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A PRELIMINARY INVESTIGATION ON THE EFFECTS OF SURFACE TREATMENTS ON THE FATIGUE STRENGTH OF TITANIUM ALLOYS Ti-150A and RC-130B

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FEBRUARY 1953

WRIGHT AIR DEVELOPMENT CENTER

NOTICES

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McGregor & Werner, Inc., Dayton
250 May 1953

FOREWORD

This report was initiated under Research and Development Order No. 615-11, "Titanium Metals and Alloys", and was administered under the direction of the Materials Laboratory, Directorate of Research, Wright Air Development Center, with Lt F. E. Binns acting as project engineer.

ABSTRACT

The evaluation of the effects of various treatments on the fatigue properties of titanium bar stock alloys Ti-150A and RC-130B was made. The various treatments of Ti-150A and their corresponding fatigue endurance limits are as follows:

1. Machined and polished - 68,000 psi
2. Ground - 63,000 to 70,000 psi
3. Ten percent permanently stretched and ground - 54,000 psi (wide scatter of data)
4. Ground and scaled - 56,000 psi
5. Machined notched - 40,000 psi
6. Ground and notched - 21,000 psi

The fatigue strength varied from about 35 to 45 percent of the tensile ultimate strength for the different treatments, except for the notched condition as would be expected. RC-130B gave endurance limits of about 67,000 psi (approximately 45 percent of tensile ultimate strength) for the ground, unnotched condition, and about 24,000 psi for the ground notched material. The wide range of values for the ground Ti-150B alloy and for the 10 percent stretched and ground Ti-150A alloy may have been due to various degrees of surface cold work, and surface discontinuities, caused by grinding and cold work. In addition, radiography identified tungsten inclusions which were probably a contributing factor. In general, the surface treatment has a marked effect upon the fatigue strength of titanium and its alloys. For the conditions tested, a machined and polished surface produced the optimum fatigue properties.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDING GENERAL:

M. E. SORTE
Colonel, USAF
Chief, Materials Laboratory
Directorate of Research

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INTRODUCTION

The variation in fatigue strength of metals with different surface treatments is a well known fact. Previous work in this field on process "A" titanium containing approximately 0.4%C produced by the Remington Arms Company, was performed by the Materials Laboratory on 0.06 inch sheet in the "as annealed" condition and on 0.066 inch sheet in the "as cold rolled" condition. Reversed flexural fatigue tests were made in Krouse sheet fatigue machines operating at a speed of 1725 rpm. The endurance limits for the "as annealed" sheet were good but for the "as cold rolled" sheet were poor, especially in the direction of rolling. On the surface of the cold rolled samples shallow pits were found which may have been caused by pickling procedures before cold rolling. The pits were removed by surface grinding 0.001 inch of material from each side of the specimens. The endurance limit was very much increased indicating the surface defects to be essentially responsible for the low fatigue values of the "as cold rolled" material. The results obtained are:(1)

Condition	Direction	Endurance Limit (psi)	% of Ultimate Strength
"As Annealed"	Trans.	48,000	51
	Long.	51,500	54
"As Cold Rolled"	Trans.	43,000	36
	Long.	31,000	26.5
"As Cold Rolled and Surface Ground	Long.	47,000	40

Additional work was later done at the Materials Laboratory on three pieces of commercial titanium sheet submitted by the Remington Arms Company. The pieces were reported to have come from one ingot which had been cold rolled to a thickness of about 0.06 inch. It was reported that one piece had been vacuum annealed; another piece air annealed, descaled in sodium hydride, and pickled in a nitric-hydrofluoric acid solution; and the remaining piece kept in the "as cold rolled" condition. The three pieces were tested in a Krouse sheet fatigue machine both parallel and transverse to the direction of rolling with the following results:

Condition	Direction	Fatigue Strength At 20X10^6 Cycles (psi)
Annealed and Pickled	Transverse	44,500
	Longitudinal	42,000
Vacuum Annealed	Transverse	42,000
	Longitudinal	33,000
"As Cold Rolled"	Transverse	39,000
	Longitudinal	33,000

The fatigue values were higher in the transverse direction than in the longitudinal direction for all conditions. No completely satisfactory reasons could be given to account for the annealed and pickled samples producing the best results and the cold rolled specimens the poorest results.

In order to gain more fundamental knowledge of this complex problem and consequently produce titanium with optimum fatigue properties, the Materials Laboratory decided to conduct a preliminary investigation on the effects of different surface treatments on the fatigue strength of titanium in preparation for more intensive studies. A research contract with the University of Michigan has now been initiated in which a more fundamental approach to the problem is being made.

For the preliminary investigation covered by this report two commercial titanium alloys were chosen because of their availability and practical applications. Titanium Metals Corporation of America and Rem-Cru Titanium, Incorporated, supplied alloy bar stock. Rotating beam fatigue tests were chosen for the investigation since a closer control of variables could be obtained by this method than in sheet fatigue testing.

OUTLINE OF WORK

The method of attack chosen for the testing program was as ollows: (1) Alloy bar stock cut into specimens; (2) Specimens adiographed to determine relative amount and distribution of tungten inclusions; (3) As received mechanical properties determined t room temperature and Charpy impact tests performed at 800, 600, 00, 200, 75 and -100°F; (4) Samples subjected to various types f treatments; (5) Fatigue properties evaluated by rotating beam method for all treatments; (6) Mechanical properties determined for selected treatments to show their relationship to fatigue strength; (7) Specimens metallographically examined to determine structure and homogeneity; and (8) "SN" curves drawn for the different conditions tested and a comparison made of the fatigue strengths.

The conditions tested may be divided into the categories of scaling, cold work, and surface preparation. The following table lists the types of treatments and the evaluation of mechanical properties chosen for Ti-150A.

