WADC TECHNICAL REPORT 54-546

PILOT PRODUCTION OF PROMISING ELEVATED TEMPERATURE TITANIUM-BASE ALLOYS

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FOREWORD

This report was prepared by the Armour Research Foundation under USAF Contract No. AF 33(616)-2060. This 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. G. Hahn acting as project engineer.

Armour Research Foundation personnel who contributed to the project were: Messrs. Donald H. Turner and Benjamin R. Rajala who served as project engineers, Mr. Harold D. Kessler and Dr. Donald J. McPherson who served consecutively as supervisors, and Dr. Frank A. Crossley who served as consultant.

This report covers period of work from May 1, 1953 to March 31, 1955.

ABSTRACT

Melting procedures and equipment to produce ingots weighing up to 100 pounds of promising titanium-base alloys developed under Air Force Contract No. AF 33(038)-22806 are described. In order to furnish ingots of this size, it was necessary to expand the existing arc melting facilities substantially. A non-consumable electrode arc furnace of 20-pound capacity employing a magnetic field to direct the arc was designed and fabricated. The capacity of the consumable electrode furnace previously developed at Armour Research Foundation was increased to a theoretical maximum of 300 pounds of titanium by the incorporation of a continuous casting mechanism and increasing the diameter of the mold. Ingots weighing up to 113 pounds and up to 6 inches in diameter were successfully cast. Titanium-base alloy stock of the following compositions was supplied to the Air Force's contractors: (1) 6% aluminum, (2) 6% aluminum-4% vanadium, (3)6% aluminum-0.5% silicon, and (4) 7% aluminum-3% molybdenum. It was recommended that the 6% Al-0.5% Si alloy be dropped from the program since it proved to embrittle upon exposure to elevated temperature creep conditions.

Evaluation reports were received from Pratt & Whitney Aircraft Division of United Aircraft, Wright Aeronautical Division of Curtiss-Wright and the General Electric Company, Aircraft Gas Turbine Division. These reports cover only the 6% Al alloy. In general, the 6% Al alloy was found to possess good creep resistance, good weld bend characteristics and satisfactory fatigue properties. With a load of 40,000 psi at 800°F for 300 hours, a creep extension 0.08% was obtained. An as-welded bend ductility of 3.5 T and endurance limits of 55,000 and 60,000 psi were found. The alloy meets several of the requirements originally listed as desirable for titanium-base alloys early in the program.

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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I. INTRODUCTION

A number of titanium-base alloys developed under Air Force Contract No. AF 33(038)-22806 warrant consideration for application in jet engines. This report summarizes the accomplishments in supplying pilot quantities of these alloys in the form of ingots, plate, sheet, rod and strip for thorough laboratory investigation and for tests and evaluation as prototype engine parts under Air Force Contract No. AF 33(616)-2060. A review of some of the results of these test programs is included. The period covered by this work is May 1, 1953 to March 31, 1955.

II. EXPERIMENTAL PROCEDURE

A. Preparation of Alloys

1. Materials

Magnesium reduced titanium sponge was used for the preparation of all alloys. Prior to melting, the sponge was screened to remove all -20 mesh material and put through a magnetic separator to remove any particles with entrapped iron. Average Brinell hardnesses of 124 and 121 were obtained on arc melted samples of the sponges. Chemical analyses of the two sponge lots are given in Table I.

High purity commercial alloying agents in elemental form and as master alloys were used in the preparation of all alloys except the 7% Al-3% Mo alloys melted in recent months. These were prepared using an aluminum-molybdenum master alloy arc melted at the Foundation. A summary of the chemical analyses and sources of the commercial materials is presented in Table I.

Ham and Herzig(1) reported the presence of a eutectic at 1760°C and 22% aluminum in the Mo-Al system. Noting the general proximity of the melting point of this alloy to that of pure titanium, it appeared to be an excellent possibility for a master alloy. Inquiries were made into the commercial availability of the alloy but no sources were found for a material of the purity desired.

Two-hundred gram buttons of the alloy were prepared from high purity aluminum shot and scrap molybdenum sheet in a tungsten-tipped electrode arc furnace under a slight positive pressure of helium. The buttons obtained were extremely friable and easily crushed to -8 +28 mesh. Chemical analyses of a number of samples were in the range 23.2 to 23.9% aluminum.

TABLE I

MATERIALS

Element	Form	Source	Purity	Impurities, %
Aluminum	Granulated Shot	Aluminum Company of America	99.81	0.12 Fe, 0.07 Si
Molybdenum	Sheet	Fansteel Metallurgical Corp.	99.9+	
Silicon	Powder	Electro Metallurgical Co. Div. Union Carbide & Carbon Corp.	99.86	0.03-0.08 O, 0.02-0.04 C, 0.02-0.03 Al, 0.005-0.015 Fe, 0.005-0.010 Pb, Trace - 0.010 Ca
Titanium	Sponge "O"	E. I. DuPont de Nemours & Co.	124 BHN	0.024 C, 0.19 Fe, 0.014 max. N, 0.03 Si
Titanium	Sponge "T"	E. I. DuPont de Nenours & Co.	121 BHN	0.029 C, 0.017 Fe, 0.010 N
Titanium-Molybdenum Master	Machined Chips	Climax Molybdenum Co.	99.7	33.0 Mo, 0.035 N
Vanadium-Aluminum Master	Chips	Electro Metallurgical Co. Div. Union Carbide & Carbon Corp.	99.0	84.17 V, 13.99 Al, 0.03 C, 0.50 Fe, 0.40 Si

2. Melting Technique

All the ingots were prepared by the double arc melting process. This process consists essentially of melting the sponge and alloy additions in a non-consumable tungsten-tipped electrode arc melting furnace, forging the resulting ingot to rod, removing the as-forged surface of the rod by centerless grinding, and then remelting the rod as a consumable electrode in another arc furnace. This double arc melting has resulted in much improved alloy homogeneity for the following reasons:

(1) All of the metal, including high melting point additions, which may not have been completely dissolved during the first melting operation, must pass through the intense heat of the arc on remelting.

(2) A larger and hotter molten pool is maintained in the consumable electrode furnace than in the non-consumable type because higher currents are applied.

B. Melting Equipment

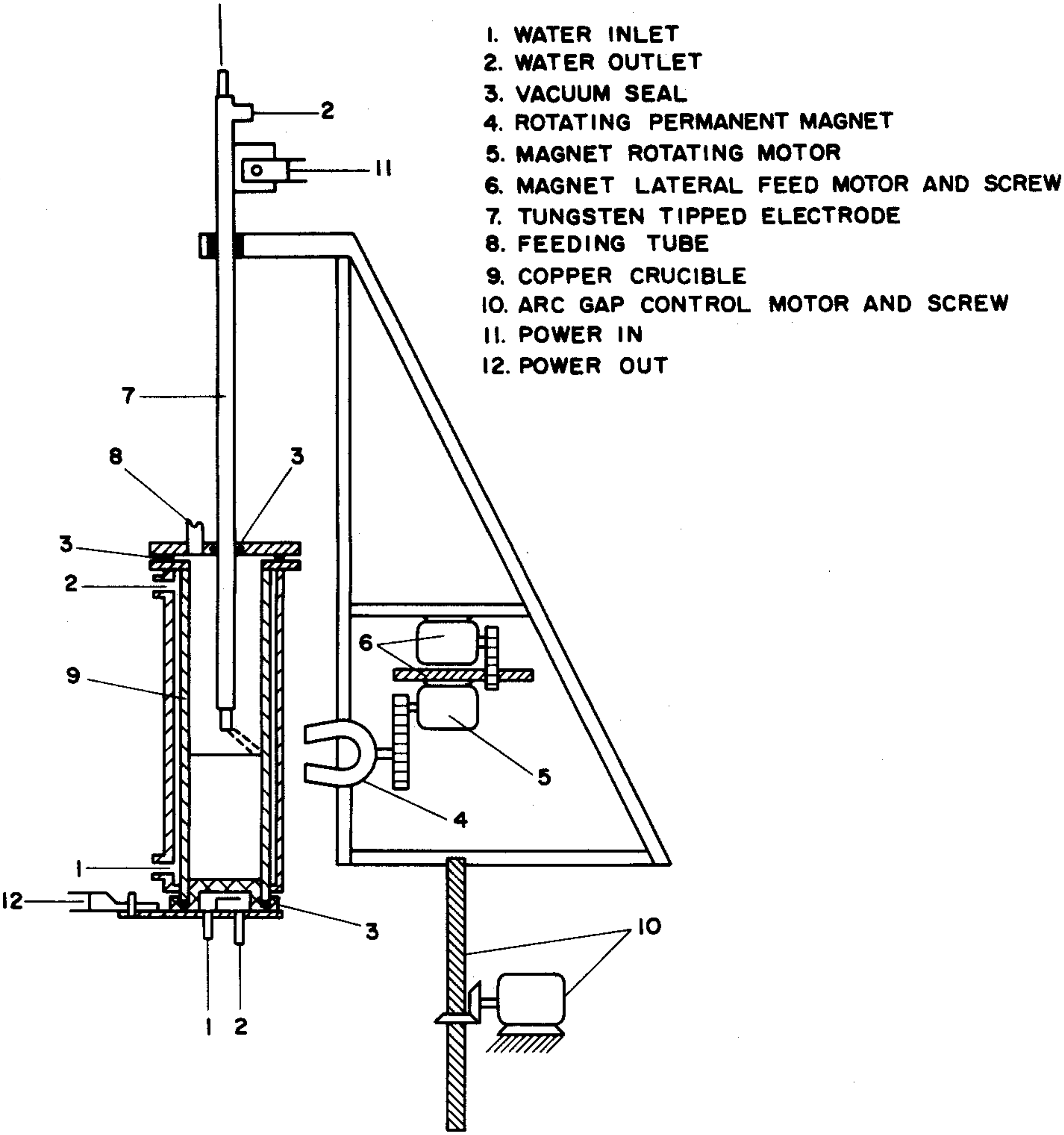
Considerable expansion of the existing arc melting facilities was necessary in order to produce the large ingots demanded by the "Pilot Production" program. This expansion involved the construction of a non-consumable electrode arc furnace of 20-pound capacity and increasing the capacity of the consumable electrode furnace as subsequently described.

