are listed in Tables II to V. The ultimate tensile strengths and 0.2% yield strengths at 1600°F are plotted in Figures 3 to 8.

The room-temperature ductility of this group of alloys was very low and in some instances nil. Several compositions containing about 12.5% Al had elongation values of several per cent. The room-temperature tensile strengths were moderate for titanium-base alloys. The highest value was 138 ksi for the Ti-35Cb-12.5Al alloy.

At 1600°F the ultimate tensile strengths are generally in the range 20 to 40 ksi for the 0.002 in./min. crosshead speed (0.0029 in/in/min strain rate). The ductility was good for this test condition with values ranging from 11 to as high as 76%. When the crosshead speeds were increased to 0.02 and 0.2 in./min. (0.029 and 0.29 in/in/min strain rates) the tensile strengths increased at a faster rate than that usually found for super alloys and other high-temperature metals. Also the ductility decreased in some instances to only a few per cent elongation at 0.2 in./min. crosshead speed. The Ti-17.5Cb-15Al alloys containing 0.1 or 0.2C showed the lowest strain-rate sensitivity. The alloy with 0.2C increased in strength from 41 ksi to 44 and 51 ksi when the crosshead speed was increased from 0.002 to 0.02 and 0.2 in./min., respectively. This alloy retained excellent ductility at 1600°F for all test speeds.

The yield strengths at 1600°F followed the same trend as a function of strain rate as did the ultimate strengths. The yield strengths ranged from 11 to 32 ksi at the lowest crosshead speed (0.002 in./min.) and 38 to 91 ksi at the highest speed (0.2 in./min.). Again the Ti-17.5Cb-15Al alloys with 0.1 or 0.2C showed the lowest strain rate sensitivity.

B. Stress Rupture Tests

The data obtained in stress rupture tests of 8 alloys are shown in Table VI, and are plotted in Figs. 9 to 16 in terms of rupture stress as a function of Larson-Miller parameter ($=10^{-3}T_R(C + \log t)$, where T_R is test temperature in degrees Rankine, t is rupture life in hours, and the constant, C, is assumed to be 20 for these alloys as for most).

Two of the alloys (Ti-22.5Cb-12.5Al-5Hf and Ti-22.5Cb-12.5Al-1Zr) showed considerable scatter in the results. It is very probable that this was caused by inhomogeneity in the two ingots. During testing, flaws became evident in some specimens, and these were of the type that would result from the presence of undissolved master alloy.

The highest stress-rupture strengths were shown by Ti-22.5Cb-15Al-1Sn, but Ti-22.5Cb-15Al-0.5Zr was only slightly lower. Both alloys have a density of 0.170 lb/in.^{3}, as compared with about 0.286 lb/in.^{3} for a nickel-base superalloy. Because of their lower density, the 100-hr rupture stress-to-density ratios of the two alloys approach those of the best wrought superalloys, at least up to about 1600°F. Although none of these tests were continued for 1000 hours, the curves indicate that in tests of that duration the comparison with nickel-base alloys would be more unfavorable to the titanium alloys.

Of the four alloys containing 22.5Cb and 12.5Al, the highest stress-rupture strengths were shown by Ti-22.5Cb-12.5Al-5Sn, while the other three, Ti-22.5Cb-12.5Al-1Zr, Ti-22.5Cb-12.5Al-1Hf and Ti-22.5Cb-12.5Al-5Hf, were approximately equivalent at a substantially lower strength level.

The strength of Ti-25Cb-13Al-5Hf-0.1C as heat treated for these tests was in the middle of the range for the group of alloys, and was significantly stronger than Ti-25Cb-13Al-1Zr-0.05B.

Ductilities of the alloys in stress-rupture were generally satisfactory. In tests at room temperature, however, very low ductilities were observed, as will be shown later.

C. Stress-Thermal Stability Tests

In a few cases, stress-rupture tests were terminated because of failure of the grips or because it became apparent that the test was going to require more time for completion than could be allotted to it. When such specimens were undamaged and did not show any flaws, they were tested at room temperature without further treatment. All of the injurious effects of the prior exposure were therefore preserved, and no attempt was made to distinguish among them. The results are shown in Table VII, together with data for similar specimens not previously exposed. Only one of five exposed specimens had measurable ductility, and it showed very little. However, it will also be seen, as was mentioned earlier, that with this heat treatment (3hr-1650°F-FC) the unexposed specimens are also low in ductility. Thus, the unexposed specimen of Ti-22.5Cb-15Al-1Sn was actually weaker than the specimen which had been subjected to 500 hours at 1350°F and 30,000 psi, although the former had a slight amount of ductility, while the latter did not.

The alloy that retained some ductility (0.4% el.) was Ti-22.5Cb-12.5Al-1Zr which was exposed for 600 hours at 1200°F and 20,000 psi.

D. Oxidation Test

The results of a 100 hr, 1000°C oxidation test of 10 alloys are shown in Table VIII. The effects observed are similar to those previously found with alloys of this type. Typical effects of such exposure are illustrated metallographically in Figs. 17 to 21, which show specimens exposed in previous tests of the same temperature and duration.

It was again observed in stress rupture tests that the rate of oxidation is very sensitive to surface contamination.

IV. DISCUSSION

The basic intent of this program has been to develop a series of alloys to extend the usefulness of titanium-base materials far beyond their current limits of about 1000°F. Alloys containing high aluminum contents (up to TiAl, 36% Al) have long been shown to have excellent oxidation resistance and stress rupture-to-weight characteristics. Adequate primary formability and engineering ductility were never available in these compositions to encourage vigorous developmental programs. It appeared at the beginning of the present series of projects that the Ti-Al-Cb alloys, having quite acceptable primary forming propensity, might provide the necessary compromises to yield titanium-base materials with highly competitive properties to 1500°F or higher.

In the course of the work, critical difficulties have become apparent, in spite of promising screening test behavior. Principal among these are an unusually high strain rate sensitivity compared to other high-temperature alloys, higher creep rates than many more dilute commercial titanium alloys, and questionable thermal stress stability.

Any further research effort would have to concentrate on critical assessments of the above properties, as well as notch sensitivity, thermal shock resistance, stress and salt corrosion and weldability. The preliminary results with carbon-containing alloys show improved strain rate and creep behavior; the possibility exists that increases in carbon content combined with appropriate heat treatment would repair some of the noted deficiencies, but engineering ductility would probably still be sub-marginal.

It is reluctantly concluded that continuing broad alloy development in this series of alloys is probably inadvisable; critical assessment of the very practical engineering behavior of the two most promising compositions, Ti-25Cb-13Al-5Hf-0.1C and Ti-22.5Cb-15Al-1Sn might be warranted. Carbon should be increased in the former and added to the latter. Recrystallization behavior and effect of heat treatment should be intensively examined before extensive property determination.

V. SUMMARY

A study has been made on the Ti-Al-Cb system for high temperature alloys with useful strengths above 1200°F. During the present program composition variations included: columbium from 17.5 to 35%, aluminum from 12.5 to 17.5%, and the addition of smaller amounts of zirconium, hafnium, tin, carbon or boron.

Short-time tensile properties were determined for one strain rate (0.0029 in/in/min.) at room temperature and for three strain rates (0.29, 0.029 and 0.0029 in/in/min.) at 1600°F. Stress-rupture properties were obtained for a variety of temperatures and stresses. The Larson-Miller parameter was used to present these stress-rupture data so that the rupture life at various temperatures could be presented on a single plot for each alloy.

These alloys show a high sensitivity to strain rate over the range studied. Nevertheless, the stresses to produce a 100-hour rupture life in the temperature range 1200 to 1600°F are very good for titanium-base alloys, and in certain instances are competitive with the commercial superalloys on a density-adjusted basis.

Excellent oxidation resistance at 1832°F (1000°C) was exhibited by all of the alloys studied.

Opposed to the advantages of oxidation resistance and high rupture strength are the disadvantages of very limited ductility at room temperature, relatively high creep, and questionable thermal stress stability, notch behavior, stressed salt corrosion, and weldability.

TABLE I

TEMPERATURES AT WHICH VARIOUS ALLOYS WERE FORGED

Alloy Composition (wt %)	Forging Temperature (°F)	Result
Ti-22.5Cb-12.5Al-1Zr	2200	Forged well
Ti-22.5Cb-12.5Al-1Hf	2200	Forged well
Ti-22.5Cb-12.5Al-5Hf	2200	Forged well
Ti-22.5Cb-12.5Al-5Sn	2200	Forged well
Ti-22.5Cb-15Al-0.5Zr	2300	Forged well
Ti-22.5Cb-15Al-1Sn	2300	Forged well
Ti-35Cb-12.5Al	2250	Forged well
Ti-35Cb-12.5Al-5Hf	2250, 2300	Forged well
Ti-35Cb-17.5Al	2100	Did not forge
Ti-30Cb-12.5Al-1Hf	2250	Forged well
Ti-30Cb-17.5Al	2000, 2100, 2250, 2350, 2400	Did not forge
Ti-30Cb-17.5Al-2Zr	2400	Did not forge
Ti-25Cb-12.5Al-1Hf	2200	Forged well
Ti-25Cb-12.5Al-5Hf	2200	Forged well
Ti-25Cb-15Al-1Hf	2350	Forged well
Ti-25Cb-15Al-5Hf	2300	Forged well
Ti-22.5Cb-12.5Al-2Hf-1Zr	2200	Forged well
Ti-20Cb-12.5Al-1Hf	2200	Forged well
Ti-20Cb-12.5Al-5Hf	2200	Forged well
Ti-20Cb-17.5Al-2Hf	2200	Forged fairly well
Ti-20Cb-17.5Al-2Zr	2400	Forged fairly well
Ti-17.5Cb-17.5Al	2250	Forged well
Ti-17.5Cb-15Al-5Hf	2300	Forged well
Ti-17.5Cb-17.5Al-2Zr	2400	Forged fairly well
Ti-17.5Cb-15Al-0.1C	2350	Forged well
Ti-17.5Cb-15Al-0.2C	2350	Forged well
Ti-25Cb-13Al-5Hf-0.1C	2200	Forged well
Ti-25Cb-13Al-1Zr-0.05B	2200	Forged well

TABLE II

TENSILE PROPERTIES OF ALLOYS TREATED 6hr-1600°F-AC AND TESTED AT ROOM TEMPERATURE WITH CROSSHEAD SPEED OF 0.002 INCH PER MINUTE

Alloy Composition (wt %)	UTS (ksi)	0.2% YS (ksi)	RA (%)	El. (% in 0.7 in.)
Ti-35Cb-12.5Al	138	138	3.5	0.2
Ti-35Cb-12.5Al-5Hf	126	120	2.5	0.5
Ti-30Cb-12.5Al-1Hf	117	---	2.5	0.1
Ti-25Cb-12.5Al-1Hf	91	---	0	0
Ti-25Cb-12.5Al-5Hf	137	114	5.6	3.0
Ti-25Cb-15Al-1Hf	121	112	3.5	1
Ti-25Cb-15Al-5Hf	116	---	1.2	0.1
Ti-22.5Cb-12.5Al-2Hf-1Zr	125	112	7.5	1.5
Ti-20Cb-12.5Al-1Hf	113	96	6	2.7
Ti-20Cb-12.5Al-5Hf	117	117	1	0.2
Ti-20Cb-17.5Al-2Hf	125	---	3	0
Ti-20Cb-17.5Al-2Zr	86	---	0	0
Ti-17.5Cb-17.5Al	111	---	2	0
Ti-17.5Cb-17.5Al-2Zr	91	84	1	0.4
Ti-17.5Cb-15Al-5Hf	82	78	2.5	0.4
Ti-17.5Cb-15Al-0.1C	85	82	*	*
Ti-17.5Cb-15Al-0.2C	105	90	**	**
Ti-25Cb-13Al-5Hf-0.1C	127	109	4	1.6
Ti-25Cb-13Al-1Zr-0.05B	129	98	7.5	5.5