Table I - Mechanical Properties Determined for Ti-150A

Treatment		Mechanical Properties		
Type	Factors Investigated	Tensile	% Elongation	Fatigue
Scaling	Scaled in air at 1300 °F for 1 Hour, and Air Cooled	Machined before Scaling X	X	Ground before Scaling X
Cold Work	Permanently Stretched 10% in Tensile Machine and Ground	X	X	X
Surface Preparation	Ground			X
Surface Preparation	Machined and Polished	X	X	X
Surface Preparation	Ground Notched			X
Surface Preparation	Machined Notched	X	X	X

Since only a limited amount of Rem-Cru Titanium bar stock was available, it was decided to confine the fatigue investigation of this material to the following two conditions; (1) Ground unnotched and, (2) Ground notched.

MATERIALS AND APPARATUS

The Titanium Metals Corporation of America supplied eight, 9/16 inch diameter bars of Ti-150A; nominal composition of 2.6% Cr, 1.3% Fe, and 0.2% O_2 by weight. The heat number for bars 1 and 2 was X-538 and for bars 3 to 8 was X-508. These melts were early experimental ones and consequently were not of comparable quality to melts produced at the present.

Rem-Cru Titanium, Incorporated, supplied five, 9/16 inch diameter bars of RC-130B; nominal composition of 4% Mn and 4% Al by weight. Only a limited amount of the alloy was available, and the heat numbers of the bars are unknown. Internal stresses of considerable magnitude were discovered in these bars during machining operations, and it was necessary to repeat the manufacturer's annealing treatment (1300°F followed by an air cool) after the bars were cut to specimen lengths.

For radiographic purposes the following procedure was employed: The bars were cut to specimen size and radiographed, then turned 90 degrees about their longitudinal axes and radiographed again in order to locate the position of stringers and inclusions. Stringers and inclusions of tungsten were found in the Ti-150A alloy with bars 3, 6, and 7 having particularly bad contamination. The RC-130B bars had only small amounts of homogeneously scattered impurities. Table II is a tabulation of the relative amounts of tungsten inclusions in the various bars.

Table II - Tungsten Inclusions Observed By X-ray

Ti-150A Bar Number	1	2	3	4	5	6	7	8
Total Specimens Cut	11	5	10	7	6	11	6	6
Free from Inclusions	9	5	1	1	1	0	0	5
Moderate Quantity of Inclusions	2	0	5	5	4	2	3	1
Large Quantity of Inclusions	0	0	4	1	1	9	3	0

RC-130B Bar Number	11	12	13	14	15
Total Samples	3	3	3	3	3
Free from Inclusions	1	2	0	3	1
Moderate Quantity of Inclusions	2	1	3	0	2
Large Quantity of Inclusions	0	0	0	0	0

X-ray data: tungsten target, 48 inches from specimens, 140 K.V., 8 mà., 8 minute exposure, Type A film, lead screens.

A wet analysis for carbon and tungsten was conducted on RC-130B bars 11 and 13. The results were as follows:

Bar Number	C (%)	W (%)
11	0.07	0.34
13	0.06	0.25

Microscopic examination of the Ti-150A specimens showed an all alpha structure composed of very small grains of primary alpha plus transformed beta with varying amounts of tungsten inclusions depending upon the specimens examined. The alloy exhibited definite preferred orientation in the direction of rolling. Figures 1 through 3 illustrate respectively, a cross section of sound material, a cross section showing a large tungsten inclusion, and a section taken in the direction of rolling.

Microscopic examination of RC-130B revealed a grain size much larger than observed for Ti-150A. The microstructure consists of small amounts of primary alpha plus transformation platelets of alpha in retained beta. The large number of alpha platelets and the coarse original "Beta grain size" shown in Figure 4 (area shown in photomicrograph consists of only three original grains) indicates that the material was finally heat treated very near the beta transus temperature. Very small inclusions of tungsten could be seen in only a few specimens.

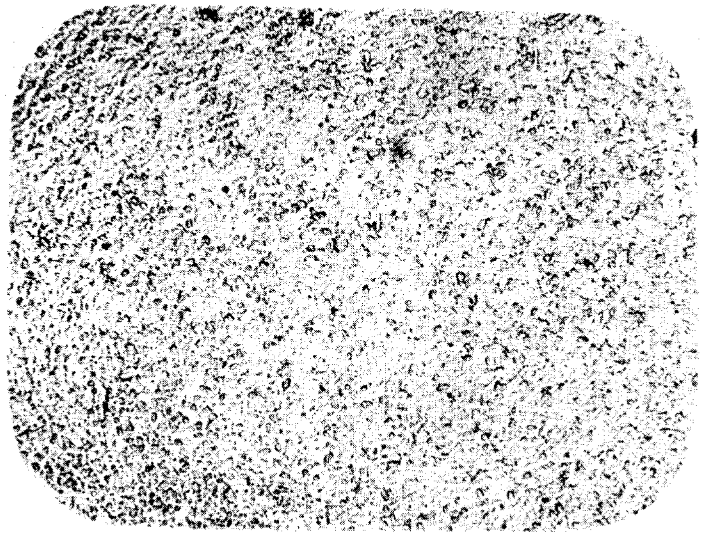


Fig. 1 **Plate** 29269-M
Magn. 500X **Diam. Etch.** 5% HF, 95% H_2O

Remarks:
Cross Section of Ti-150A, Bar 8 Illustrating small Grain Size of Sound Structure.

Fig. 2 **Plate** 29242-P
Magn. 100X **Diam. Etch.** HF and Water

Remarks
Cross Section of Ti-150A, Bar 3 Illustrating Very Large Tungsten Inclusion Near Edge.