1. Non-Consumable Electrode, Rotating Arc Melting Furnace

A non-consumable tungsten-tipped electrode arc melting furnace of 20-pound capacity which utilizes a rotating magnet to move the arc around the bath is shown schematically in Figure 1. A water jacketed, 4 in. I.D., 1/4 in. wall, copper tube and a detachable water cooled bottom serves as the ingot mold. The furnace top which contains the sight, feed, gas and vacuum tubes is fabricated from 1/2 in. brass plate. All vacuum and water seals are formed by flat neoprene gaskets or "O" rings. Electrical insulation between the top and the crucibles is provided by a Bakelite ring. A belt type charging hopper serves as the raw material reservoir.

A large horseshoe magnet is used to rotate the arc. The magnet is rotated about a horizontal axis at 4 revolutions per minute and is moved laterally along this axis to control the position of the arc. Motions of the magnet are controlled automatically except to throw the reversing switch for lateral motion at the end points of the lateral path.

Prior to operating the furnace the negative electrode is positioned vertically through a sliding seal in the furnace top so that the tungsten tip intersects the rotational axis of the magnet. The electrode is clamped rigidly into position with an electrically insulated collet. This collet, being a part of the magnet carrier, makes the electrode and magnet carrier an integral unit. The arc length is controlled by an electric motor and screw drive (Figure 1, No. 10) which raises or lowers the electrode and magnet carrier at the rate of eight inches per minute.



1. WATER INLET
2. WATER OUTLET
3. VACUUM SEAL
4. ROTATING PERMANENT MAGNET
5. MAGNET ROTATING MOTOR
6. MAGNET LATERAL FEED MOTOR AND SCREW
7. TUNGSTEN TIPPED ELECTRODE
8. FEEDING TUBE
9. COPPER CRUCIBLE
10. ARC GAP CONTROL MOTOR AND SCREW
11. POWER IN
12. POWER OUT

FIG. 1 - ROTATING ARC NON-CONSUMABLE ELECTRODE FURNACE

Both 1 and 3/4 in. diameter tungsten tips were used. The 3/4 in. tip was found to be more satisfactory because it proved very difficult to effectively cool the 1 in. diameter tip. A rather large buildup of spatter on the tip generally occurred, leading to a very erratic arc. Tungsten losses with the 3/4 in. diameter tip were generally lower and no difficulties with spatter buildup were encountered.

Power is supplied to the furnace by two 600-ampere Lincoln DC welding generators in parallel. Melting is normally carried out at 1000 to 1100 amperes and 25 to 30 volts except when charging additional material; then the current level is reduced to about 500 amperes.

The ingots produced usually required some grinding to remove the surface defects inherent with this melting technique. Ten-pound ingots were generally cast. Ingots of this size could be melted without any difficulties due to impeded vision of the operation caused by the condensation of $MgCl_2$ on the sight ports. Also, ingots of this size could be forged into convenient lengths of 1 in. diameter rods for remelting. In the later stages of the project, electrodes of 1-1/2 in. diameter were forged from the 10-pound ingots in order to reduce forging costs and the extent of contamination. The forged rods were centerless ground, removing approximately 0.040 in. from the diameter, and threaded together for remelting as a consumable electrode.

2. Consumable Electrode Arc Melting Furnace

A consumable electrode arc melting furnace of 10-pound capacity had previously been developed at the Armour Research Foundation. A General Electric automatic arc welding control, employing a Thyratron control circuit to automatically relate arc voltage to electrode feed rate, served to continuously feed the electrode as melting progressed in a water-cooled copper crucible. Two 500-ampere AC arc welding transformers in parallel supplied the power.

Extensive modification of the furnace was necessary in order to produce the 4 to 6 in. diameter ingots weighing up to 100 pounds required by the program. An ingot retracting mechanism was incorporated so that continuous casting of ingots up to 36 in. long could be accomplished. The mechanism consists essentially of a variable speed motor reducer coupled to an Acme screw which is rigidly attached to the detachable crucible bottom. The available power was increased to approximately 2500 amperes by the addition of two 500-ampere AC arc welding transformers. Crucibles, similar to the ingot molds, of 4, 5, 6 and 8 in. ID were designed and fabricated, giving the furnace a theoretical maximum capacity of 300 pounds of titanium.

An electrode feed mechanism capable of accommodating 1/2 to 1 in. diameter electrodes interchangeably was designed and fabricated with the dual purpose of serving as the electrical contact. The mechanism consists essentially of two hardened steel drive wheels with opposing spring-loaded molybdenum idling wheels on tubular shafts so that water cooling can be introduced. The mechanism was recently rebuilt to drive 1-1/2 in. diameter electrodes.

In addition, it was found necessary to add considerable water cooling to the feed mechanism housing, as severe overheating occurred in early attempts at making large melts. A molybdenum shield to deflect spatter back into the molten pool was also found necessary to eliminate jamming of the feed mechanism gearing by spatter. A schematic diagram and a photograph of the modified consumable electrode furnace are shown in Figures 2 and 3.

The surface quality of ingots cast directly in the water-cooled copper mold was sometimes such that considerable scalping of the as-cast ingot was required before final forging. It was necessary in one instance to scalp as much as 1/2 in. from a 6 in. diameter ingot. In order to improve surface quality, a 5/16 in. wall crucible liner was fabricated of AUC grade graphite. This graphite liner slip fits inside the copper mold to serve as thermal insulation between the molten pool of metal and the water cooled copper wall of the crucible. By keeping the graphite sufficiently cool to prevent wetting by the molten titanium, no contamination occurs.

With the addition of a simple clamping device to grip the graphite liner, it is possible to continuously cast ingots of good surface quality requiring the scalping of less than 1/8 in. from the as-cast ingot. Practically no abrasion of the liner occurs during continuous casting. A few surface hot tears are encountered but these are easily removed by grinding. Figure 4 shows the 6 in. crucible with the graphite liner and a 113-pound, 6% Al ingot as-cast. The original graphite liner was used for five melts before replacement was necessary; then the abrasion resulting from removing the ingot from the crucible after cooling was the only cause for replacement.

Prior to melting, the system is evacuated and flushed twice with argon and then filled to a slight positive pressure of argon. Melting is started by striking an arc between the lower end of the alloy electrode and a "stool" of the same alloy composition, which is secured to the mold base. The electrode is continuously fed downward to maintain a steady arc of 30 to 35 volts and 2000 to 2300 amperes. When the ingot has been built up to approximately 8 in., the positive pressure of argon is increased to 4 pounds and the ingot retracting mechanism is started and adjusted to the casting rate. The positive pressure of argon is sufficient to maintain a steady flow of argon around the hot ingot inside the crucible. The portion of the ingot outside of the crucible is at a red heat causing some slight surface contamination. However, this is much less severe than that encountered in a normal forging operation. The portion of the ingot remaining in the crucible is uncontaminated as can be seen in Figure 4.