* Broke at shoulder

** Broke in shoulder

TABLE III

TENSILE PROPERTIES OF ALLOYS TREATED 6hr-1600°F-AC AND TESTED AT 1600°F WITH A CROSSHEAD SPEED OF 0.2 INCH PER MINUTE

Alloy Composition (wt %)	UTS (ksi)	0.2% YS (ksi)	RA (%)	El. (% in 0.7 in.)
Ti-35Cb-12.5Al	81	75	6.5	1.8
Ti-35Cb-12.5Al-5Hf	95	86	14.5	8.1
Ti-30Cb-12.5Al-1Hf	64	54	35	32
Ti-25Cb-12.5Al-1Hf	76	64	6	5
Ti-25Cb-12.5Al-5Hf	65	50	46	38
Ti-25Cb-12.5Al-5Hf	91	80	8.5	3.1
Ti-25Cb-15Al-1Hf	72	60	13.3	12
Ti-25Cb-15Al-5Hf	84	63	3.5	4.7
Ti-22.5Cb-12.5Al-2Hf-1Zr	50	41	19	11
Ti-20Cb-12.5Al-1Hf	51	43	61	27
Ti-20Cb-12.5Al-5Hf	58	46	11.5	24
Ti-20Cb-17.5Al-2Hf	79	79	2	0.2
Ti-20Cb-17.5Al-2Hf	95	91	6	1.4
Ti-20Cb-17.5Al-2Zr	99	86	3.8	1.2
Ti-17.5Cb-17.5Al	67	55	8.5	8.1
Ti-17.5Cb-17.5Al-2Zr	82	60	11	5.7
Ti-17.5Cb-17.5Al-2Zr	57	52	12	9
Ti-17.5Cb-15Al-5Hf	69	52	13.5	12.5
Ti-17.5Cb-15Al-0.1C	53	38	59	29
Ti-17.5Cb-15Al-0.2C	51	44	81	50
Ti-25Cb-13Al-5Hf-0.1C	75	56	46	27
Ti-25Cb-13Al-1Zr-0.05B	77	56	19	13

TABLE IV

TENSILE PROPERTIES OF ALLOYS TREATED 6hr-1600°F-AC AND TESTED AT 1600°F WITH A CROSSHEAD SPEED OF 0.02 INCH PER MINUTE

Alloy Composition (wt %)	UTS (ksi)	0.2% YS (ksi)	RA (%)	El. (% in 0.7 in.)
Ti-35Cb-12.5Al	51	44	32	24
Ti-35Cb-12.5Al-5Hf	64	57	14.6	14
Ti-30Cb-12.5Al-1Hf	38	33	38	43
Ti-25Cb-12.5Al-1Hf	61	49	90	95
Ti-25Cb-12.5Al-5Hf	40	32	56	40
Ti-25Cb-15Al-1Hf	32	26	60	37
Ti-25Cb-15Al-5Hf	55	45	12	11.5
Ti-22.5Cb-12.5Al-2Hf-1Zr	37	29	40	33
Ti-20Cb-12.5Al-1Hf	33	29	57	35
Ti-20Cb-12.5Al-5Hf	33	24	70	49
Ti-20Cb-17.5Al-2Hf	63	51	29	21
Ti-20Cb-17.5Al-2Zr				
Ti-17.5Cb-17.5Al	51	49	14.5	8.6
Ti-17.5Cb-17.5Al-2Zr	63	50	7	8
Ti-17.5Cb-15Al-5Hf	58	49	19	19
Ti-17.5Cb-15Al-0.1C	42	34	71	28
Ti-17.5Cb-15Al-0.2C	44	41	86	45
Ti-25Cb-13Al-5Hf-0.1C				
Ti-25Cb-13Al-1Zr-0.05B				

TABLE V

TENSILE PROPERTIES OF ALLOYS TREATED 6hr-1600°F-AC
AND TESTED AT 1600°F
WITH A CROSSHEAD SPEED OF 0.002 INCH PER MINUTE

Alloy Composition (wt %)	UTS (ksi)	0.2% YS (ksi)	RA (%)	El. (% in 0.7 in.)
Ti-35Cb-12.5Al	31	23	34	28
Ti-35Cb-12.5Al-5Hf	44	27	22	34
Ti-30Cb-12.5Al-1Hf	28	21	14	19
Ti-25Cb-12.5Al-1Hf	34	30	30	28
Ti-25Cb-12.5Al-5Hf	21	16	98	60
Ti-25Cb-12.5Al-5Hf	41	32	12	11
Ti-25Cb-15Al-1Hf	15	12	67	25
Ti-25Cb-15Al-5Hf	38	23	17	17
Ti-22.5Cb-12.5Al-2Hf-1Zr	22	14	24	22
Ti-20Cb-12.5Al-1Hf	42	34	19	14
Ti-20Cb-12.5Al-1Hf	38	28	28	20
Ti-20Cb-12.5Al-5Hf	19	15	99	65
Ti-20Cb-17.5Al-2Hf	38	31	37	23
Ti-20Cb-17.5Al-2Zr	37	19	47	40
Ti-17.5Cb-17.5Al	33	29	22	21
Ti-17.5Cb-17.5Al-2Zr	40	32	20	42
Ti-17.5Cb-15Al-5Hf	42	34	20	11
Ti-17.5Cb-15Al-0.1C	34	18	93	45
Ti-17.5Cb-15Al-0.2C	41	32	97	76
Ti-25Cb-13Al-5Hf-0.1C	24	21	92	50
Ti-25Cb-13Al-1Zr-0.05B	21	11	55	32

TABLE VI

RESULTS OF STRESS RUPTURE TESTS

Alloy Composition (wt %)	Temp (°F)	Stress (psi)	Time (hr)	Larson-Miller Parameter	RA (%)	Elongation (%)
Ti-22.5Cb-12.5Al-1Hf	1200	30,000	278.4	37.3	21	18
Ti-22.5Cb-12.5Al-1Hf	1350	22,000	35.4	39.0	45	27
Ti-22.5Cb-12.5Al-1Hf	1650	7,500	7.2	44.0	83	70
Ti-22.5Cb-12.5Al-1Zr	1200	35,000	71.6	36.3	51	19
Ti-22.5Cb-12.5Al-1Zr	1200	20,000	601.8-No failure	37.8		5.3
Ti-22.5Cb-12.5Al-1Zr	1350	18,000	112	39.9	47	37
Ti-22.5Cb-12.5Al-1Zr	1350	22,000	67	39.5	75	47
Ti-22.5Cb-12.5Al-1Zr	1500	15,000	14.1	41.4	77	35
Ti-22.5Cb-12.5Al-1Zr	1500	12,000	10.3	41.2	83	40
Ti-22.5Cb-12.5Al-1Zr	1500	9,000	4.7	40.5	79	50
Ti-22.5Cb-12.5Al-1Zr	1650	10,000	1.4	42.5	86	44
Ti-22.5Cb-12.5Al-1Zr	1650	7,500	5.6	43.8	87	52
Ti-22.5Cb-12.5Al-1Zr	1650	5,000	22.1	45.0	86	60
Ti-22.5Cb-12.5Al-5Hf	1200	40,000	157.5	36.8	5.5	9
Ti-22.5Cb-12.5Al-5Hf	1200	30,000	256.6	37.2	6.3	6.7
Ti-22.5Cb-12.5Al-5Hf	1350	30,000	34.8	39.0		
Ti-22.5Cb-12.5Al-5Hf	1350	25,000	105.7	39.9	15.5	23
Ti-22.5Cb-12.5Al-5Hf	1350	20,000	162	40.2	17.5	25
Ti-22.5Cb-12.5Al-5Hf	1500	15,000	24.3	41.9	58	32
Ti-22.5Cb-12.5Al-5Hf	1500	12,000	17.3	41.6	87	44
Ti-22.5Cb-12.5Al-5Hf	1650	10,000	>4.1	>43.5	83	64
Ti-22.5Cb-12.5Al-5Hf	1650	6,000	6.5	43.9	95	81
Ti-22.5Cb-12.5Al-5Hf	1650	7,500	2.7	43.1	95	72
Ti-22.5Cb-12.5Al-5Sn	1200	70,000	2.1	33.7	11	5.3
Ti-22.5Cb-12.5Al-5Sn	1200	65,000	11.3	34.9	16	6.4
Ti-22.5Cb-12.5Al-5Sn	1200	50,000	10.8-No failure	34.9		1.9
Ti-22.5Cb-12.5Al-5Sn	1200	20,000	502.8-No failure	37.7		0.14

TABLE VI (Cont.)

Alloy Composition (wt %)	Temp (°F)	Stress (psi)	Time (hr)	Larson-Miller Parameter	RA (%)	Elongation (%)
Ti-22.5Cb-12.5Al-5Sn	1350	35,000	130.9	40.0	8.5	9
Ti-22.5Cb-12.5Al-5Sn	1350	22,000	500.7-No failure	41.1	6	3.9
Ti-22.5Cb-12.5Al-5Sn	1500	18,000	92.2	43.0	48	20
Ti-22.5Cb-12.5Al-5Sn	1500	15,000	119-No failure	43.2		4
Ti-22.5Cb-12.5Al-5Sn	1650	7,500	501.4-No failure	48		20
Ti-22.5Cb-15Al-0.5Zr	1200	75,000	4.6	34.3	12.5	3.8
Ti-22.5Cb-15Al-0.5Zr	1200	60,000	212.1	37.0	11	4.8
Ti-22.5Cb-15Al-0.5Zr	1200	25,000	383.5-No failure	37.4		1
Ti-22.5Cb-15Al-0.5Zr	1350	45,000	11.1-No failure	36.3		
Ti-22.5Cb-15Al-0.5Zr	1350	45,000	62.0	39.4	85	40
Ti-22.5Cb-15Al-0.5Zr	1500	25,000	59.8	42.6	59	35
Ti-22.5Cb-15Al-0.5Zr	1500	22,000	99.1-No failure	43.1	15	18
Ti-22.5Cb-15Al-0.5Zr	1500	15,000	660.3	44.7	85	40
Ti-22.5Cb-15Al-0.5Zr	1650	14,000	44.8	45.7	90	70
Ti-22.5Cb-15Al-0.5Zr	1650	10,000	125	46.7	86	88
Ti-22.5Cb-15Al-1Sn	1200	75,000	23.8	35.4	Broke in threads	
Ti-22.5Cb-15Al-1Sn	1200	75,000	22.6	35.4	3.3	3.4
Ti-22.5Cb-15Al-1Sn	1200	60,000	148.7	36.8	4	4
Ti-22.5Cb-15Al-1Sn	1350	40,000	190.9	40.3	14	8
Ti-22.5Cb-15Al-1Sn	1350	30,000	500.3-No failure	41.0	6	4.7
Ti-22.5Cb-15Al-1Sn	1500	25,000	95.3	43.0	65	47
Ti-22.5Cb-15Al-1Sn	1500	20,000	365.5	44.2	53	52
Ti-22.5Cb-15Al-1Sn	1500	15,000	884.8	45.0	88	58
Ti-22.5Cb-15Al-1Sn	1650	15,000	32.0	45.4	77	43
Ti-22.5Cb-15Al-1Sn	1650	10,000	201.3*	47.0	86	81

TABLE VI (Cont.)

Alloy Composition (wt %)	Temp (°F)	Stress (psi)	Time (hr)	Larson-Miller Parameter	RA (%)	Elongation (%)
Ti-25Cb-13Al-5Hf-0.1C	1200	70,000	12.6	35.0	16	9
Ti-25Cb-13Al-5Hf-0.1C	1200	55,000	105.8	36.6	5.5	8
Ti-25Cb-13Al-5Hf-0.1C	1350	35,000	26.1	38.8	8.7	18
Ti-25Cb-13Al-5Hf-0.1C	1350	25,000	179.3	40.3	11.6	16.5
Ti-25Cb-13Al-5Hf-0.1C	1500	18,000	41.1	42.4	26	30
Ti-25Cb-13Al-5Hf-0.1C	1650	12,000	5.4	43.7	93	57
Ti-25Cb-13Al-1Zr-0.05B	1200	60,000	25.1	35.5	Broke at shoulder	13
Ti-25Cb-13Al-1Zr-0.05B	1200	50,000	57.4	36.1	9.5	11
Ti-25Cb-13Al-1Zr-0.05B	1350	25,000	64.7	39.4	40	32
Ti-25Cb-13Al-1Zr-0.05B	1500	12,000	59.7	42.6	83	57
Ti-25Cb-13Al-1Zr-0.05B	1650	10,000	7.5	44.1	87	60

* Interrupted test.