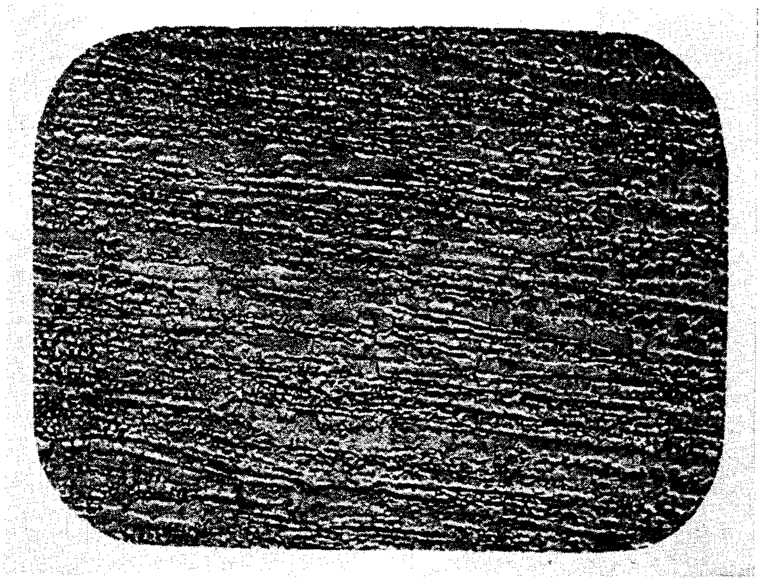


Fig. 3 Plate 29260-M
Magn. 500X Diam. Etch 3 Glycerin, 1 HF, 1 HNO_3
Remarks:
Section Taken in Direction of Rolling of Ti-150A, Bar 6 Illustrating Elongated Grains.

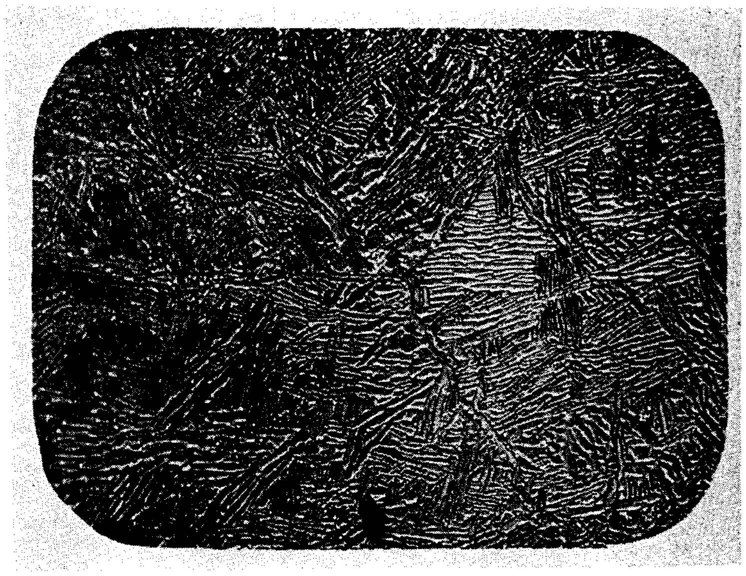


Fig. 4 Plate 29259-M
Magn. 500X Diam. Etch 3 Glycerin, 1 HF, 1 HNO_3
Remarks:
Cross Section of RC-130B, Bar 11 Illustrating Coarse Original Beta Grains, Transformation Platelets of Alpha in Retained Beta and minor amounts of Primary Alpha.

For both alloys, the mechanical properties were determined for a sample from each bar and are reported in Table III along with the values reported by the producers.

Table III - Mechanical Properties

Material (Specimen)	Bar. No.	Ultimate Tensile Strength (psi)	Yield Strength (psi)	Elongation in 1.5 in. (%)	Compressive Strength (psi)
Ti-150A (2) Producer's Values	—	140,000 to 160,000	120,000 min.	15 min.	—
Ti-150A Actual Values	1	142,900	127,800	23.5	140,200
	2	138,200	124,100	24.5	—
	3	147,000	131,000	19.5	129,800
	4	142,600	125,500	22.5	—
	5	155,000	140,800	23.5	—
	6	137,500	124,000	21.5	130,800
	7	137,300	122,000	23.5	—
	8	143,300	125,800	24.0	—
	Average	142,975	127,625	22.8	133,600
RC-130B (3) Typical Producer's Values	-	150,000	140,000	15	—
RC-130B Actual Values	11	159,200	154,400	11	—
	12	152,700	140,900	11	—
	13	152,500	149,900	12	—
	14	151,500	145,500	11.5	—
	15	152,200	144,900	13	—
	Average	153,620	147,120	11.7	—

PROCEDURE

The alloy bar stock was cut into pieces for fatigue and tensile testing, radiographed, made into specimens, and given the treatments previously outlined. Wherever possible specimens from each bar were used for each condition tested. All fatigue data and tensile data were recorded with particular attention paid to the extent of tungsten inclusions in each specimen.

Rotating beam fatigue specimens were made according to the dimensions shown in Air Force drawing X42A3150. The notched fatigue specimens were made to the dimensions shown in drawing X33A2648. The notch was a 60 degree "V" notch having 0.010 inch radius at the bottom. The notch gage diameter was the same as the gage diameter of the unnotched specimens. Tensile specimens were subsize with a gage section 3/8 inch in diameter by 2 inch gage length. The notched tensile specimens were of the same dimensions with a 60 degree "V" notch having 0.010 inch radius at the bottom, leaving a notch gage diameter of 0.05 inches less than the gage diameter of the unnotched specimens. The compression specimens were subsize with a gage section of 9/16 inch diameter by 1 inch gage length. The Charpy impact specimens had a cross section of 3/8 inch by 3/8 inch with a notch depth of 3/16 inch.