C. Forging Practice

All forging for this program was accomplished by Lawndale Forging and Tool Works under the direct supervision of Foundation personnel. Drop forges with flat and swaging dies were used. Gas fired furnaces were used for heating during the first year of work. Electric furnaces have since been adopted. Maximum forging temperatures for the alloys prepared ranged from 1090° to 1150°C (2000° to 2100°F), depending upon the alloy and the application (see Table II).

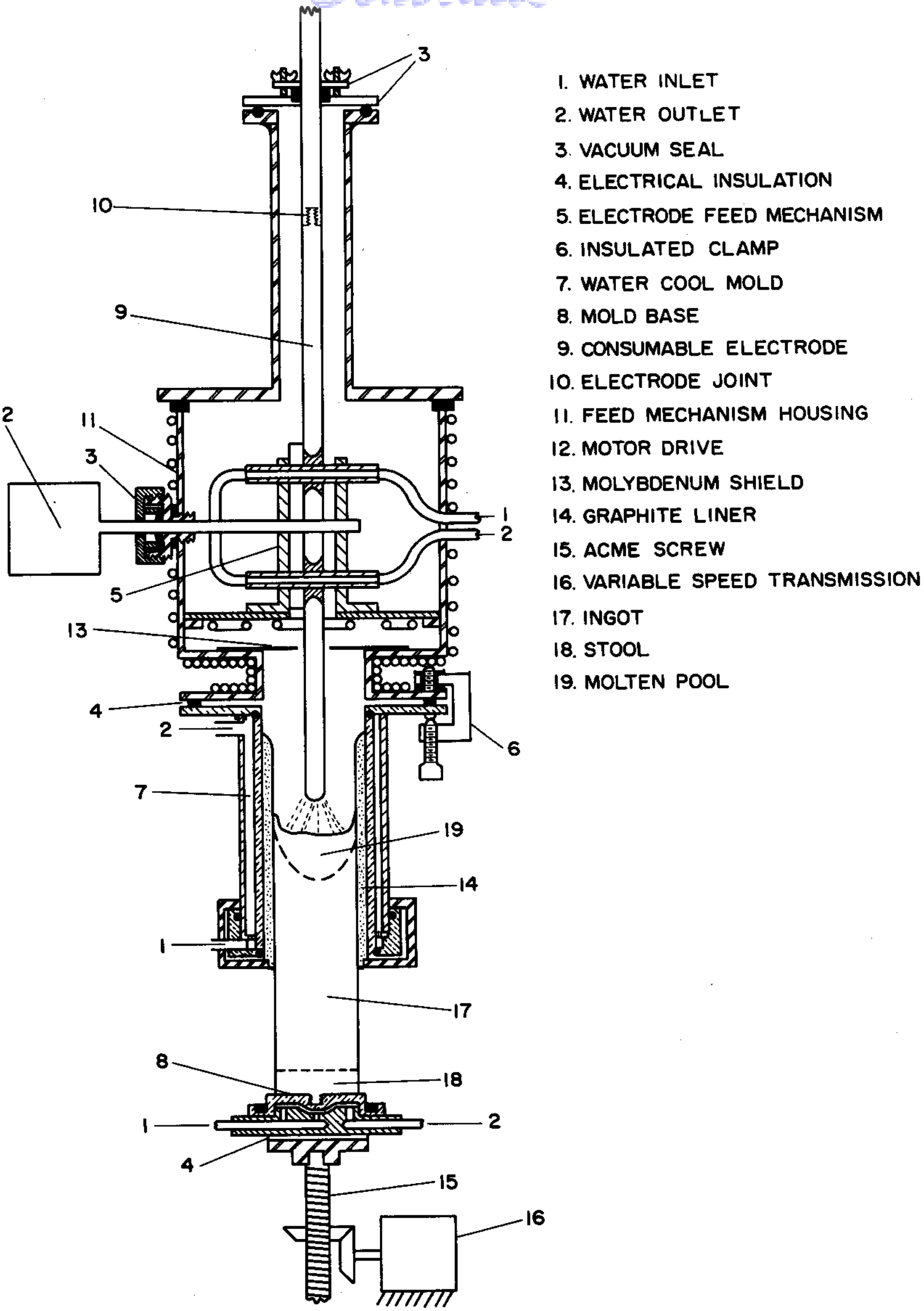


FIG. 2 - SCHEMATIC DRAWING OF CONSUMABLE ELECTRODE FURNACE

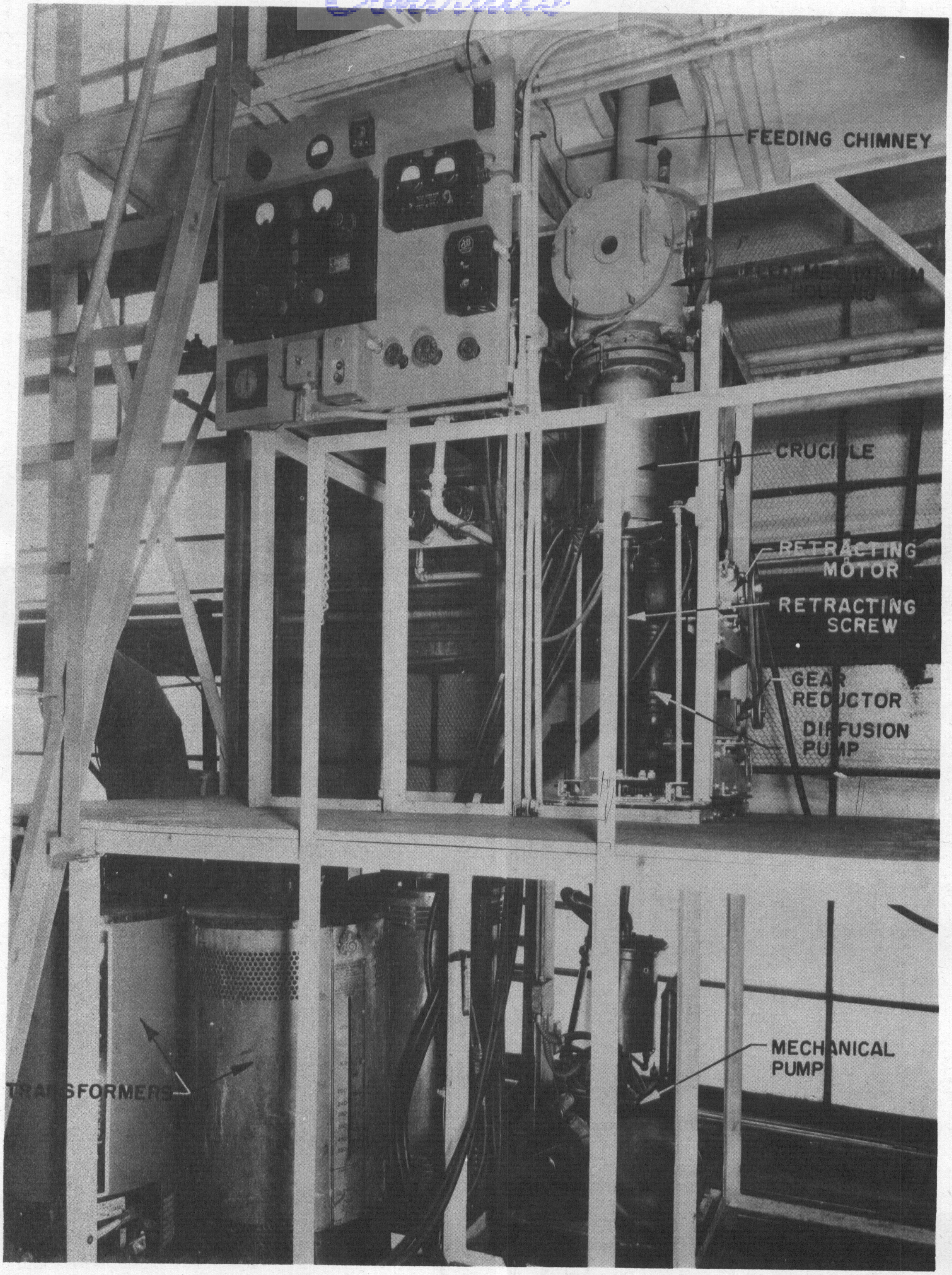


FIG. 3 - CONSUMABLE ELECTRODE FURNACE

FIG. 4 - SIX INCH CRUCIBLE WITH GRAPHITE LINER AND A 113-POUND Ti-6% Al INGOT AS CAST

TABLE II

APPROXIMATE MAXIMUM FORGING TEMPERATURES

Alloy Composition	Forging Temperature, °C (°F)
6% Al	1090 (2000)
6% Al-4% V	1090 (2000)
6% Al-0.5% Si	1150 (2100)
7% Al-3% Mo	1090 (2000)

D. Rolling Practice

Rolling of plate and sheet less than 12 in. wide was done at the Armour Research Foundation. All rolling of rod and sheet wider than 12 in. was done by the Republic Steel Corporation, Massilon, Ohio. Maximum rolling temperatures for the alloys rolled at Armour ranged from 900° to 955°C (1650° to 1750°F). Electric furnaces were utilized for the heating of this material.