TABLE VII

TENSILE DATA FOR SEVERAL ALLOYS
TESTED AT ROOM TEMPERATURE
WITH A CROSSHEAD SPEED OF 0.02 INCH PER MINUTE

Alloy Composition (wt %)	UTS (ksi)	0.2% YS (ksi)	RA (%)	El. (%)	Prior Treatment*
Ti-22.5Cb-12.5Al-1Hf	116	93	4.8	3.7	A
Ti-22.5Cb-12.5Al-1Zr	101	84	10	3.8	A
Ti-22.5Cb-12.5Al-1Zr	80	77	0.8	0.4	A + 600hr-1200°F-20ksi
Ti-22.5Cb-12.5Al-5Hf	128	---	1.6	0.1	A
Ti-22.5Cb-15Al-0.5Zr	123	108	3.3	1.2	A
Ti-22.5Cb-15Al-0.5Zr	54	---	0	0	A + 383hr-1200°F-25ksi
Ti-22.5Cb-15Al-0.5Zr	63	---	Broke in threads		A + 99hr-1500°F-22ksi
Ti-22.5Cb-15Al-1Sn	68	---	1.6	0.1	A
Ti-22.5Cb-15Al-1Sn	77	---	0	0	A + 500hr-1350°F-30ksi
Ti-22.5Cb-12.5Al-5Sn	83	---	0	0	A + 10hr-1200°F-50ksi

*A = 3hr-1650°F-FÇ

TABLE VIII

OXIDATION OF TITANIUM ALLOYS EXPOSED TO STILL AIR AT 1000°C(1832°F) FOR 100 HOURS

Alloy Composition (wt %)	Specimen Weight (g)*	Weight Gain (g)	Depth of Oxidation (in.)
Ti-35Cb-12.5Al	4.534	0.032	< 0.001
Ti-35Cb-12.5Al-5Hf	4.363	0.026	< 0.001
Ti-30Cb-12.5Al-1Hf	4.155	0.023	< 0.001
Ti-25Cb-12.5Al-5Hf	4.633	0.069	0.001
Ti-25Cb-15Al-5Hf	4.520	0.031	0.001
Ti-25Cb-15Al-1Hf	4.277	0.036	< 0.001
Ti-17.5Cb-17.5Al	4.645	0.035	< 0.001
Ti-17.5Cb-17.5Al-2Zr	4.604	0.072	< 0.001
Ti-17.5Cb-15Al-5Hf	4.462	0.018	< 0.001

*Surface area 4.8 cm^2.

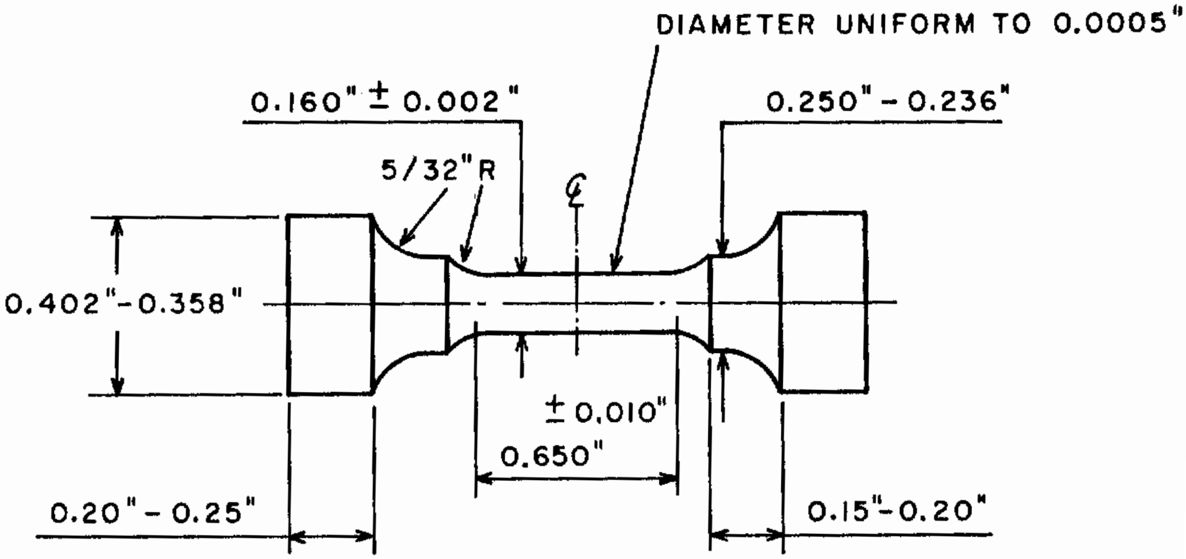


FIG. 1 HOUNSFIELD TENSILE TEST PIECE.

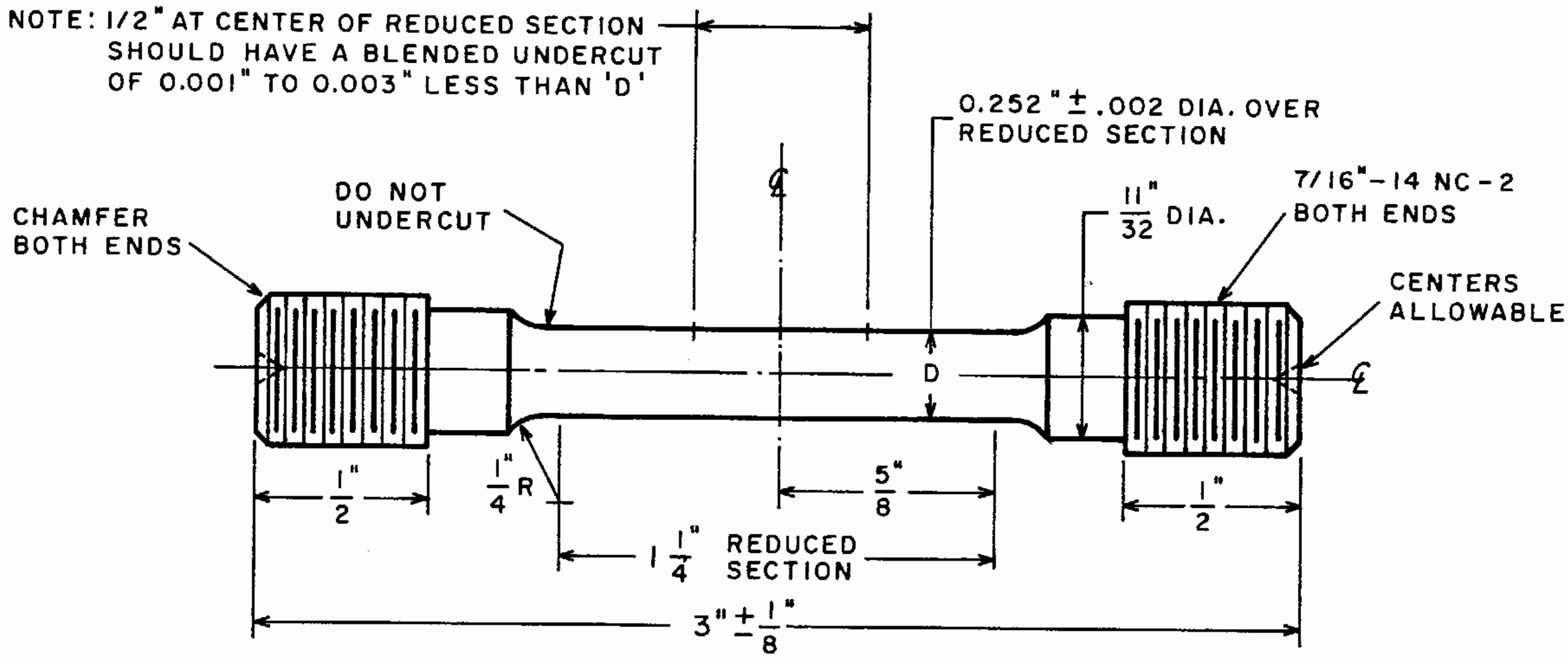


FIG. 2 - THREADED TENSILE SPECIMEN.