Machined specimens were turned in two operations. A rough cut, using speeds between 85 and 95 surface feet per minute and feeds between 0.003 to 0.008 inch per revolution was made with high speed tools. The finishing cut was made by carbide tip tools using a speed of 100 to 120 surface feet per minute and feeds between 0.002 to 0.004 inch per revolution. Less than 0.02 inch thickness of material was removed in the finishing operation. Machining operations were done dry except for thread cutting where a sulfurized oil was used for lubrication. The polishing operation was accomplished by a super-finisher using a Norton 500C 18T6 abrasive stone and kerosene lubricant.

Fatigue specimens which were ground were machined to 0.010 of their final gage diameter and then ground to final size. Grinding was done on a 46 grit size wheel, designation 32A46-H12VBCP, manufactured by Carborundum Company. A wheel with 60 grit size was tried but yielded poor results. A grinding solution of water and soluable oil was used. The method of grinding was by "plunge cut"; i.e. the wheel is formfitting and wide enough to accommodate the gauge length of a specimen so that the specimen is ground in one operation.

In order to minimize the warpage of samples which were scaled, the specimens were hung vertically in the scaling furnace, and only the sample's gauge section was ground to final size. After scaling, the gauge section of the specimen was carefully aligned in a lathe, and then the grips of the specimen were machined to final size.