III. SUMMARY OF STEERING COMMITTEE MEETINGS

Steering committee meetings were held on December 7, 1953 and June 16, 1954 at the Armour Research Foundation. These meetings were held to familiarize jet engine manufacturers' representatives with promising titanium-base alloys for elevated temperature applications and to determine the distribution of pilot quantities of the alloys selected for evaluation. The selection of alloys was made by the jet engine representatives.

The meetings were conducted as follows:

After the introductions were made, the purpose of the meeting and the scope and purpose of the program was stated. Thereafter Dr. F. A. Crossley presented tensile, creep and stress-rupture data on the most promising alloys developed and tested under Contract No. AF 33(038)-22806. The data presented at these meetings may be found in the summary report WADC TR 54-278, Part I for this contract. Immediately following, a round table discussion was held at which time the manufacturers' representatives expressed their views on titanium alloys currently in application, the properties desired for future applications, and the ARF alloys they considered most promising. Finally, the distribution and allocation of pilot quantities of the alloys was jointly determined by the engine manufacturing representatives and the Foundation. The alloys selected and quantity requested are listed in Table V.

Participants at the December 7, 1953 meeting were:

Materials Laboratory, WADC - Maj. R. J. Kotfila and Lt. A. Forrest

General Electric (A.G.T. Division) - Messrs. W. C. Kunkler, R. A. Baughman and J. E. Fox

Pratt & Whitney Aircraft - Mr. R. H. Thielemann

Allison Division of General Motors - Mr. P. E. Hamilton

Wright Aeronautical - Mr. L. A. Luini

Republic Steel - Mr. V. W. Whitmer

Armour Research Foundation - Dr. M. Hansen, Mr. H. D. Kessler, Dr. F. A. Crossley, Messrs. W. F. Carew and D. H. Turner

Participants at the June 16, 1954 meeting were:

Materials Laboratory, WADC - Maj. R. J. Kotfila, Lt. G. Hahn and Mr. E. Hassell

General Electric (A.G.T. Division) - Messrs. R. A. Baughman and G. Wile

Pratt & Whitney Aircraft - Mr. R. H. Thielemann

Wright Aeronautical - Mr. L. A. Luini

Republic Steel - Mr. V. W. Whitmer

Armour Research Foundation - Dr. M. Hansen, Mr. R. A. Lubker. Drs. D. J. McPherson and F. A. Crossley, Messrs. W. F. Carew and D. H. Turner

In the general discussions the significant points made were as follows:

To be desirable for jet engine applications, the forgeable titanium-base alloys should have 0.1 to 0.3% creep extension in 500-1000 hours at 800°-900°F under stress of 40,000-60,000 psi; 0.1 and 0.2% offset yield strengths of 110,000 and 120,000 psi, respectively; 15% minimum elongation, and 60,000-65,000 psi endurance limit as bar; a minimum of 35-40% reduction in area, plus a limiting specification of 150 parts per million of hydrogen.* For sheet applications, the properties desired were variously expressed as follows:

(1) Sheet having 0.1-0.3% 1000 hour creep extension at 650°F under stress of 80,000 to 90,000 psi.

(2) Sheet alloy having 1% creep extension in 1000 hours at any temperature under a stress of 40,000 psi.

The alloys currently in use are C-130 AM, Ti-140 A and Ti-155 A, but these are unsatisfactory for most future applications.

IV. SUMMARY OF ALLOYS PREPARED AND DISTRIBUTED

A list of all ingots prepared under this program is given in Table III. The as-cast weights of the ingots include the stool which was subsequently cut off and re-used in most cases. The 5-1/2 in. diameter ingots were cast in the graphite liner. All other ingots were cast in the water cooled copper mold. The results of chemical analyses of turnings from various sections of the ingots are presented in Table IV. A good degree of homogeneity is indicated. Materials requested by and supplied to the various participating agencies are summarized in Table V. All materials requested were either supplied directly or sent to the Republic Steel Corporation for rolling to the specified dimensions.

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*It should be noted that since the above meeting was held limits for hydrogen content have been set as follows: sheet 150 ppm, bar 125 ppm.

TABLE III

COMPOSITION AND WEIGHT OF INGOTS CAST

Nominal % Composition	Melt No.	Sponge Used	Diam. in.	As-Cast Weight, lbs.	Scalped Weight, lbs.
6 Al	313	0	6	40	20
	322	0	6	47	24
	347	0	6	62	41
	348	0	6	64	45
	398	0	5-1/2	113	90
	484	0	6	53	45
6 Al-4 V	433	0	5-1/2	35	30
	434	0	5-1/2	30	20
	445	0	6	40	34
	540	0	4	9	8
	590	T			
	595	T	5-1/2	40	33
6 Al-0.5 Si	446	0	5-1/2	89	74
7 Al-3 Mo	483	0	4	20	18
	532	0	5-1/2	35	30
	569	T	5-1/2	80	57
	580	T	6	76	63
	604	T	6	57	47

TABLE IV

CHEMICAL ANALYSES OF INGOTS

Nominal % Composition	Melt No.	Sample Location	Results of Analyses					
			% Al	% V	% Si	% Mo	% N_2	% C
6 Al	313	Top	6.15				0.017	
		Bottom	6.20				0.016	
	322	Top	6.08				0.019	
		Middle	6.11				0.018	
		Bottom	6.12				0.019	
	347	Top	6.14				0.012	
		Bottom	6.23				0.012	
	348	Top	6.12				0.017	
		Bottom	6.20				0.018	
	398	Top	6.30				0.017	
		Middle	6.22				0.018	
		Bottom	6.21				0.020	
	484	Bottom	6.06				0.032	
6 Al-4 V	433	Top	6.12	4.15			0.020	0.044
		Bottom	5.81	4.04			0.020	0.052
	434	Top	5.88	4.71			0.026	
		Bottom	5.96	4.74			0.032	
	445	Bottom	5.95	4.03			0.021	
	540	Bottom	5.96	4.20			0.032	
	590	Bottom	6.23	4.33			0.046	0.049
	595	Side	6.25	4.10			0.012	0.044
		Bottom	6.25	4.12			0.011	0.054
6 Al-0.5 Si	446	Middle	6.00		0.50		0.030	0.020
7 Al-3 Mo	483	Bottom	7.30			3.23	0.034	
	532	Bottom	7.25			3.07		
	569	Top	7.38			3.25	0.019	0.052
		Middle	7.27			3.28	0.021	0.044
		Bottom	7.12			3.22	0.020	0.049
	580	Top	7.24			2.97	0.016	0.052
		Bottom	7.32			3.05	0.014	0.060
		Side	7.22			3.19	0.014	0.057
	604	Side	6.92			3.16	0.020	0.051