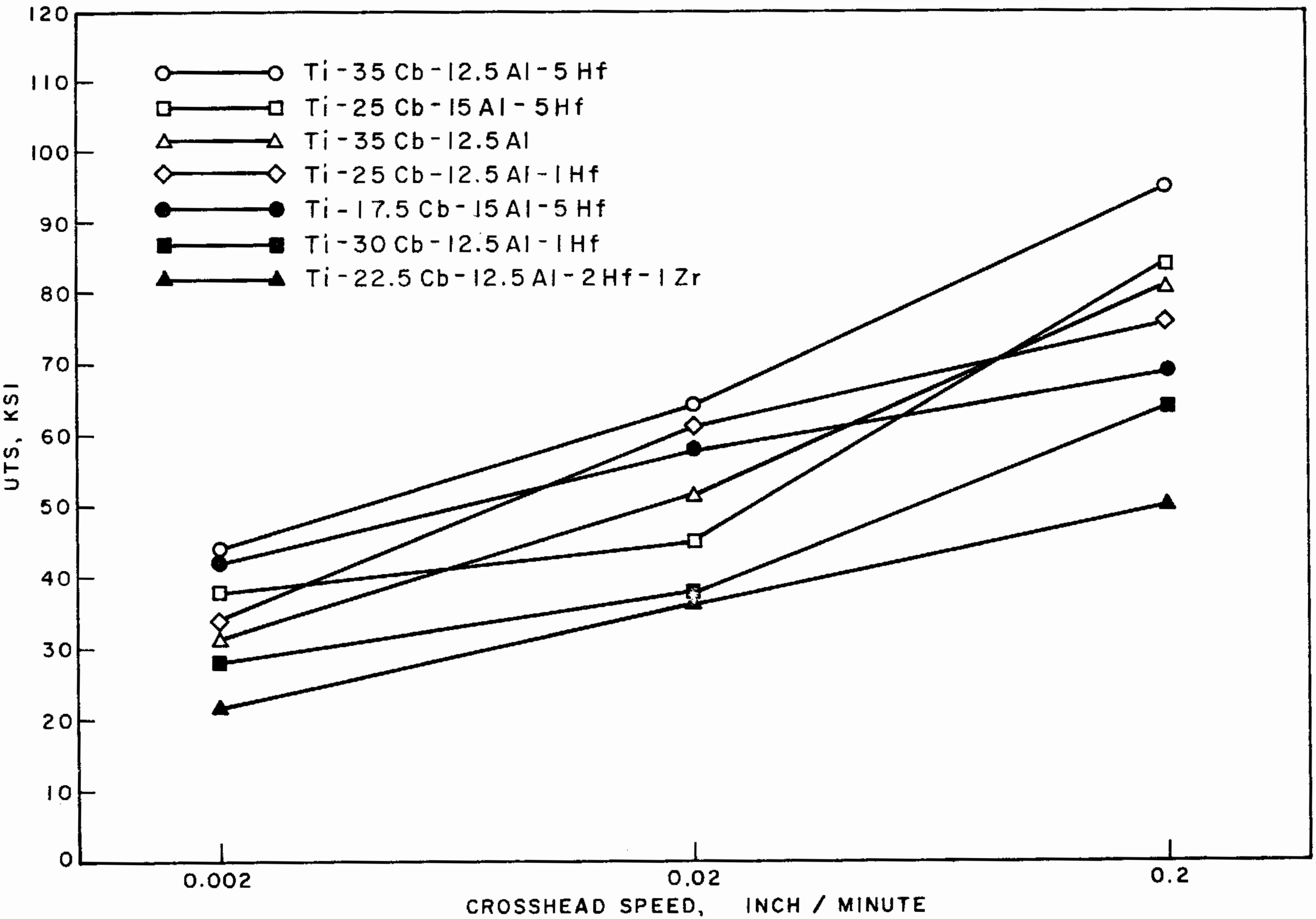


FIG. 3 - ULTIMATE TENSILE STRENGTH OF TITANIUM ALLOYS AT 1600°F

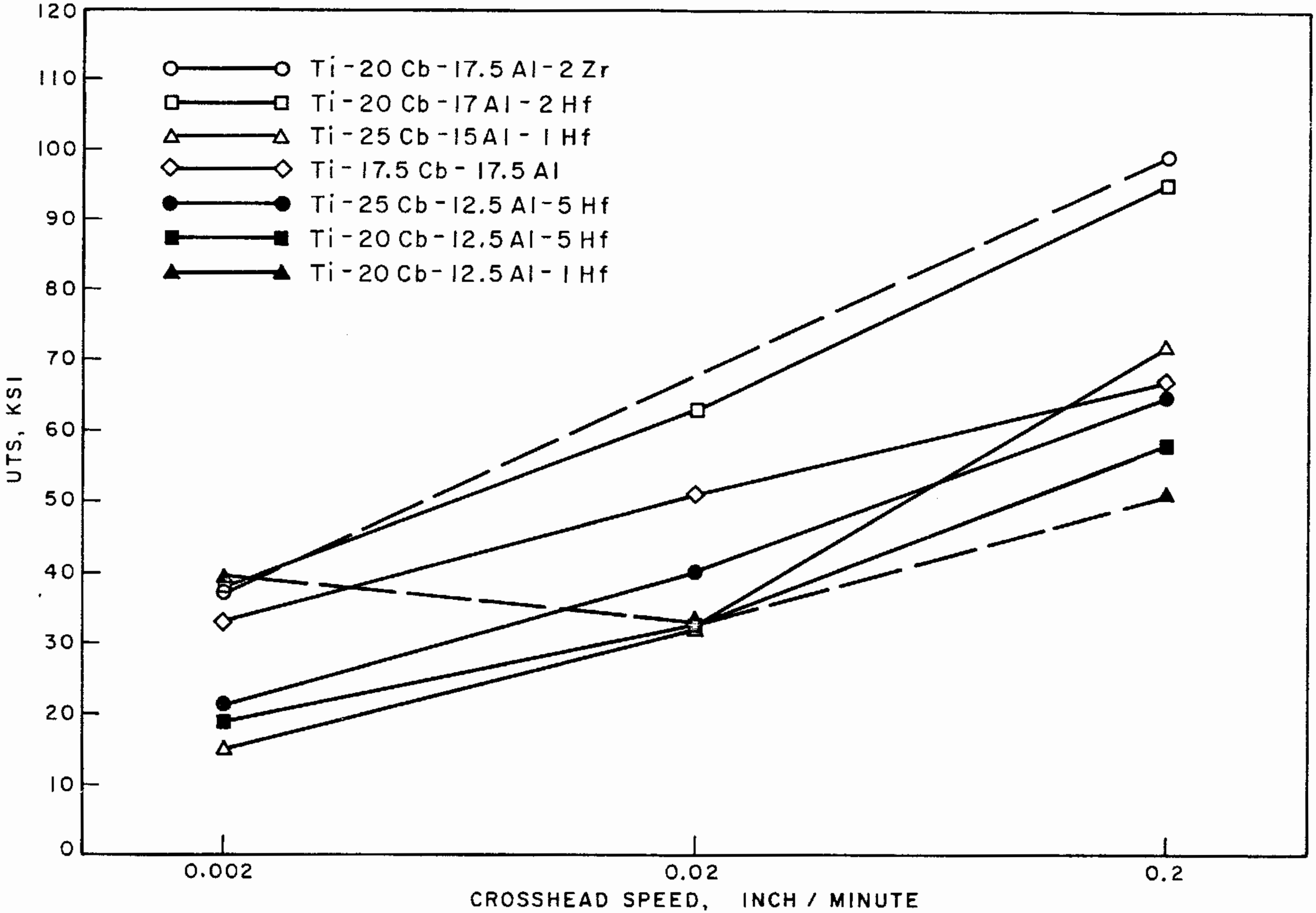


FIG. 4 - ULTIMATE TENSILE STRENGTH OF TITANIUM ALLOYS AT 1600°F.

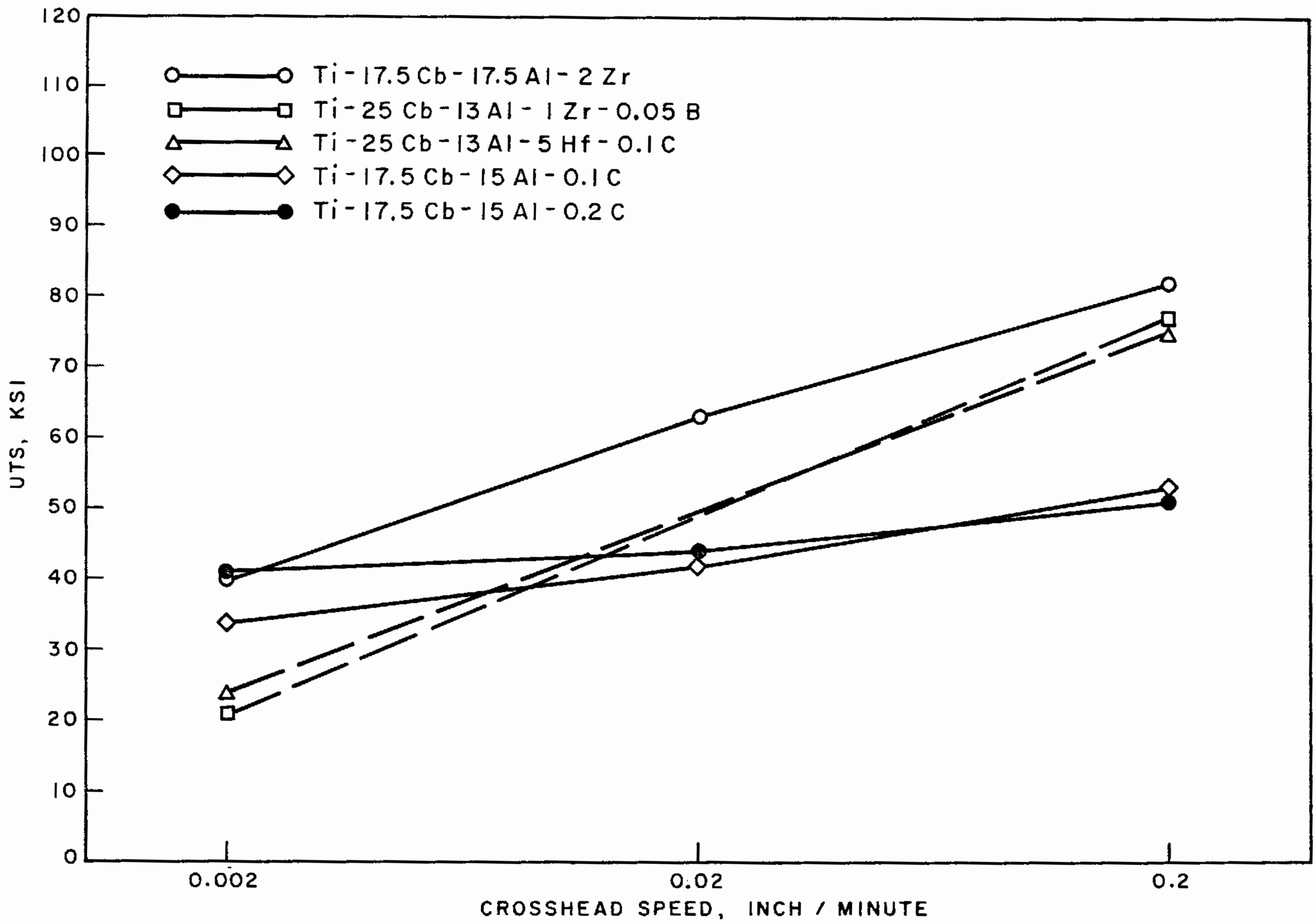


FIG. 5 - ULTIMATE TENSILE STRENGTH OF TITANIUM ALLOYS AT 1600°F.

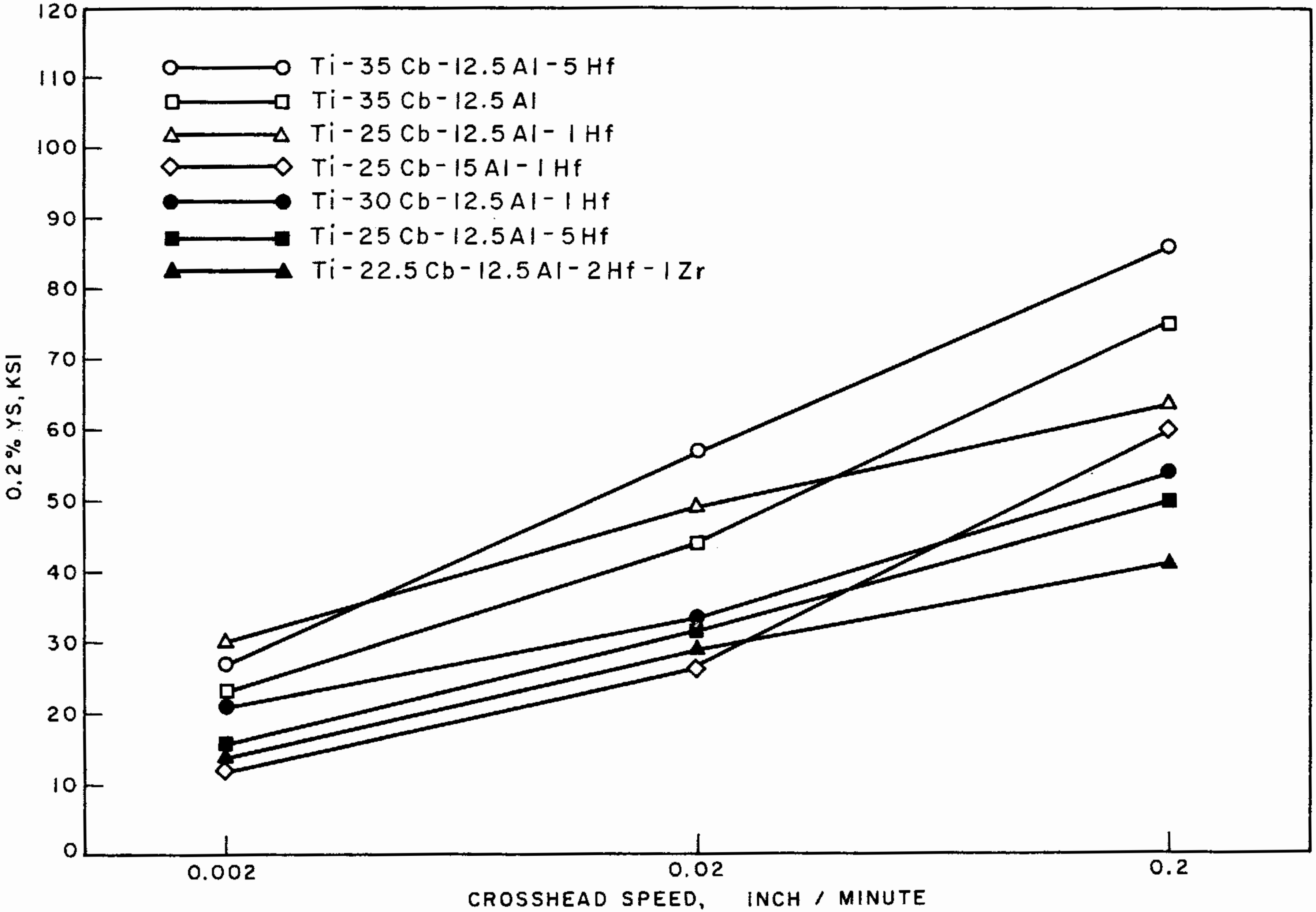


FIG. 6 - YIELD STRENGTH OF TITANIUM ALLOYS AT 1600°F.