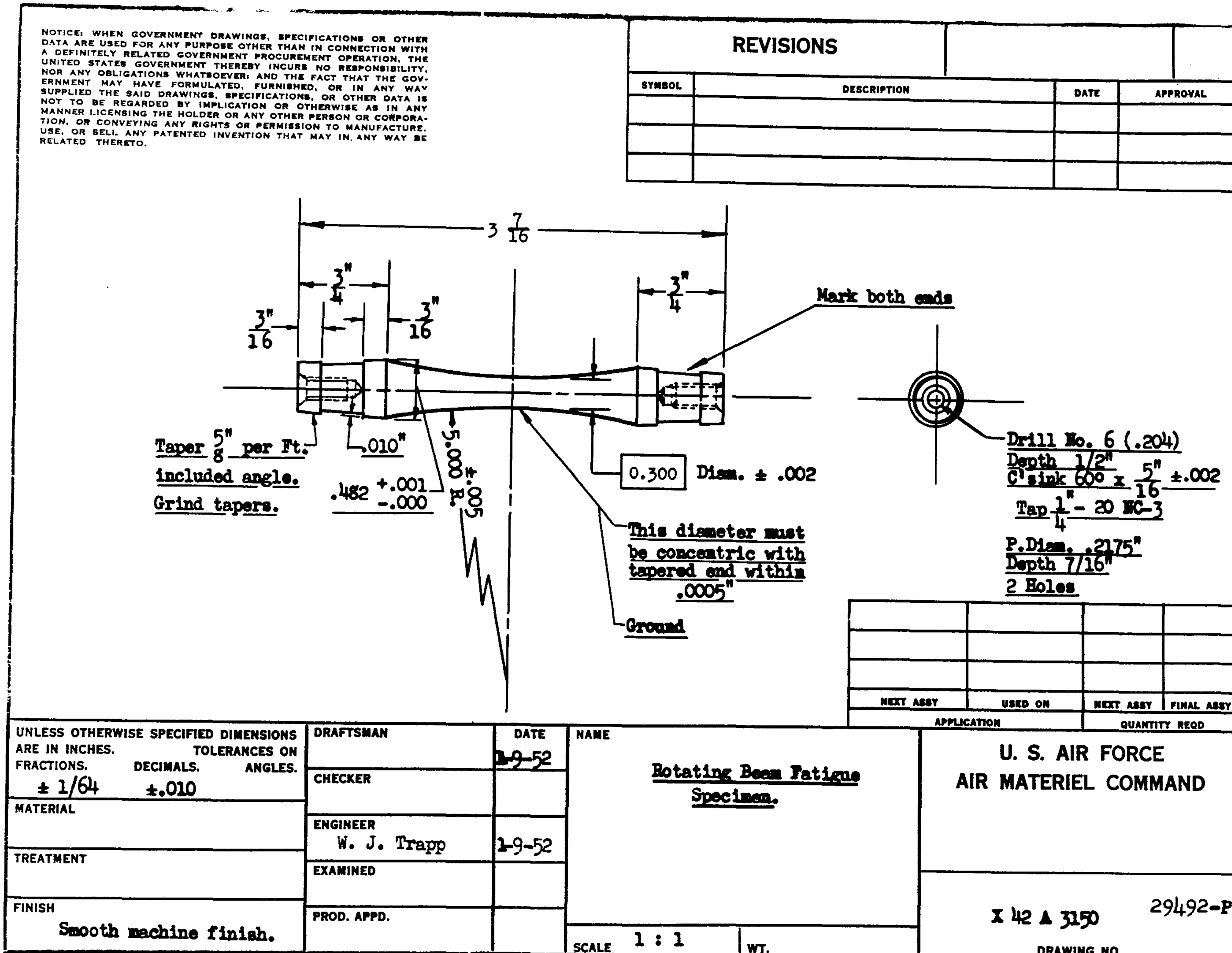


FIGURE 5. ROTATING BEAM FATIGUE SPECIMEN

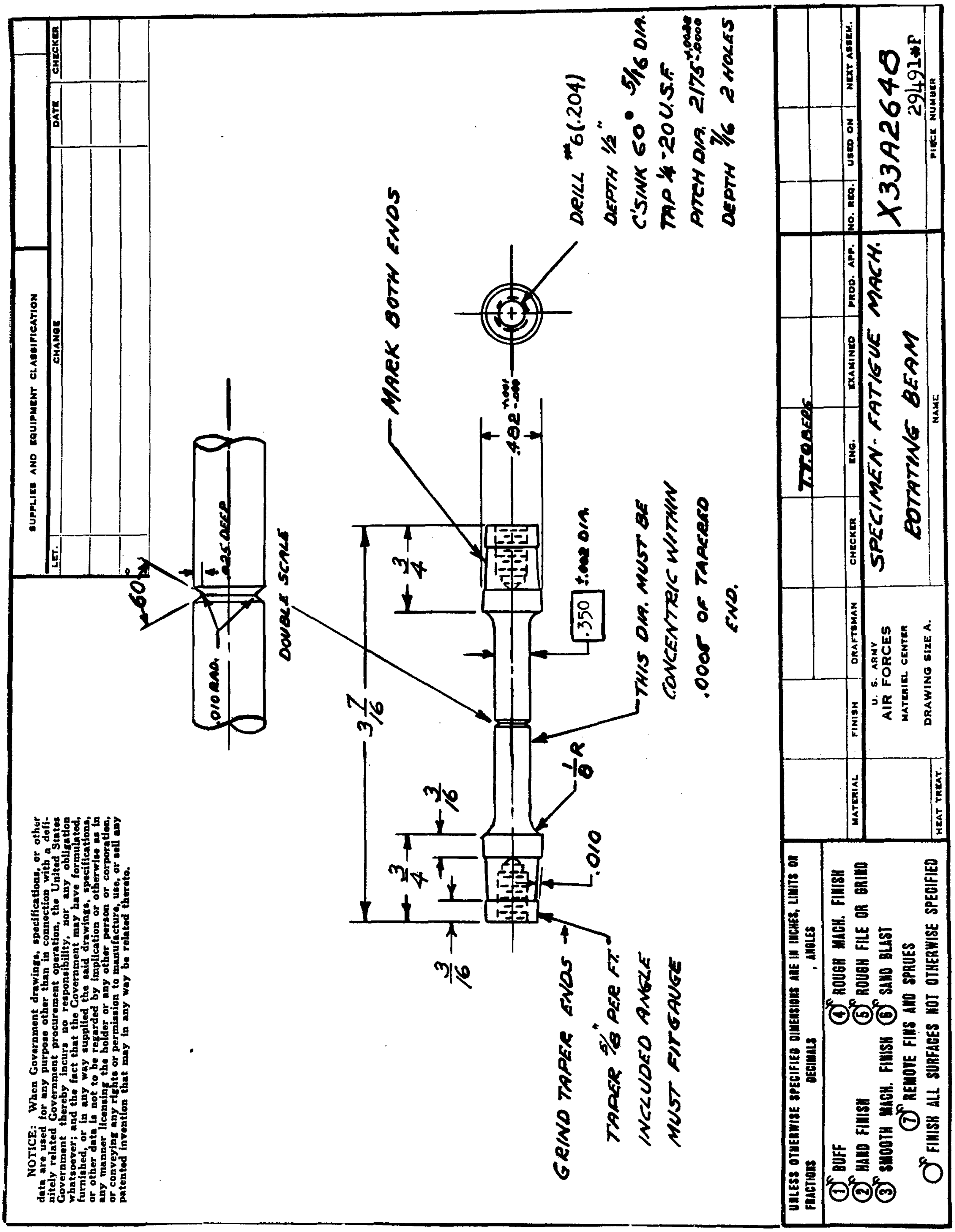


FIGURE 6. SPECIMEN-FATIGUE MACHINE ROTATING BEAM

RESULTS

The tensile properties of Ti-150A for the conditions tested are given in Table IV. The ground, scaled for one hour at 1300°F, and air cooled specimens gave approximately the same tensile properties as the as received bars. The 10 percent permanently stretched and ground specimens gave a greater tensile strength but less elongation than the as received bars due to cold work. The machined notched specimens exhibit tensile strengths slightly higher than the 10 percent stretched samples.

Table IV - Tensile Properties of Ti-150A For Different Treatments

Treatment	Mechanical Properties	Bar Number 1	3	6
Machined, Scaled For 1 Hour At 1300°F, and Air Cooled	Ultimate Strength (psi)	145,000	144,900	137,300
	Yield Strength (psi)	134,000	136,400	127,400
	Elongation in 1.5 in. (%)	22.0	22.5	22.5
10% Permanently Stretched And Ground To Final Dimensions	Ultimate Strength (psi)	162,800	167,200	155,500
	Yield Strength (psi)	158,000	161,100	146,900
	Elongation in 1.5 in. (%)	13.5	14.5	11.5
Machined Notched	Ultimate Strength (psi)	165,000	177,000	167,000
	Yield Strength (psi)	154,000	161,000	155,000
	Elongation in 1.5 in. (%)	1.5	2.0	2.5

The impact results for both alloys are recorded in Table V and are shown graphically in Figure 7.