TABLE V

MATERIALS REQUESTED AND SUPPLIED

Organization	Alloy	Requested		Supplied			Date Shipped
		Size	Amount	Melt No.	Size	Quantity	
Allison Div. of General Motors	6 Al	3/4-1 in. round	10 ft.	322	13/16 in. round	10-1/2 ft.	11-23-53
	7 Al-3 Mo	3/4-1 in. round	10 ft.	483	1 in. round	10 ft.	6-3-54
	6 Al-0.5 Si	3/4-1 in. round	10 ft.	446	1 in. round	10 ft	5-4-54
	6 Al-4 V	5/8 in. round	30 ft.	595	5/8 in. round	31 ft.	11-19-54
General Electric (A.G.T. Division)	6 Al	6 in. dia.	50-lb ingot	348	5-1/2 in. dia.	45-lb ingot	12-4-53
	6 Al-4 V	0.060 x 10 in. sheet	6 sq. ft.	445	0.060 x 10 in. sheet	8 sq. ft.	5-7-54
	6 Al-4 V	1/4 x 1 in. strip	28 ft.	590	1/4 x 1 in. strip	23 ft.	11-24-54
	6 Al-0.5 Si	6 in. dia.	50-lb ingot	446	5 in. dia.	48-lb ingot	5-6-54
	7 Al-3 Mo	3/4 in. round	50 ft.	569		(a)	11-11-54
Pratt & Whitney Aircraft	6 Al	7/8 in. round	60 ft.	347	7/8 in. round	36	12-16-53
				398	7/8 in. round	24	3-26-54
	6 Al-4 V	7/8 in. round	60 ft.	483, 434, 445	7/8 in. round	54	4-23-54
	7 Al-3 Mo	3/4 in. round	50 ft.	569, 580		(a)	11-11-54
Sylvania Electric Products, Atomic Energy Division	6 Al-4 V	3/8 x 5 x 24 in.	1 piece	532	3/8 x 5 x 24 in.	1 piece	8-10-54
Wright Aeronautical Div. of Curtiss-Wright Corp.	6 Al	1/2 in. round	20 ft.	313	9/16 in. round	22 ft.	11-23-53
	6 Al	3/8 in. round	150 ft.	313, 322	7/16 in. round	68 ft.	11-23-53
				398	1/2 in. round	46 ft.	3-26-54
				484	1/2 in. round	98 ft.	6-3-54
	6 Al	0.060 x 20 in. sheet	15 sq. ft.	398	10 x 20 x 3/4 in.	(b)	3-29-54
	7 Al-3 Mo	1/2 in. round	25 ft.	580		(a)	11-11-54
	7 Al-3 Mo	3/4 in. round	25 ft.	580		(a)	11-11-54

TABLE V (continued)

MATERIALS REQUESTED AND SUPPLIED

Organization	Alloy	Requested		Melt No.	Supplied		Date Shipped
		Size	Amount		Size	Quantity	
Materials Laboratory, WADC	6 Al-0.5 Si	1/2 x 2 x 24 in.	1 piece	446	1/2 x 2 x 24 in	1 piece	5-4-54
	6 Al-4 V	1/2 in. round	25 ft.	590	1/2 in. round	24 ft.	11-5-54
	7 Al-3 Mo	1 x 12 x 12 in.	1 piece	532	1 x 12 x 12 in.	(c)	7-28-54
Eaton Manufacturing Co.	7 Al-3 Mo	5/16 x 1-8/8 in. strip	50 ft	604	5/16 x 1-7/8 in. strip	38 ft.	3-24-55

(a) Billet sent to Republic Steel Corporation for rolling to rod of requested dimension.

(b) Slab sent to Republic Steel for rolling to 20 in. wide sheet.

(c) Slab sent to Republic Steel for rolling to 0.060 in. sheet.

Evaluation reports have been received only on the Ti-6% Al alloy. Reports have been received from Pratt & Whitney, Wright Aeronautical, and General Electric. The Pratt & Whitney report gives elevated temperature tensile (including notched tensile) and creep data and room temperature tensile properties of creep test specimens. This report is reproduced in Appendix I. It was concluded that creep properties of Ti-6% Al at temperatures from 800° to 1000°F and stresses from 20,000 to 40,000 psi were superior to those of AMS 4925 (4% Al-4% Mn), PWA 676 (2.7% Cr-1.3% Fe), and CF 216 (5% Al-1.4% Cr-1.3% Fe-1.3% Mo) titanium alloys; however, tensile properties of Ti-6% Al bar stock from 70° to 800°F were inferior to those of AMS 4925 titanium alloy bar stock. A letter accompanying this report expressed doubt that very much would be done with the 6% Al alloy because the 6% Al-4% V composition looked still more promising for present applications.

Two reports from Wright Aeronautical are reproduced in Appendices II and III. The first report contains a study of microstructure for two-hour anneals at temperatures from 1200° to 1800°F. Some grain growth takes place at temperatures as low as 1500°F; however, it is our view that recrystallization by nucleation and growth did not take place in the as-received material at any of the annealing temperatures. Elevated temperature tensile data and hardness measurements as a function of annealing temperature are given. It was reported that the room temperature strength of the 6% Al alloy was inferior to that of RC-130 B, but that the hot strength was superior. The 1000°F yield strength (0.2% offset) of RC-130 B was given as 40,000 psi compared to 60,000 psi for the 6% Al alloy.

The second Wright Aeronautical report describes: (1) fatigue properties, notched and unnotched, (2) compressor blade forgings, and (3) tensile, weld bend and formability properties of sheet. The standard R. R. Moore fatigue limit was 55,000 psi. Fatigue limits for several notch conditions were determined. Fatigue limits obtained for 9/16 in. diameter bar stock with a notch root radius of 0.005 in. were: (1) ground notch - 13,000 psi; (2) ground notch, annealed at 1200°F for 5 hours, air cooled - 15,000 psi; and (3) machined notch, annealed at 1200°F for 5 hours, air cooled - 15,000 psi. However, 5/8 in. bar stock with the same notch geometry had a fatigue limit of 25,000 psi for the machined notch. The improved performance of the 5/8 in. diameter stock is apparently due to having removed more of the surface material. The notch description indicates that the theoretical stress concentration factor, K_t, (calculated by the Neuber method(7)) is approximately 4. The author has inserted plots of fatigue values for A-110 AT, C-130 AM, Ti-6% Al-4% V and Ti-6% Al on Figures 1 and 2, Appendix III, for comparison purposes. Figure 1 indicates that the notched fatigue strength (approximately equivalent radii) for A-110 AT and C-130 AM exceeds the fatigue strength obtained for Ti-6% Al. It is shown in Figure 2 that the standard fatigue strength of Ti-6% Al for ground specimens exceeds that for ground specimens of A-110 AT and C-130 AM. For hand finished specimens all the commercial alloys are superior to Ti-6% Al.

Unfortunately, the compressor blades were forged from stock with surface imperfections at a temperature that was much too low, i.e., 1500°F. Consequently, the blades are of little use for a fair evaluation of the alloy.

Sheet 0.062 in. thick was rolled. The surface texture was very rough. This surface condition was probably due to rolling at 1500°F, a temperature considered too low for rolling the 6% Al alloy. The equiaxed structure of the sheet was due to its being hot rolled in the α field. A dispersed second phase of unknown origin was much in evidence in the sheet. A bend radius of 3.5 T was obtained for specimens in the as-welded condition. Post-weld annealing at 1400°-1500°F produced the smallest bend radius of 2.7 T. Post weld annealing at 1100°F or above appears to be necessary to prohibit embrittlement of the weld upon heating in the 700°-1000°F range. Formability of the sheet was poor.

It was concluded that the combination of the tensile properties, grain size stability, weldability and notched fatigue indicate that the alloy has potential as a welding alloy with elevated temperature properties superior to the commercial alloys.

The report received from General Electric is reproduced in Appendix IV. An experimental compressor ring 13-5/8 in. OD x 8-5/8 in. ID x 2 in. thick was forged from a 5-3/8 in. diameter ingot. This piece then was rolled into a ring 19.25 in. OD x 16.25 in. ID x 1.875 in. thick. Forging temperatures were between 1900°-2000°F. Ring rolling was accomplished quickly--about one minute was required. After rolling, the ring was annealed at 1500°F for two hours followed by air cooling.

The ring was sectioned into test specimens and the following testing was done: (1) tensile at 600°, 800° and 1000°F, (2) stress-rupture at 1000°F, (3) impact from -100° to 800°F, and (4) fatigue. Figures 5, 6 and 7 compare tensile data obtained for the 6% Al alloy by the three aircraft groups with C-130 AM, A-110 AT and Ti-6% Al-4% V. Pratt & Whitney and Wright Aeronautical data are for forged bar. The Pratt & Whitney and Wright Aeronautical data are generally in agreement and differ significantly only in reduction in area at 70° and 1000°F. In comparison, the General Electric data for the forged ring shows slightly higher ultimate tensile strength and considerably poorer reduction in area at 600°F. Also, these data show much lower strength and much higher ductility properties at 1000°F.