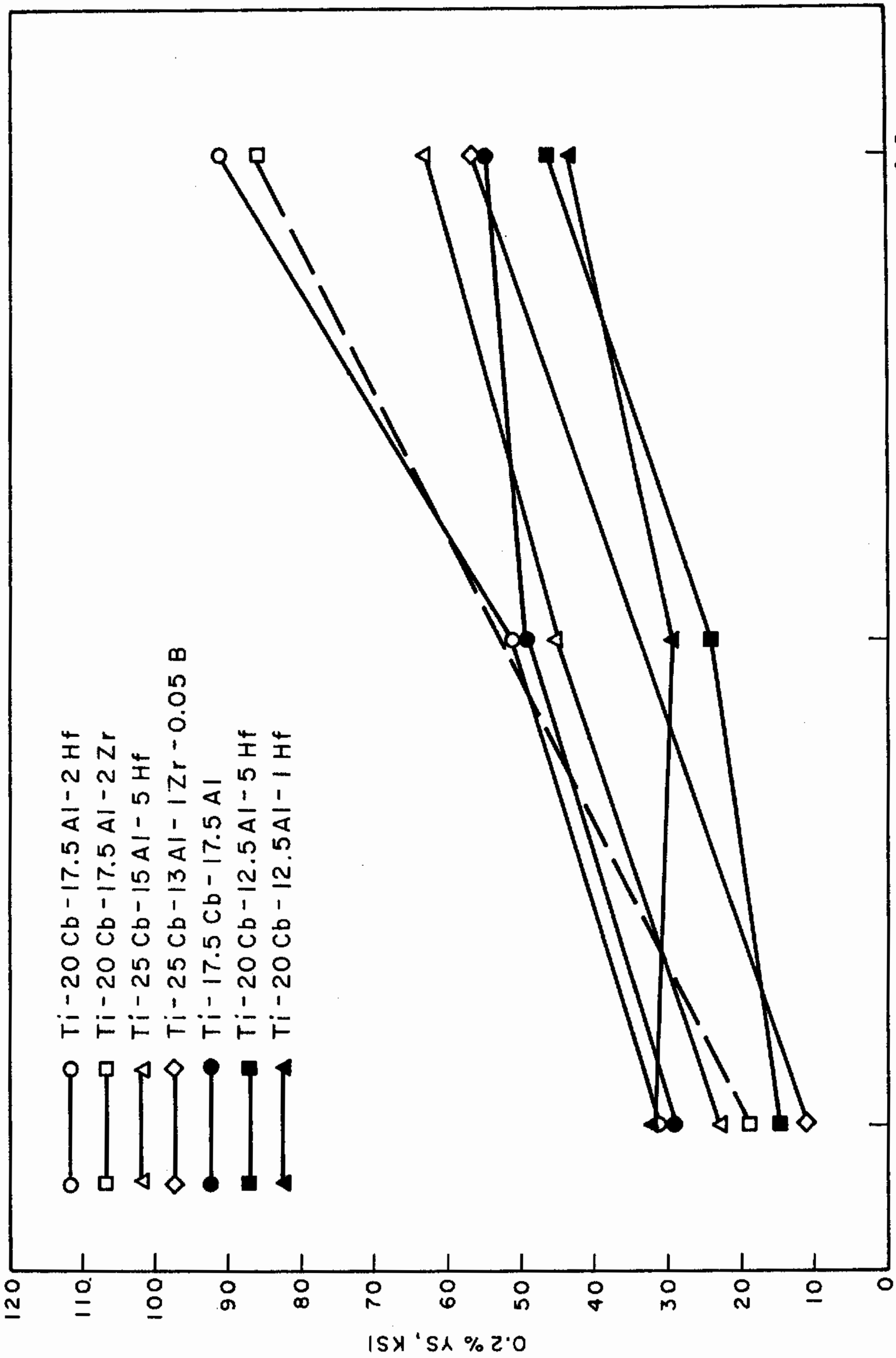


FIG. 7 - YIELD STRENGTH OF TITANIUM ALLOYS AT 1600°F.

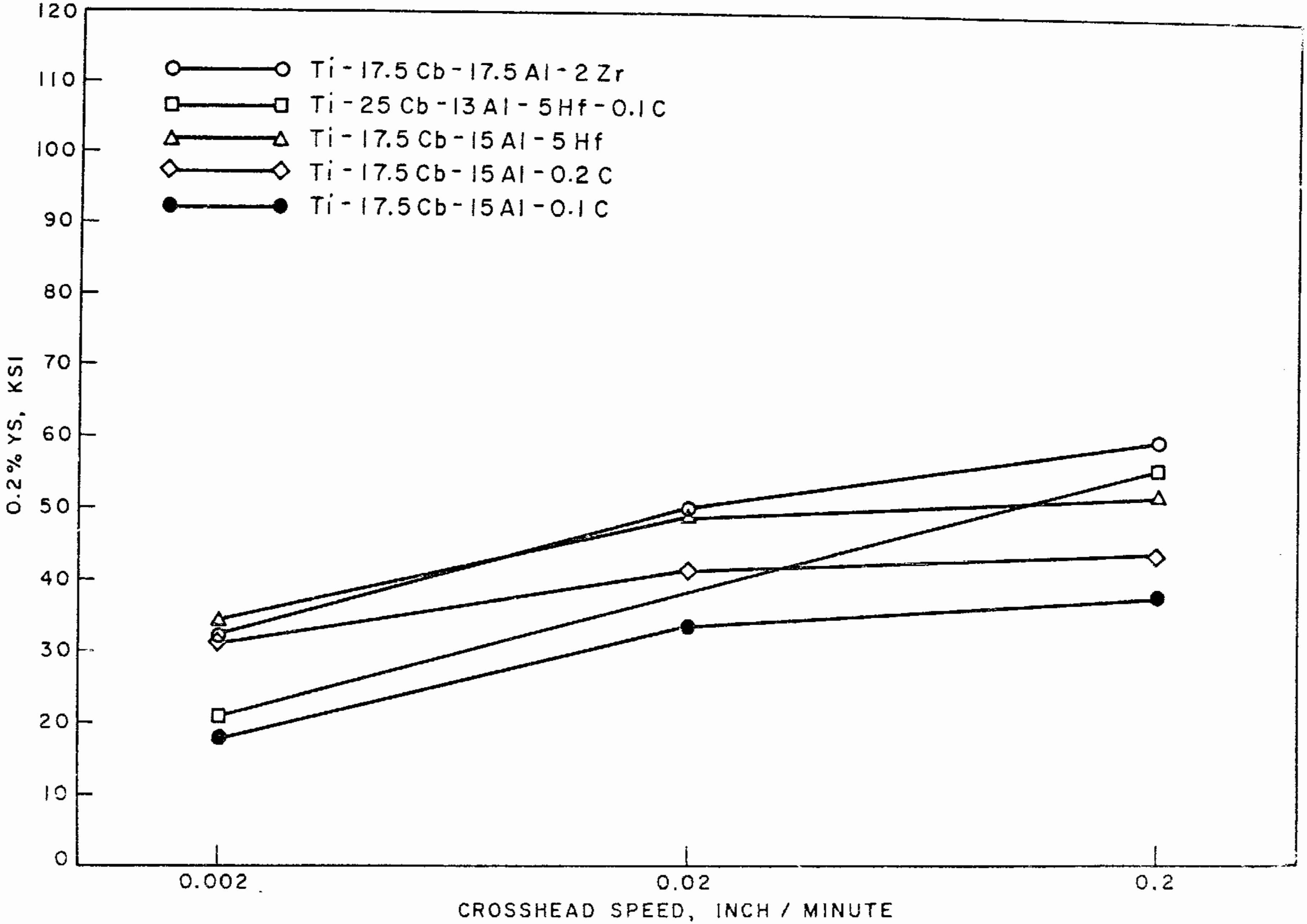


FIG. 8 - YIELD STRENGTH OF TITANIUM ALLOYS AT 1600°F.

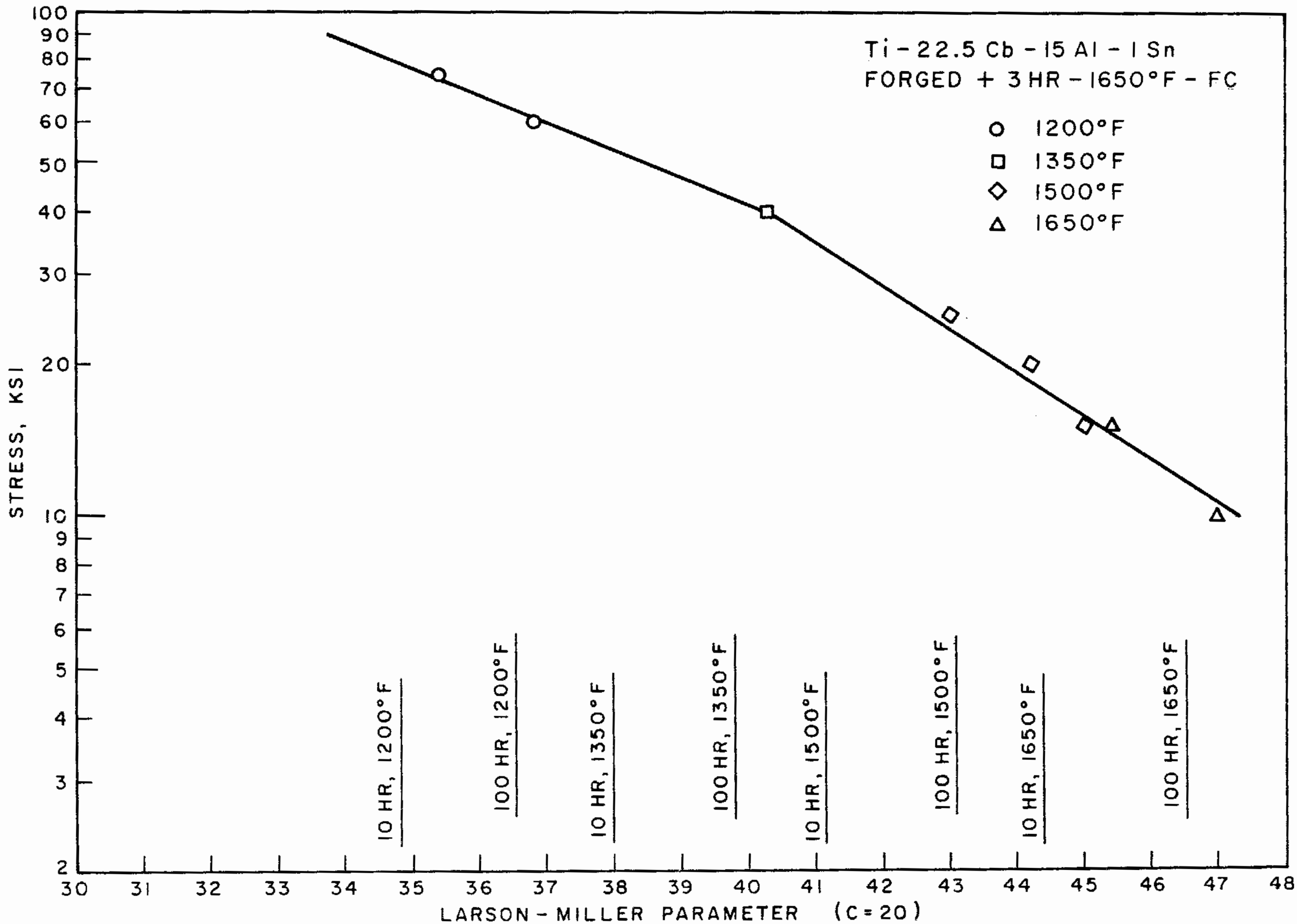


FIG. 9 - STRESS RUPTURE DATA FOR Ti-22.5Cb-15Al-1Sn.