Table V - Charpy Impact Properties

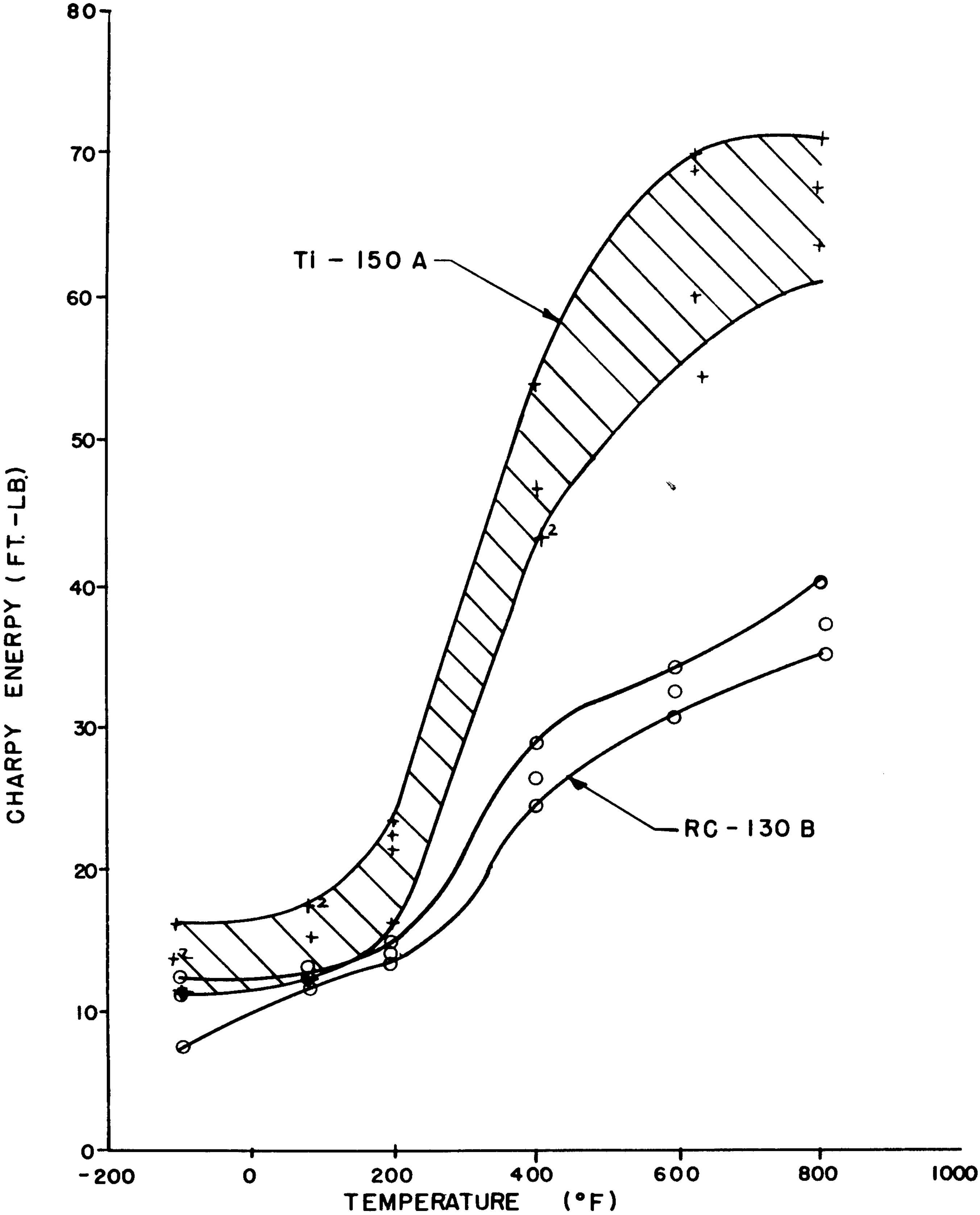
Alloy	Bar No.	Temperature (°F)					
Ti-150A	—	800	620	400	200	78	-100
Charpy Impact Energy (ft-lb.)	1	62	60	47	23	17	13
	2	—	51	43	21	17	13
	4	67	70	54	22	12	16
	5	71	69	43	16	15	11
RC-130B	—	800	600	400	200	75	-100
Charpy Impact Energy (ft-lb.)	12	40	34	29	14	12	11
	14	35	32	24	13	11	6.5
	15	37	30	26	14.5	12.5	12

The impact properties of Ti-150A are considerably higher than those of RC-130B. The transition temperature for both alloys was roughly 300°F but was much more pronounced for Ti-150A than for RC-130B. It should be noted in this comparison that Ti-150A had a lower tensile level than RC-130B in the as received states of the alloys.

The fatigue data determined for Ti-150A are given in Table VI and for RC-130B in Table VII. Figure 8 shows the "SN" curves for Ti-150A and Figure 9 shows the "SN" curves for RC-130B.

For Ti-150A, the different treatments and their corresponding endurance limits are as follows:

1. Machined and polished - 68,000 psi
2. Ground - 63,000 to 70,000 psi
3. 10% permanent stretch and ground - 54,000 psi (widely scattered data)
4. Ground and scaled - 56,000 psi
5. Machined and notched - 40,000 psi
6. Ground notched - 21,000 psi



CHARPY IMPACT ENERGY VS. TEMPERATURE

FIGURE 7

Table VI - Rotating Beam Fatigue Data of Ti-150A For Different Surface Treatments

Ground, Scaled 1 Hour At 1300°F, and Air Cooled			10% Permanently Stretched and Ground			Machined And Polished		
Bar No.	Stress (psi)	Cycles	Bar No.	Stress (psi)	Cycles	Bar No.	Stress (psi)	Cycles
2	70,000	58,700	1	70,000	2,217,900	4	75,000	74,000
3	65,000	78,000	2	65,000	7,658,000	4	72,000	528,000
4	60,000	388,000	3	62,000	1,442,000	7	70,000	15,375,000
5	58,000	1,953,000	6	60,000	71,000	7	70,000	23,422,000
6	57,000	3,583,000	4	60,000	3,963,000	4	68,000	150,000
7	56,000	25,000,000*	5	58,000	14,281,000	1	68,000	25,000,000*
8	56,000	40,000,000*	8	56,000	442,000	Others Failed in Grip		
1	55,000	35,000,000*	7	54,000	20,000,000*			
Ground Notched			**Machined Notched**			**Ground**		
1	50,000	13,500	4	50,000	34,000	2	80,000	41,000
2	40,000	29,200	5	43,000	14,444,000	3	75,000	37,900
4	35,000	47,000	6	42,000	14,049,000	4	75,000	125,000
5	30,000	91,000	7	41,000	309,000	6	72,000	85,500
3	30,000	815,000	8	40,000	4,487,000	7	72,000	92,200
6	28,000	129,000	3	40,000	20,000,000*	8	70,000	209,000
7	25,000	183,000	2	30,000	5,400,000 *	1	70,000	20,000,000*
8	21,000	20,000,000*	1	25,000	10,000,000*	1	70,000	30,000,000*
						3	67,000	64,400
						8	67,000	74,700
						2	65,000	20,000,000*
						5	64,000	80,800
						6	64,000	164,000
						7	60,000	20,000,000*