The tensile properties of Ti-6% Al-4% V and C-130 AM are generally better than for Ti-6% Al at all temperatures except at approximately 1000°F. At this temperature the ultimate tensile strength and the yield strength of C-130 AM drops to lower values. A-110 AT exhibits lower tensile and yield strengths than Ti-6% Al but has essentially the same reduction of area and elongation.

Impact values for V-notch Charpy bars increased linearly from 15 ft-lbs at -100°F to 30 ft-lbs at 800°F. The fatigue limit (Krouse rotating beam 2000 cycles per min.) was about 60,000 psi compared to 55,000 psi obtained by Wright Aeronautical (R. R. Moore). The General Electric report carried no text and no microstructures. Judging from the mechanical properties, it appears that the forged ring could be considered successful.

With reference to the statements of properties desirable in alloys made at the steering committee meeting of December 7, 1953, the following may be said on the basis of the information now available:

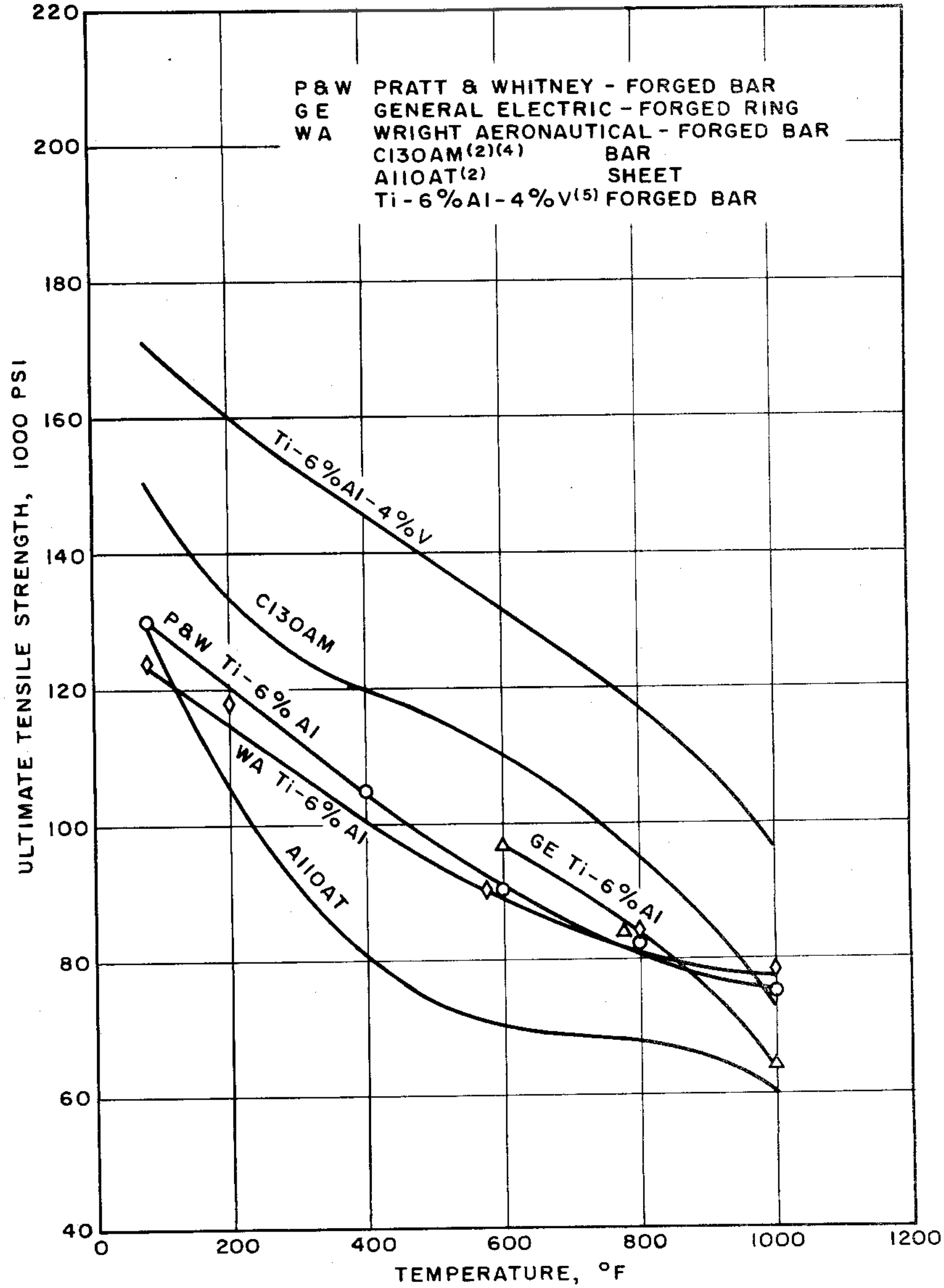

FIG. 5- COMPARISON OF ULTIMATE TENSILE STRENGTH OF Ti-6%Al, A110AT, C130AM AND Ti-6%Al-4%V

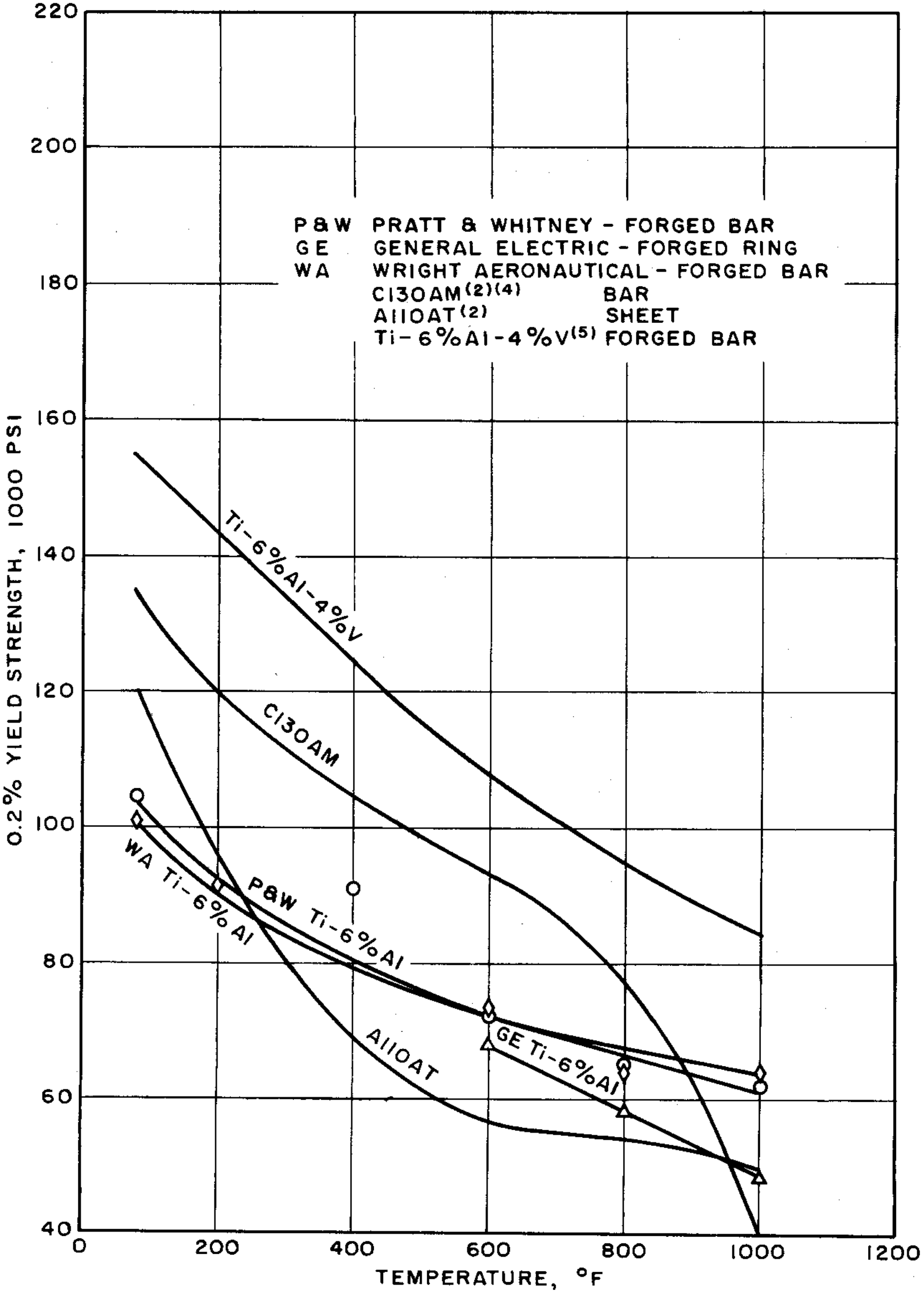

FIG. 6 - COMPARISON OF YIELD STRENGTHS OF Ti-6% Al, A110AT, C130AM AND Ti-6% Al-4% V

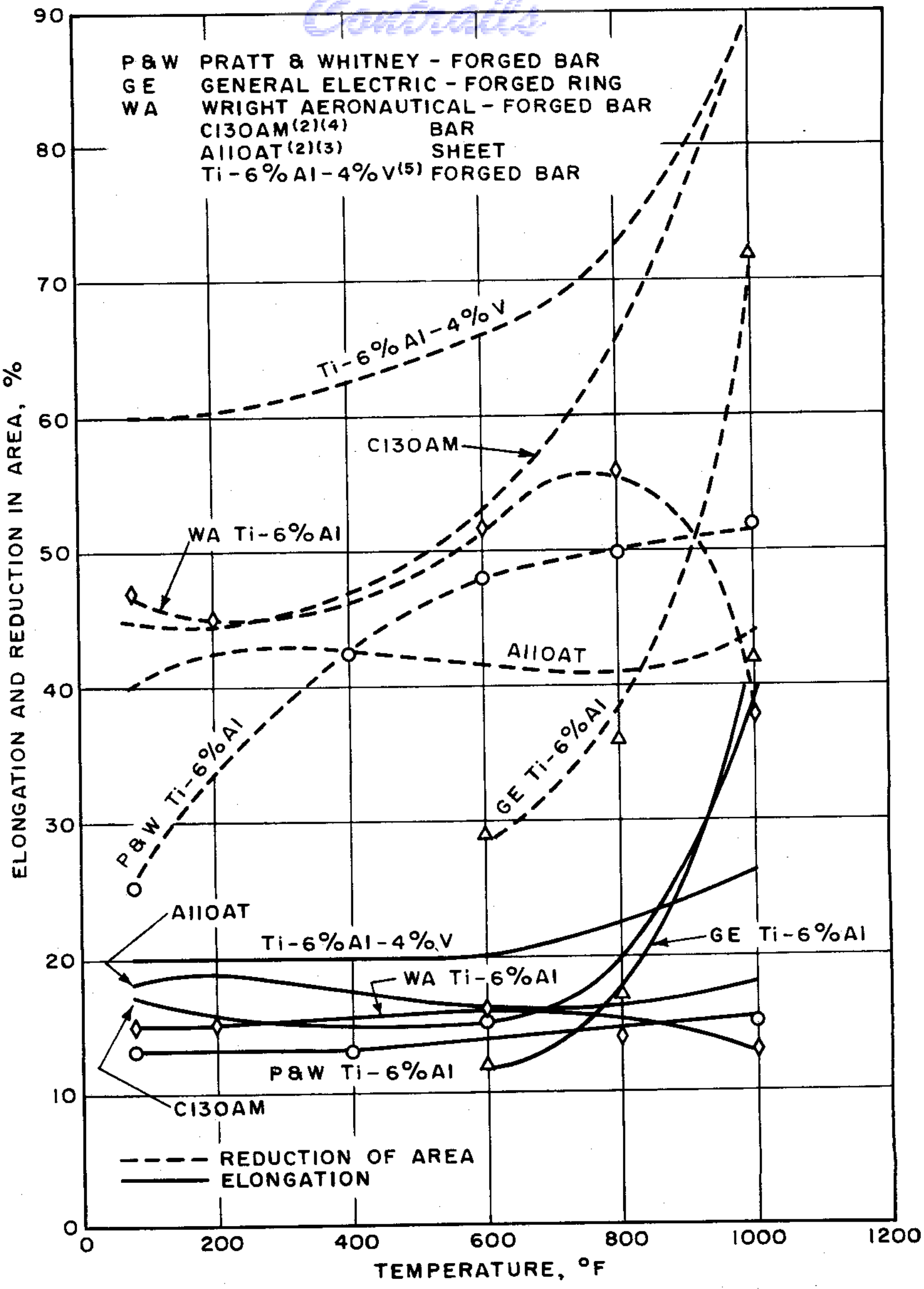

FIG. 7 - COMPARISON OF TENSILE DUCTILITY PROPERTIES OF Ti-6%Al, A110AT, C130AM AND Ti-6%Al-4%V

(1) For a weldable sheet having 0.1-0.3% creep extension in 1000 hours at 650°F under a stress of 80,000-90,000 psi--the 6% Al alloy is inadequate from the strength standpoint; the 7% Al-3% Mo alloy may satisfy from the strength standpoint but may leave something to be desired from the standpoints of forming and welding.

(2) For an alloy having 0.3% creep extension in 500-1000 hours at 800°-1000°F under a stress of 60,000 psi--the 7% Al-3% Mo alloy may prove satisfactory for a temperature of 800°F.

(3) For an alloy having 0.1 and 0.2% offset yield strengths of 110,000 and 120,000 psi, respectively, 15% elongation minimum and 60,000-65,000 psi endurance limit as bar--the 6% Al alloy comes very close to meeting this requirement.

(4) For a sheet alloy having 1% creep extension in 1000 hours at any temperature under a stress of 40,000 psi--the 6% Al alloy looks good for temperatures up to somewhat above 800°F.

(5) For an alloy having 0.1% creep extension up to 900°-1000°F under stress of 50,000 psi--7% Al-3% Mo will not meet this requirement at 1000°F and it is doubtful that it could meet it at 900°F.

(6) For an alloy having 0.5% total deformation in 1000 hours at temperatures up to 900°F under a stress of 40,000 psi--the 6% Al would satisfy for temperatures somewhat greater than 800°F, and for 900°F the 7% Al-3% Mo alloy might possibly satisfy.