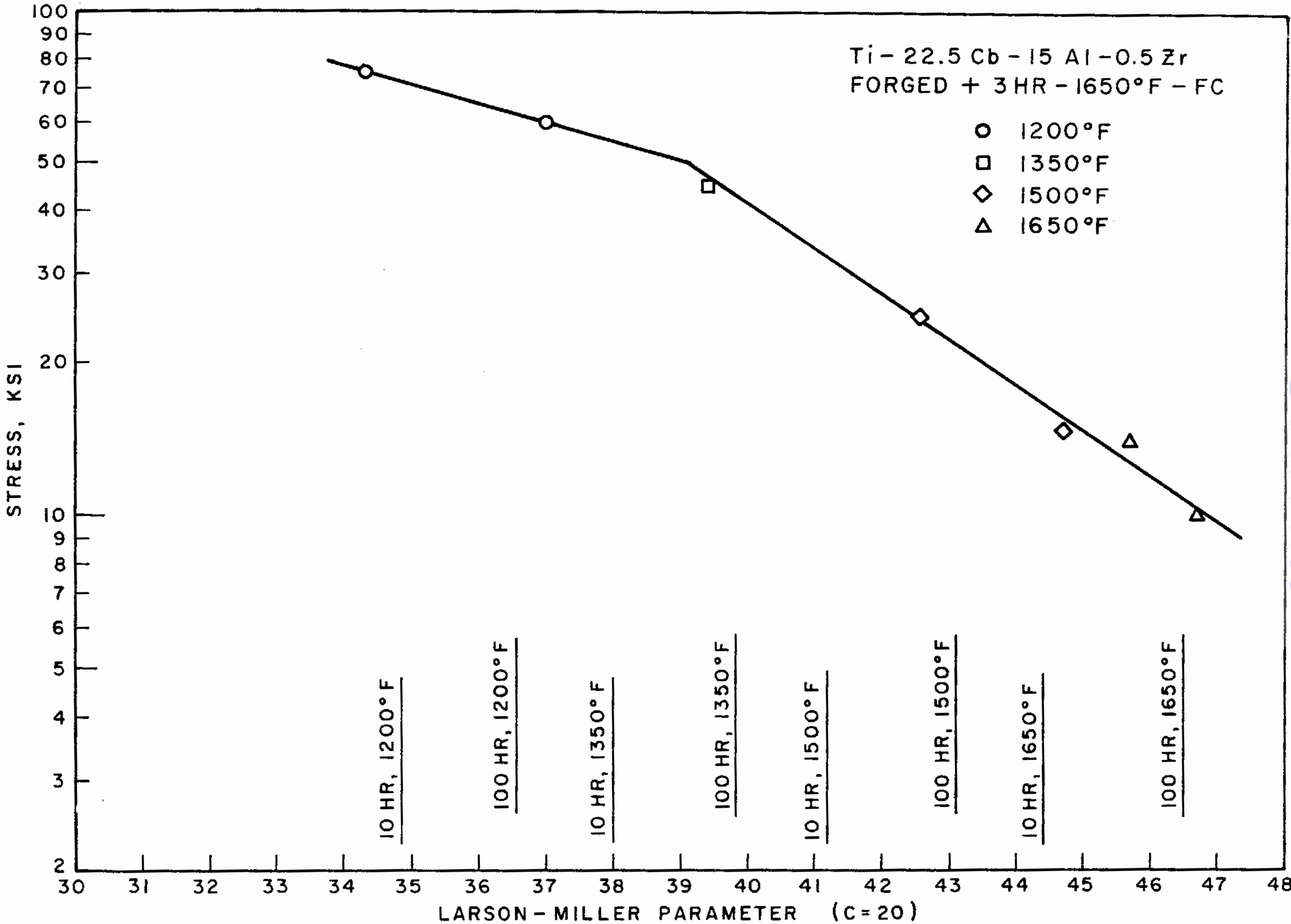


FIG. 10 - STRESS RUPTURE DATA FOR Ti-22.5Cb-15Al-0.5Zr.

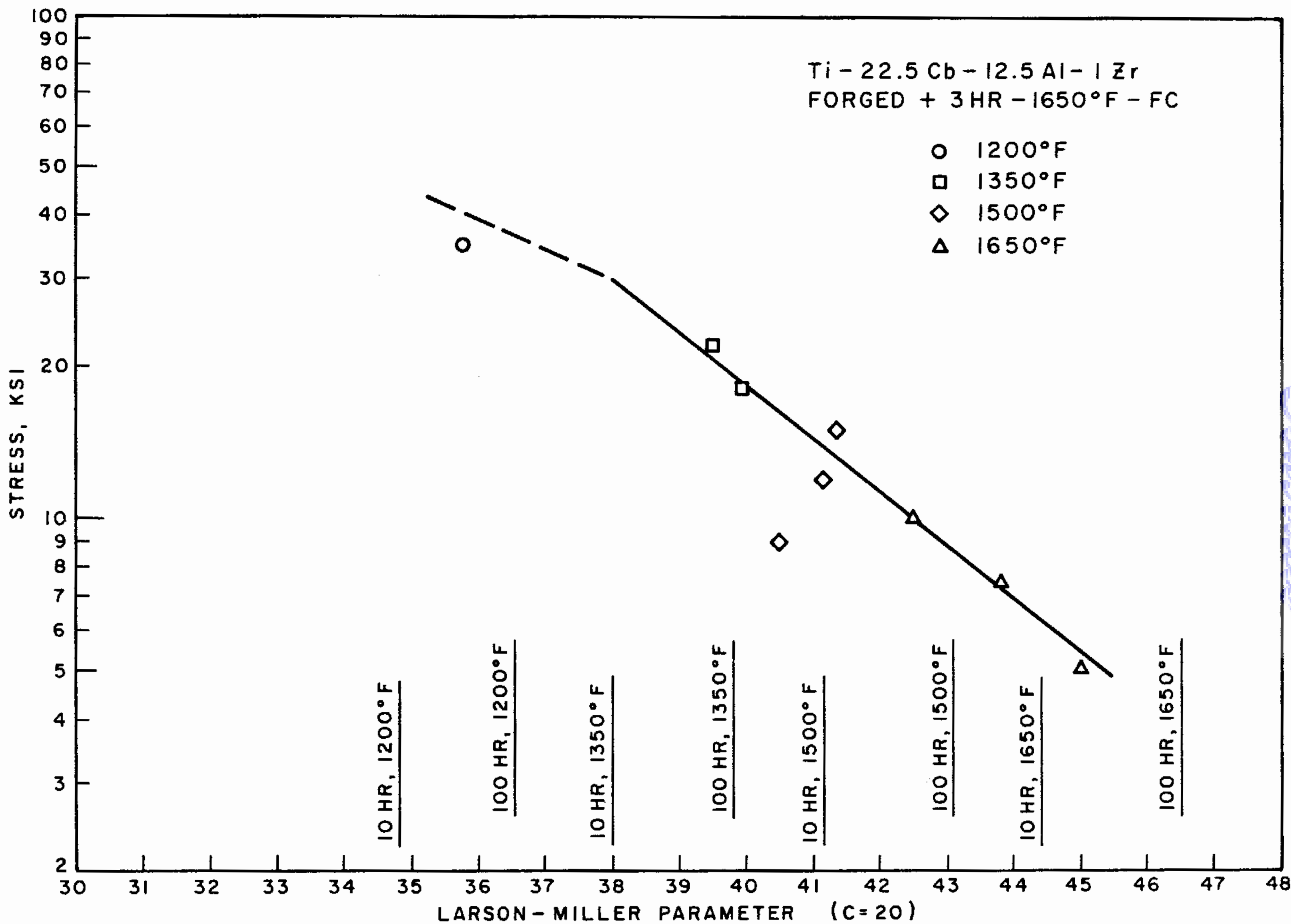


FIG. 11 - STRESS RUPTURE DATA FOR Ti-22.5Cb-12.5Al-1Zr.

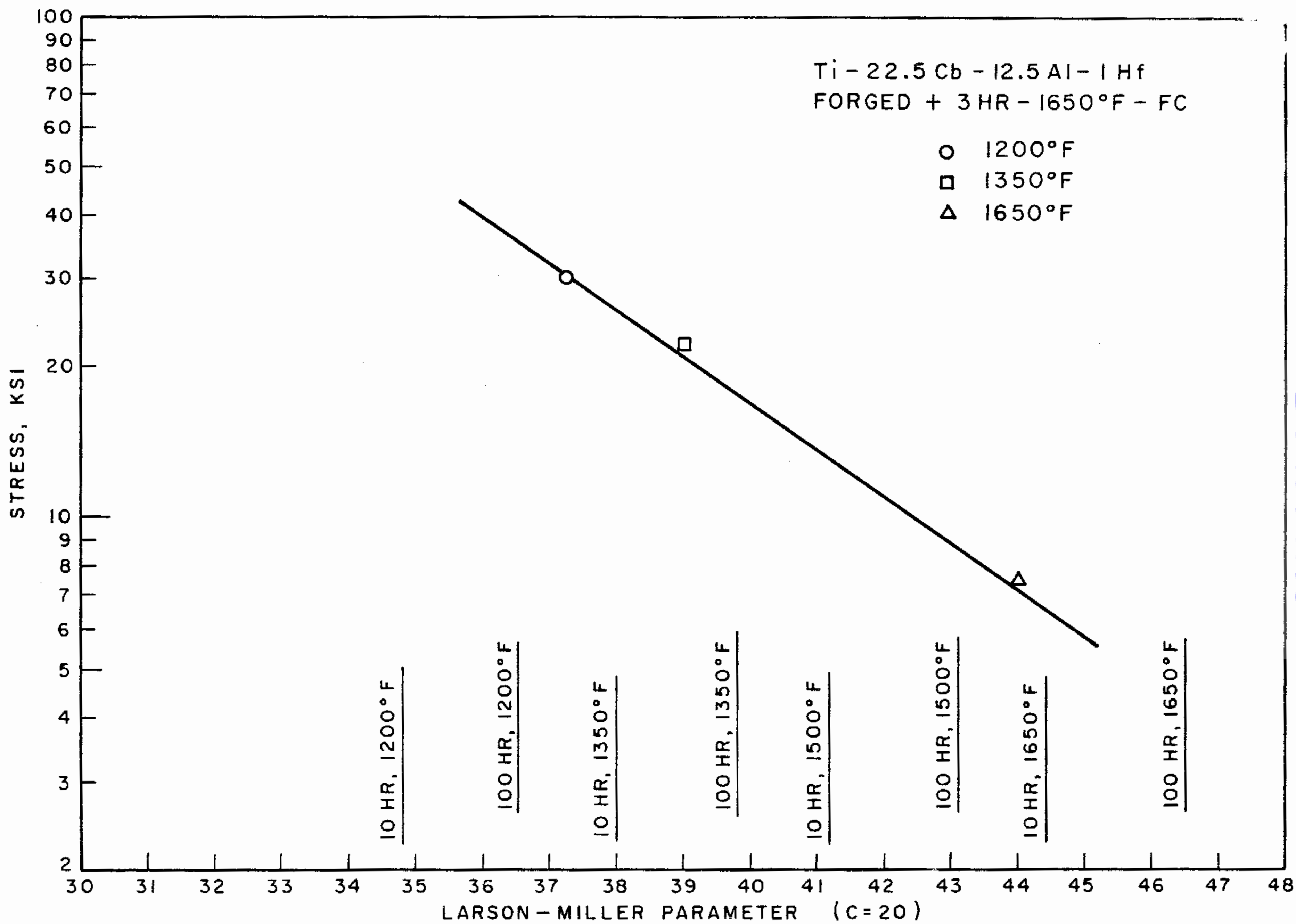


FIG. 12 - STRESS RUPTURE DATA FOR Ti-22.5Cb-12.5Al-1Hf.

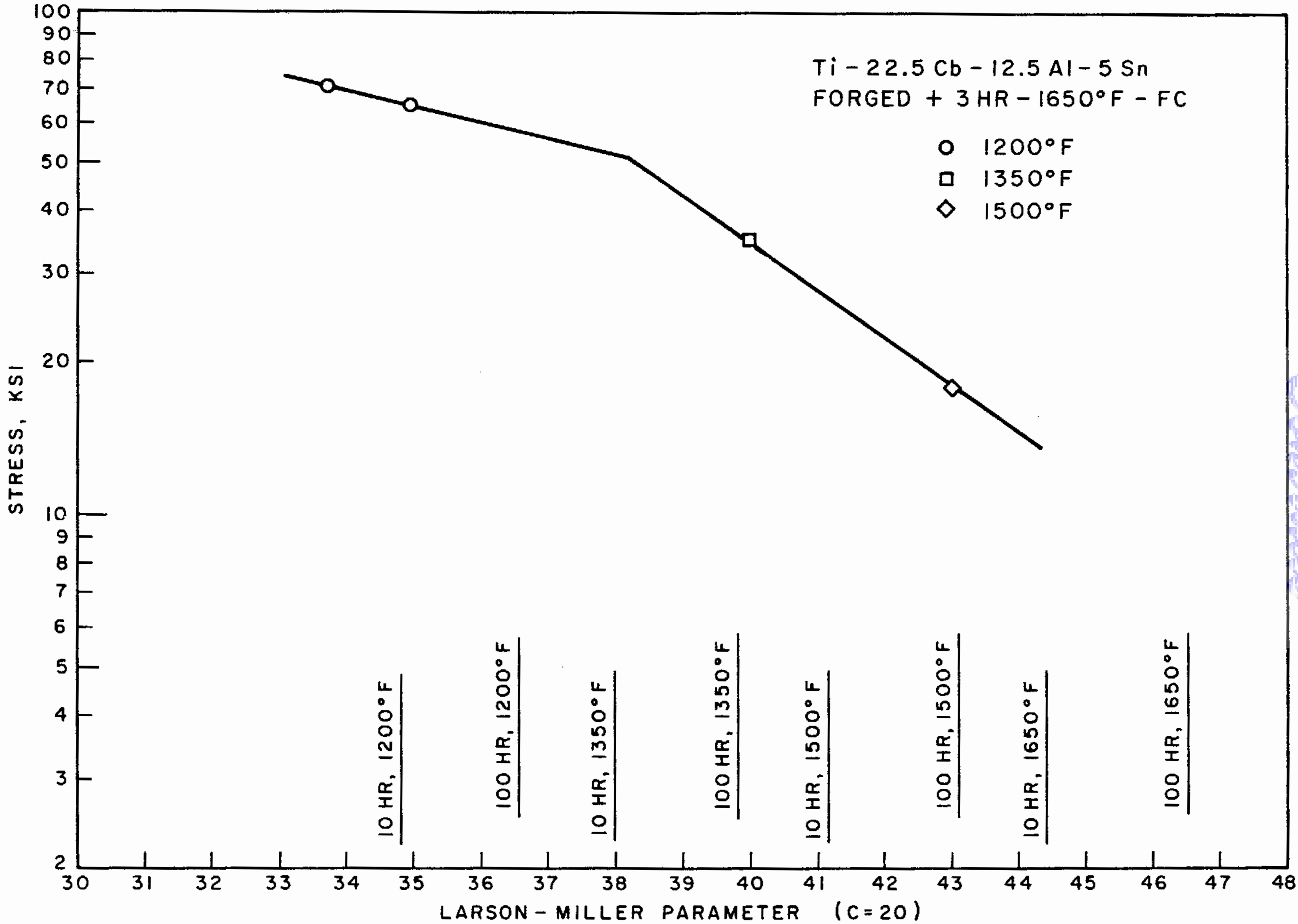


FIG. 13 - STRESS RUPTURE DATA FOR Ti-22.5Cb-12.5Al-5Sn.