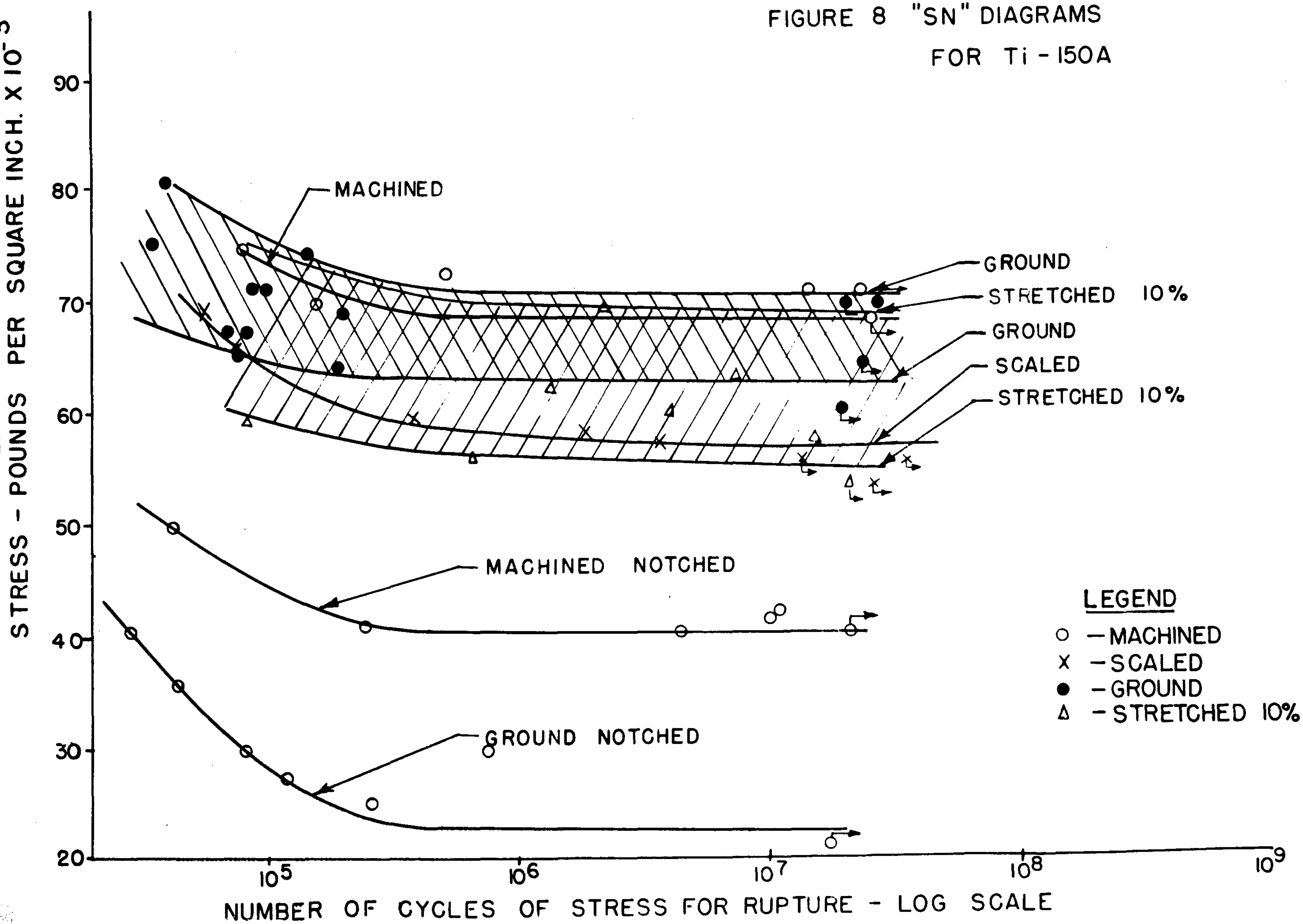
* - No failure

Table VII - Rotating Beam Fatigue Data of RC-130B
For Notched and Unnotched Specimens

Bar No.	Ground Stress (psi)	Cycles	Bar No.	Ground Notched Stress (psi)	Cycles
13	85,000	288,000	12	40,000	93,500
15	85,000	41,400	14	35,000	153,000
13	75,000	5,000,000*	11	30,000	276,700
15	75,000	76,600	13	28,000	351,000
11	70,000	131,000	15	26,000	337,400
13	70,000	188,000	14	25,000	795,000
14	69,000	90,000	12	25,000	25,000,000 *
14	68,000	112,000	14	23,000	20,000,000*
13	68,000	20,000,000*	—	—	—
12	65,000	20,000,000*	—	—	—
15	65,000	20,000,000*	—	—	—