It was a primary objective of this program to be able to assess the various reports from cooperating engine manufacturers and to make recommendations concerning the specific desirability of commercial adoption of the better performing compositions. Unfortunately, the times involved in getting pilot quantities of the experimental alloys into the hands of the engine people and their working thorough testing and reporting on these into already crowded schedules have made it impossible to make such recommendations within this contract period. More reports should be completed during the next contract period and it is believed that firm recommendations can be made within the next few months.

Even so, one of the compositions included in this program has become commercial during the course of the work--Ti-6% Al-4% V. Considerable experience is being gained with the alloy in many quarters and generally satisfactory reports indicate that it should assume a permanent place among the useful commercial titanium alloys.

APPENDIX I

REPORT ON TESTS AND EVALUATION OF Ti-6% Al ALLOY

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Division of United Aircraft Corporation
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I. INTRODUCTION

Creep and tensile property determinations were made on Ti-6% Al obtained from Armour Research Foundation. This material was received as 1 in. round bar stock in the as-forged condition.

II. EXPERIMENTAL PROCEDURE

The ingot (Heat No. 347) was melted from "O" sponge at BHN 124. The forging temperature was 2000°F, and the finishing temperature was 1900°F.

Composition of the bar stock was 6.29 Al, 0.043 C, 0.006 N, balance Ti. Hardness of the bar was RC 32-34. Radiographic examination of six lengths revealed a large seam in one bar and many dense unidentified inclusions in another. Specimens were machined to avoid these defects. Bar stock was stress-relieved at 1200°F for 1 hour and air cooled.

Smooth tensile specimens were machined with 0.250 and 0.505 in. diameter gauges. Notched tensile bars were machined to 0.375 in. diameter reduced to 0.250 in. diameter at the notch by a 60° V-notch with a 0.005 in. notch radius. Two notched and two smooth tensile bars were heated in air at 800°F for 1000 hours, and air cooled prior to tensile testing. Creep specimens were machined per MD2 263 with a 0.357 in. gauge diameter for a 3.0 in. length. Results of tensile tests at temperatures from 70° to 1100°F are detailed in Table I. Creep data are shown in Table II and are plotted in Figure 1. Room temperature tensile properties of creep tested specimens are listed in Table III. Two creep tested bars fractured through oxidized cracks in the gauge lengths. Average tensile data from 70° to 1000°F, as compared with C-130 AM titanium alloy bar stock, are shown in Table IV.