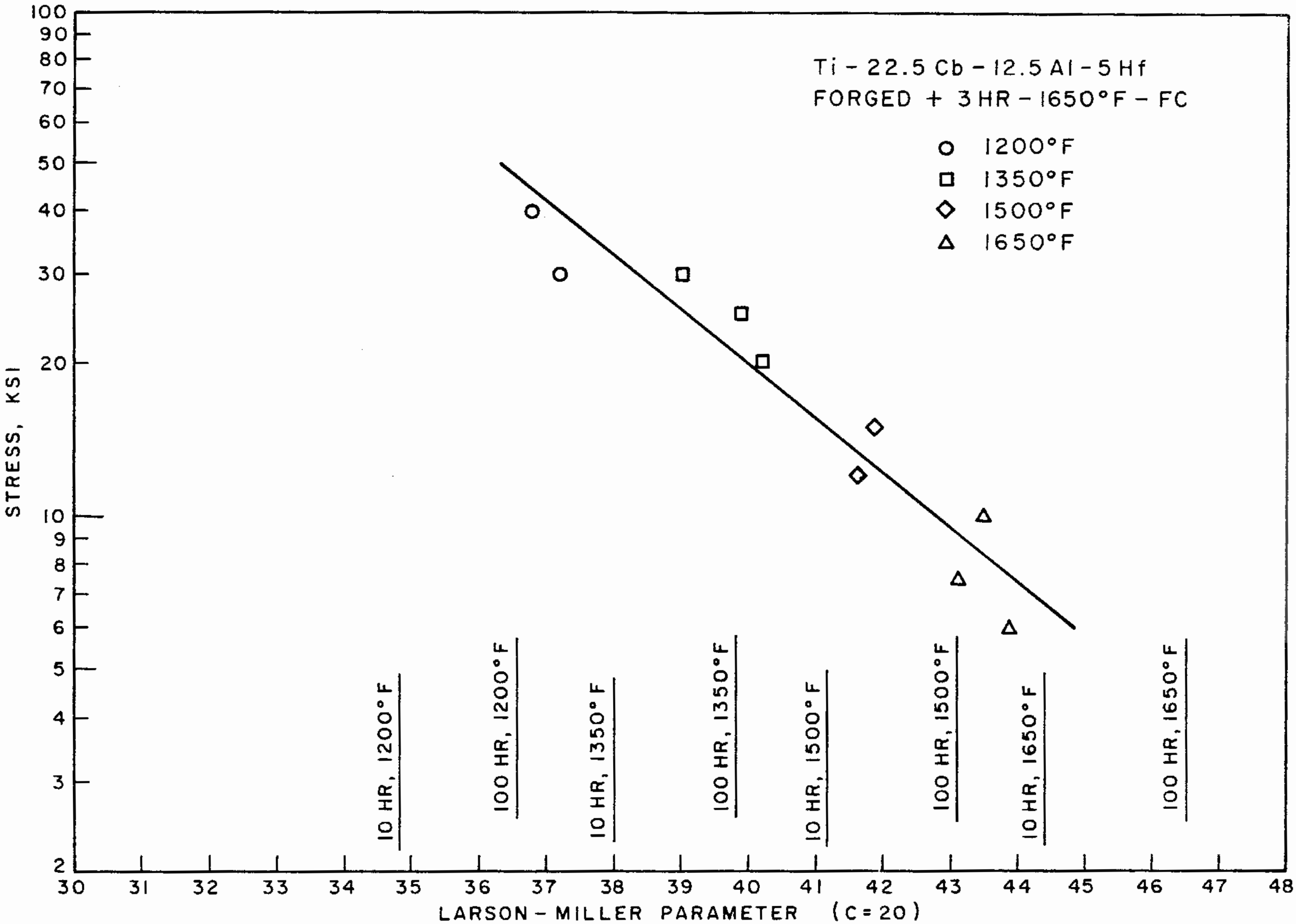


FIG. 14 - STRESS RUPTURE DATA FOR Ti-22.5Cb-12.5Al-5Hf.

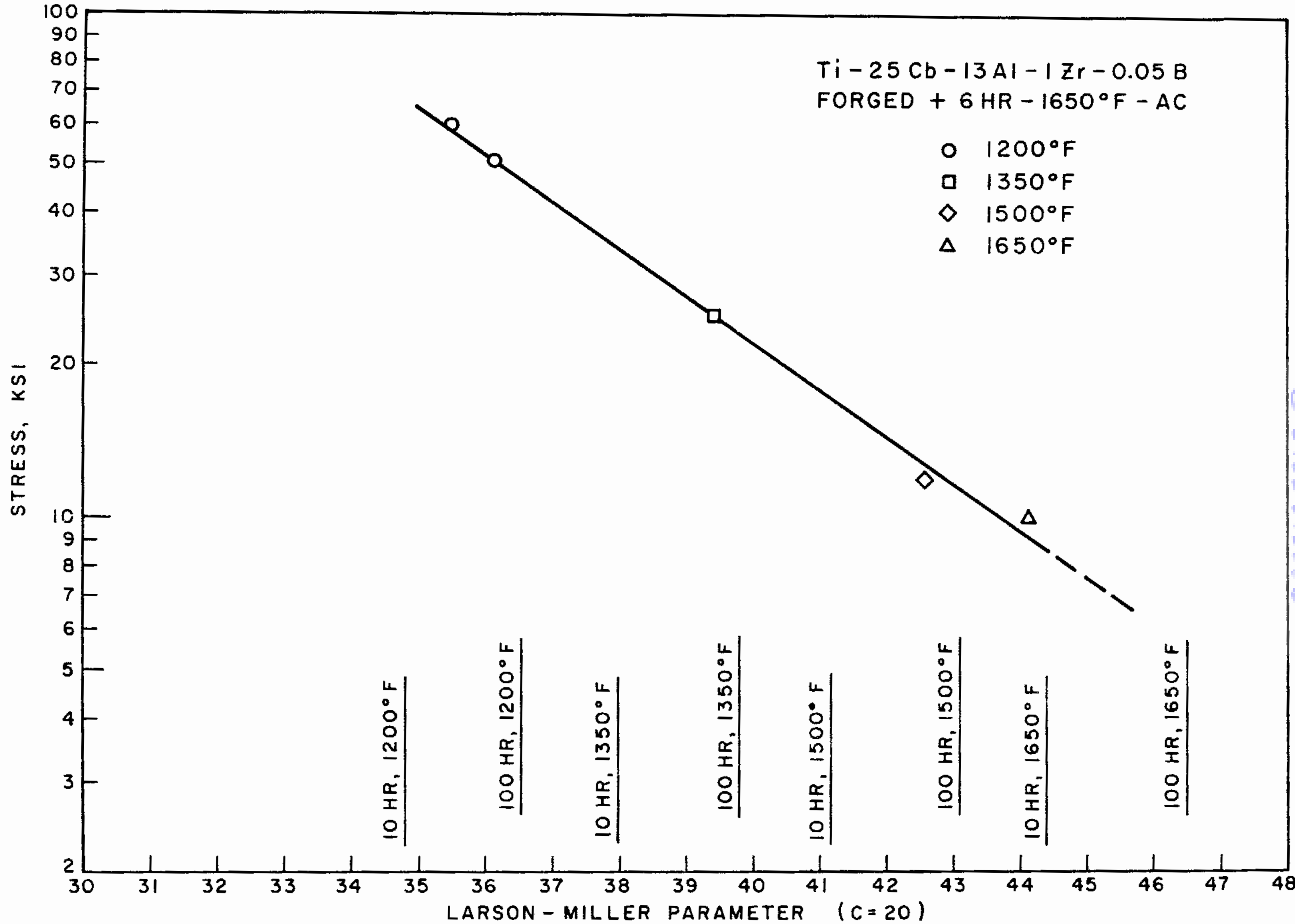


FIG. 15 - STRESS RUPTURE DATA FOR Ti-25Cb-13Al-1Zr-0.05B.