* No failure

FIGURE 8 "SN" DIAGRAMS
FOR Ti - 150A



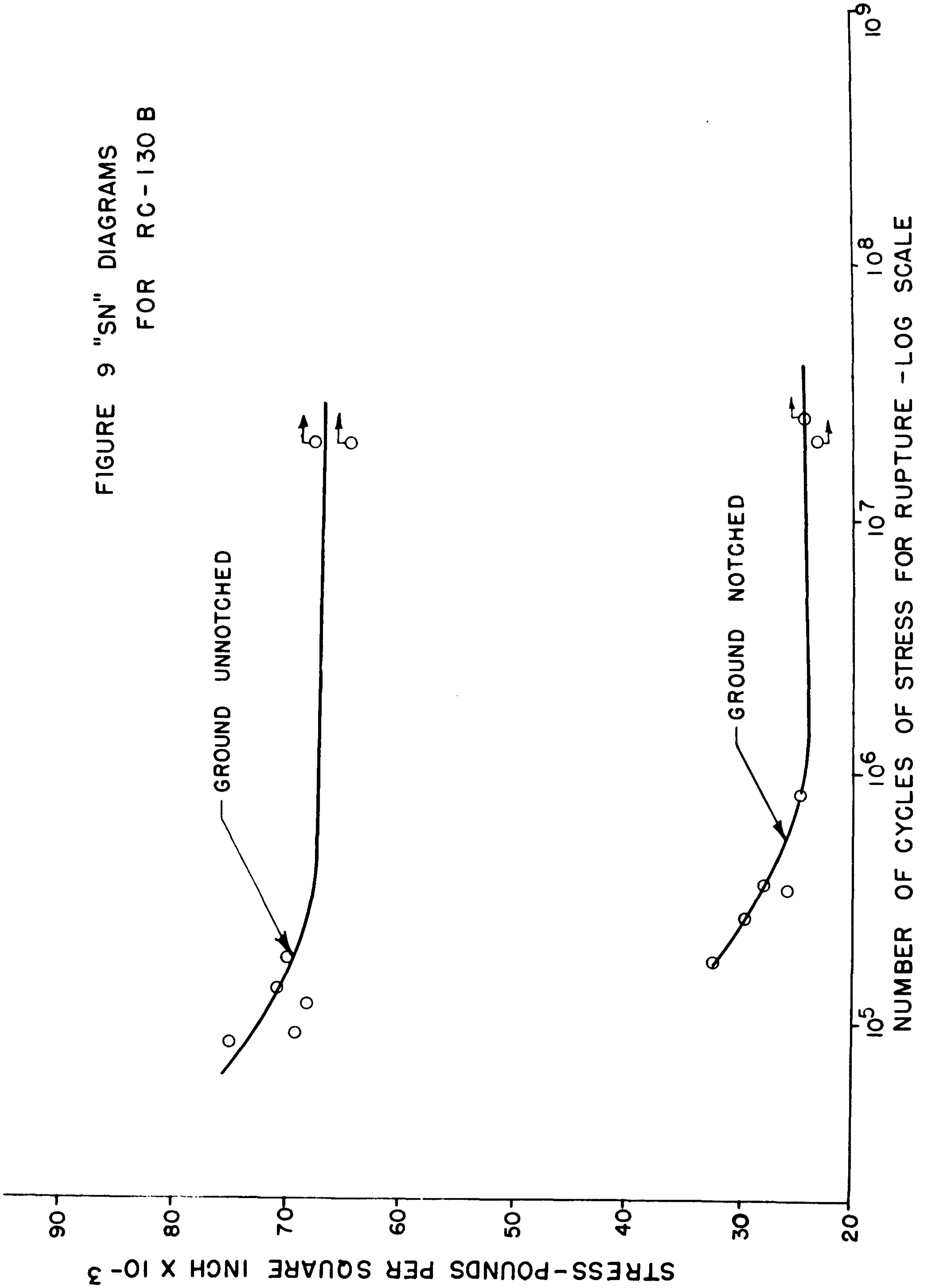


FIGURE 9 "SN" DIAGRAMS FOR RC-130 B

The range of fatigue values for the ground and for the 10 percent permanently stretched and ground specimens should be noted. Specimens with inclusions near the surface always gave results in the lower range of fatigue values, but some sound specimens also gave low results.

For Ti-150A, the fatigue strength varies between 35 to 45 percent of the tensile ultimate strength for the different conditions except for the notched specimens as should be expected.

RC-130B gave fatigue endurance limits of about 67,000 psi, approximately 45 percent of tensile ultimate strength, for the ground unnotched condition and about 24,000 psi for the ground notched condition.

CONCLUSIONS

The machined and polished fatigue specimens produced the highest fatigue strength, and in no case did the other treatments improve the fatigue strength of the titanium alloys. For stainless steels, cold work increases the fatigue strength as contrasted to the results obtained on Ti-150A. It does not seem probable that Ti-150A had been over cold worked, for a 10 percent stretch is well within the 15 percent minimum elongation of this alloy. The notch sensitivity of both alloys with respect to fatigue strength is greater than that for stainless steel.

The wide range of values for the ground Ti-150A alloy and for the 10 percent stretched and ground Ti-150A alloy may be due - besides tungsten inclusions - to various degrees of surface cold work, surface irregularities, and surface discontinuities caused by grinding and cold work. The very small range of values obtained for the ground and scaled, and machined and polished conditions is probably due to the more even surface conditions which results from these treatments.

The reason the ground unnotched RC-130B alloy specimens did not give a wide range of values is unknown. It should be noted, however, that a large grain size and very few homogeneously scattered tungsten inclusions were present in this alloy as compared to Ti-150A.

In general, the surface treatment to which titanium is subjected, will have a marked effect upon the fatigue strength, and for the conditions tested, a machined plus polished surface will give the optimum fatigue properties.

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