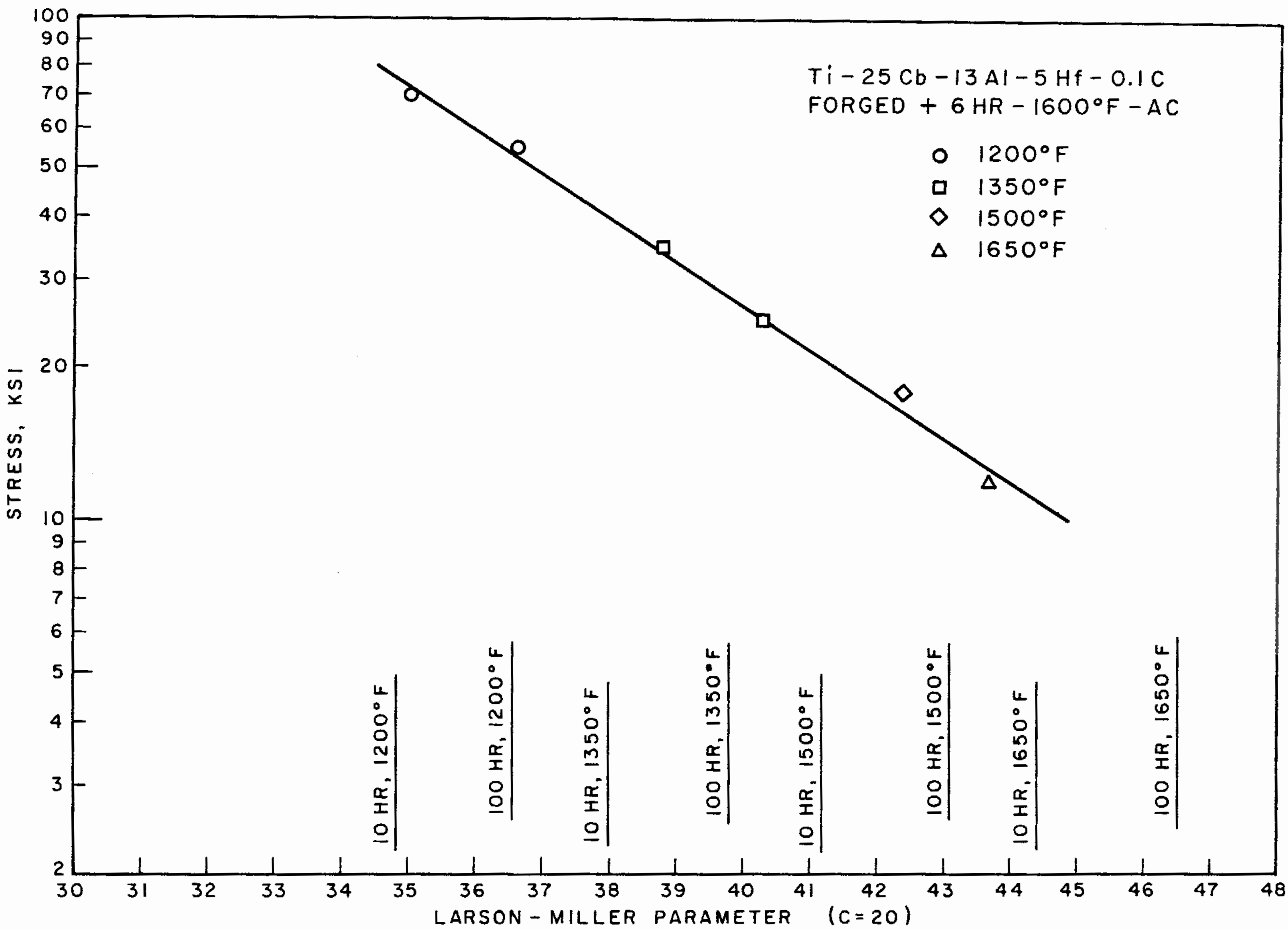
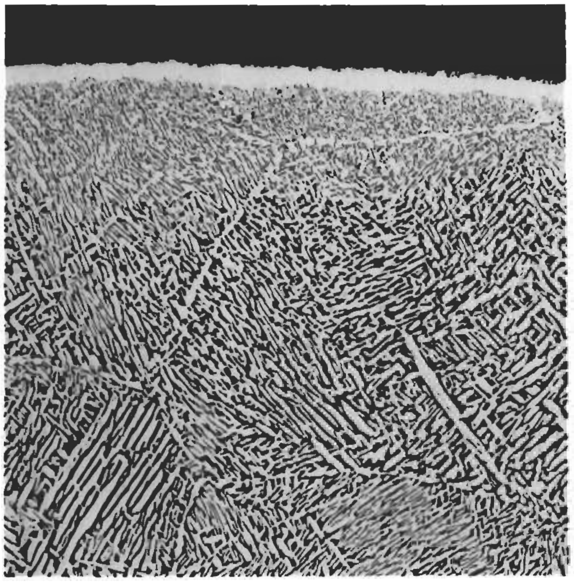
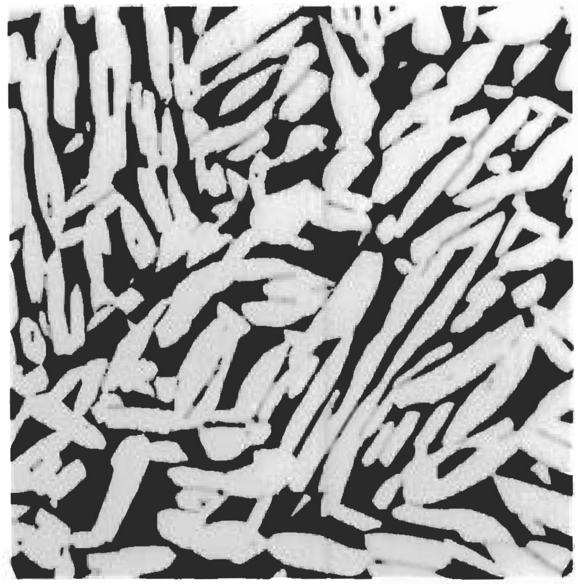


FIG. 16 - STRESS RUPTURE DATA FOR Ti-25Cb-13Al-5Hf-0.1C.



Neg. No. 21983 100X BF

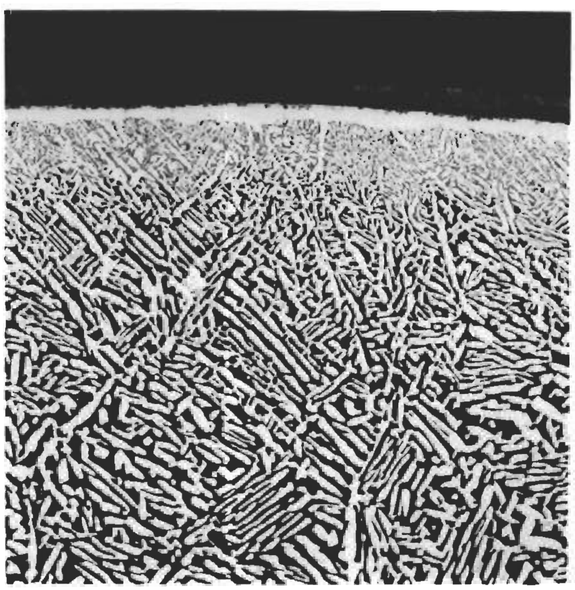
(a) Edge



Neg. No. 21966 500X BF

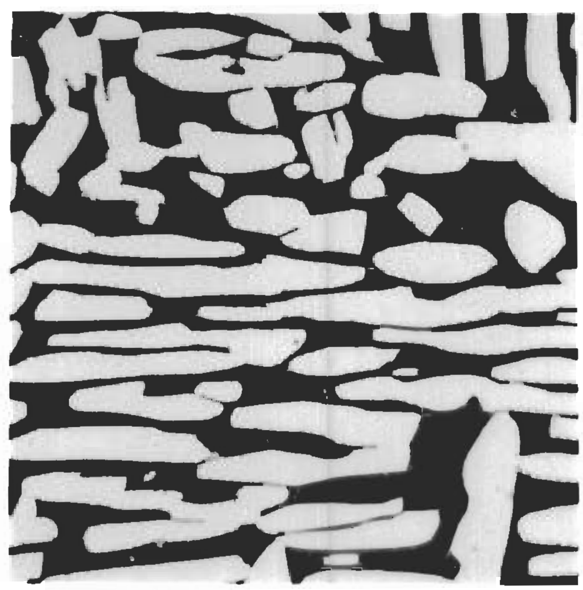
(b) Center

Fig. 17 - Ti-22.5Cb-12.5Al-1Hf. After 100 hr, 1000°C (1832°F) in air.



Neg. No. 21987 100X BF

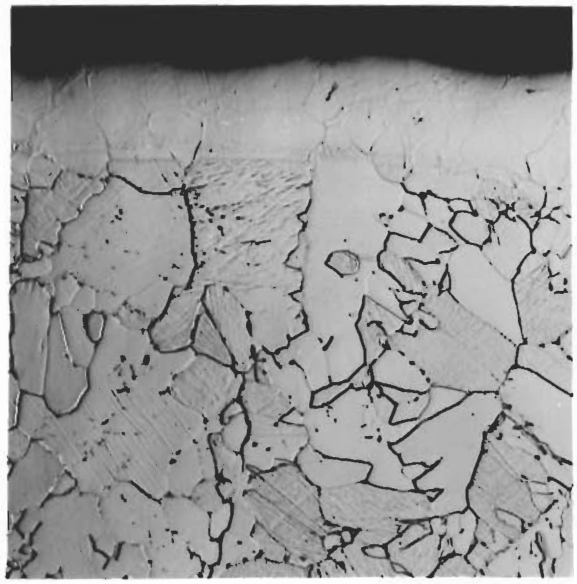
(a) Edge



Neg. No. 21972 500X BF

(b) Center

Fig. 18 - Ti-22.5Cb-12.5Al-2.5Hf. After 100 hr, 1000°C (1832°F) in air.



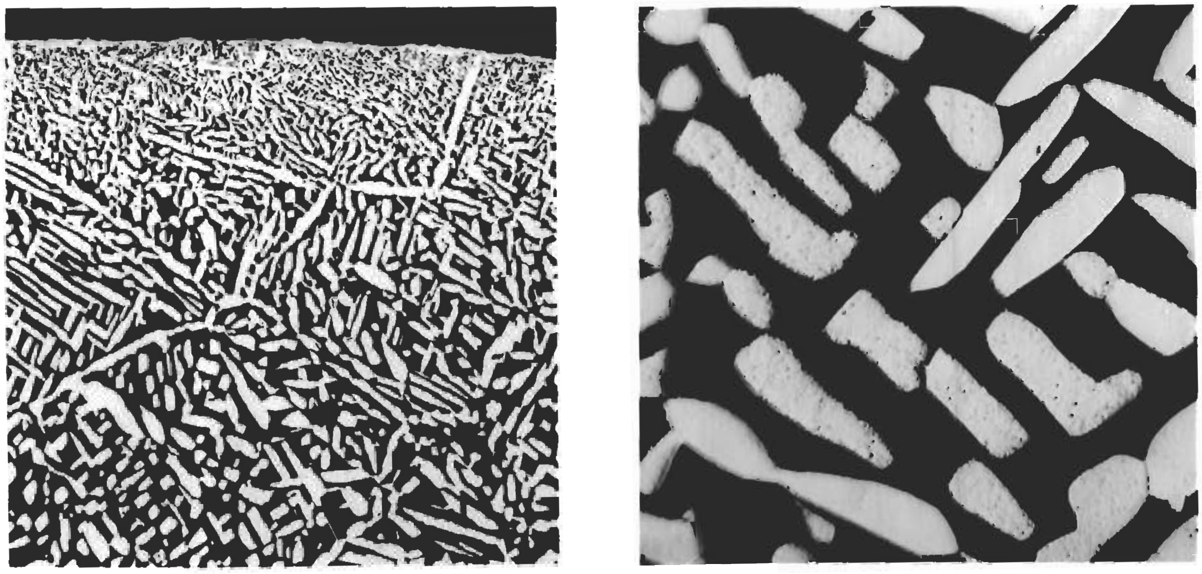
Neg. No. 21980 100X BF

(a) Edge

Neg. No. 21954 500X Oblique Light

(b) Center

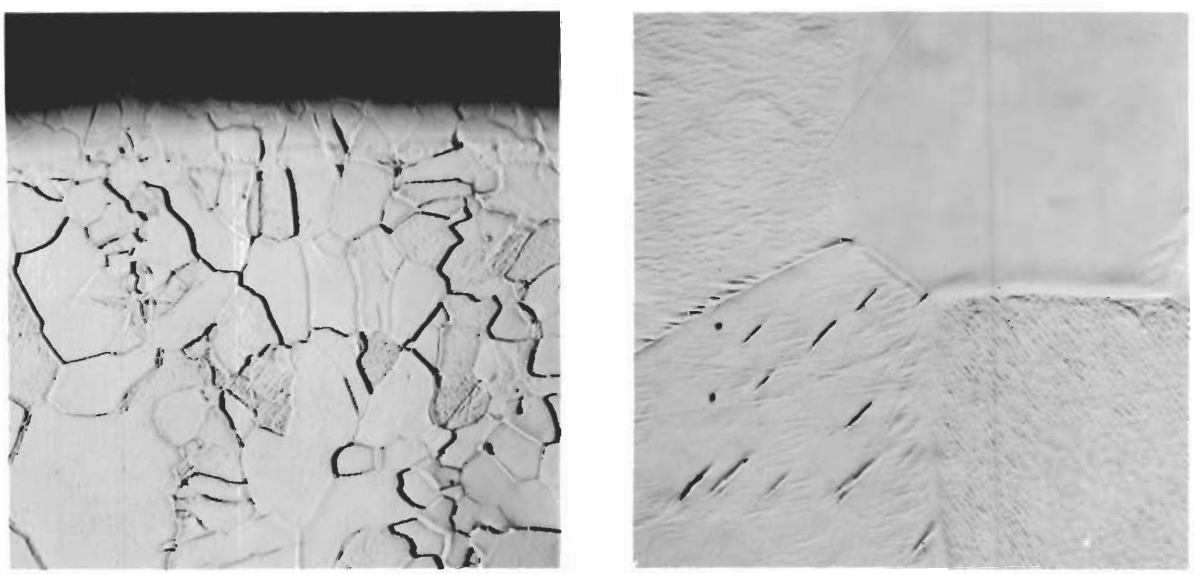
Fig. 19 - Ti-20Cb-17.5Al. After 100 hr, 1000°C (1832°F) in air.



Neg. No. 21988 100X BF Neg. No. 21974 500X Oblique Light

(a) Edge (b) Center

Fig. 20 - Ti-22.5Cb-12.5Al-2Zr. After 100 hr, 1000°C (1832°F) in air.



Neg. No. 22059 100X Oblique Light Neg. No. 22042 500X Oblique Light

(a) Edge (b) Center

Fig. 21 - Ti-22.5Cb-15Al-0.5Sn. After 100 hr, 1000°C (1832°F) in air.