III. DISCUSSION OF RESULTS

Tensile properties of C-130 AM titanium alloy bar stock as reported in Table IV are higher than those obtained for a disc of the same alloy.

Existence of the oxidized crack exposed by fracture of creep specimen D 5406 in 70°F tensile test indicates the specimen had either reached third stage creep, or some unknown mechanism of brittle failure was occurring. This specimen ran 432 hours at 30,000 psi at 800°F, with only 0.07% total plastic elongation. Similar behavior was noted for C-130 AM and Ti-155 AX titanium alloys.

IV. CONCLUSIONS

Notched tensile tests indicated that the material was notch strengthened at room and elevated temperatures. Heating for 100 hours at 800°F caused no loss in smooth bar ductility but did cause a lowering of notched bar tensile strength. Although the Ti-6% Al alloy has been reported as an all-alpha structure, its microstructure is similar to that of an alpha-beta alloy (Ti-150 A), see Figure 2.

V. CONTRIBUTING PERSONNEL

Information contained herein was reported by H. N. Tiemann, tensile tests were conducted by J. Liese, creep tests by R. F. Moore. All work was performed under Account No. 702233, Lab. No. B-8101.

TABLE I

TENSILE PROPERTIES OF Ti-6% Al ALLOY BAR STOCK (HEAT 347)

Test Temp. °F	Ultimate Tensile Strength psi	Proportional Limit psi	0.2% Yield Strength psi	Elong. %	Red. Area %	MDL Print
Room	128,500	97,750	114,000	13	25	629A3
Room	133,750	100,000	117,500	15	37	430
Room	138,000*	106,000	128,000	13	29	629A3
Room	134,000*	100,000	125,000	12	26	430
400	107,000	66,750	90,500	13	45	629A3
400	104,750	85,000	93,750	13	46	430
600	93,750	61,000	75,250	16	54	629A3
600	87,750	62,500	69,500	14	42	430
900	77,250	41,500	63,250	16	53	629A3
900	75,500	36,250	59,250	13	53	430
1000	74,750	44,750	60,000	16	53	629A3
1000	76,500	---	---	15	51	430
1100	64,000	38.000	52,750	18	43	629A3
1100	68,750	34,500	54,000	14	50	430
Room	194,000	Notched Specimen				629N
Room	198,000	Notched Specimen				629N
Room	135,000*	Notched Specimen				629N
Room	135,000*	Notched Specimen				629N
1000	117,500	Notched Specimen				629N
1000	120,500	Notched Specimen				629N

* Specimen heated prior to test: 800°F-100 hours-air cooled.

TABLE II

CREEP PROPERTIES OF Ti-6% Al ALLOY BAR STOCK (HEAT 347)

D-No.	Test Temp. °F	Stress psi	Time to Elongation, hrs		Time at Test	Total Elong. %
			0.1%	1.0%		
5405	700	30,000	---	--	409	0.05
5406	800	30,000	---	--	432	0.07
5410	800	40,000	406	--	406	0.1
5407	900	30,000	12	--	409	0.2
5411	900	35,000	12	--	427	0.6
5408	1000	30,000	2.5	65	185	3.4
5409	1100	30,000	0.5	3	16	6.2

TABLE III

ROOM TEMPERATURE TENSILE PROPERTIES OF CREEP TEST SPECIMENS

D-No.	Ultimate Tensile Strength psi	Proportional Limit psi	0.2% Yield Strength psi	Elong. %	Red. Area %
5405	128,800	98,800	118,500	16	26
5406*	136,000	113,000	130,000	7	10
5410	137,200	114,100	132,300	16	26
5407	140,500	118,200	135,400	14	27
5411	134,000	110,000	132,500	7	8
5408	137,200	114,800	131,200	13	22
5409*	130,200	107,500	128,000	7	11

* Failed through oxide-discolored crack.

TABLE IV

COMPARISON OF AVERAGE TENSILE DATA OF Ti-6% Al WITH C-130 AM

Alloy	Temp, °F	Ultimate Tensile Strength psi	0.2% Yield Strength psi	Elong. %	Red. Area %
Ti-6 Al	70	130,000	114,000	13	25
C-130 AM	70	155,000	147,000	18	--
Ti-6 Al	400	105,000	91,000	13	45
C-130 AM	400	125,000	107,000	16	--
Ti-6 Al	600	90,000	72,000	15	48
C-130 AM	600	115,000	94,000	18	--
Ti-6 Al	800	82,000	64,000	15	50
C-130 AM	800	108,000	86,000	22	--
Ti-6 Al	1000	75,000	60,000	15	52

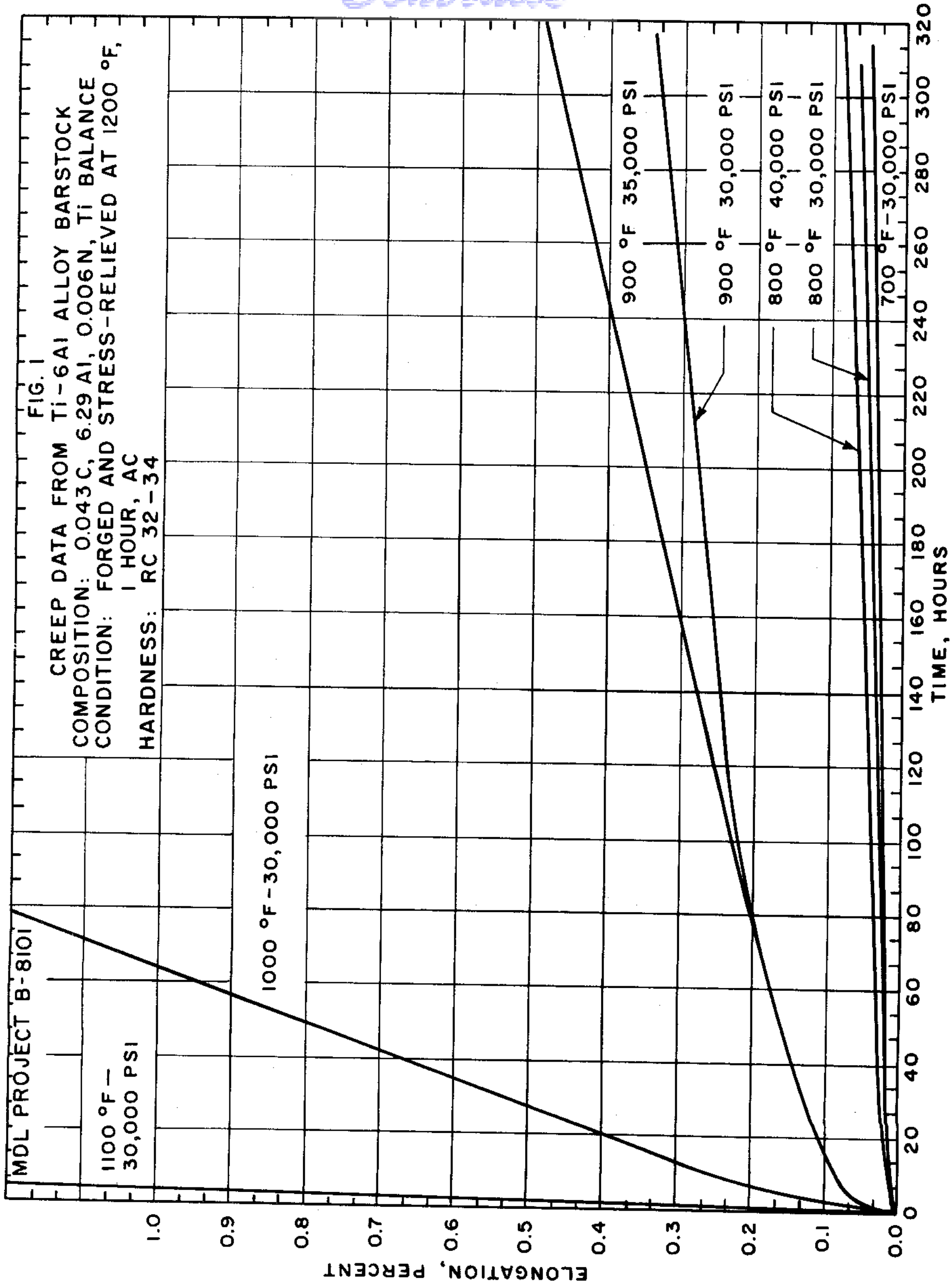
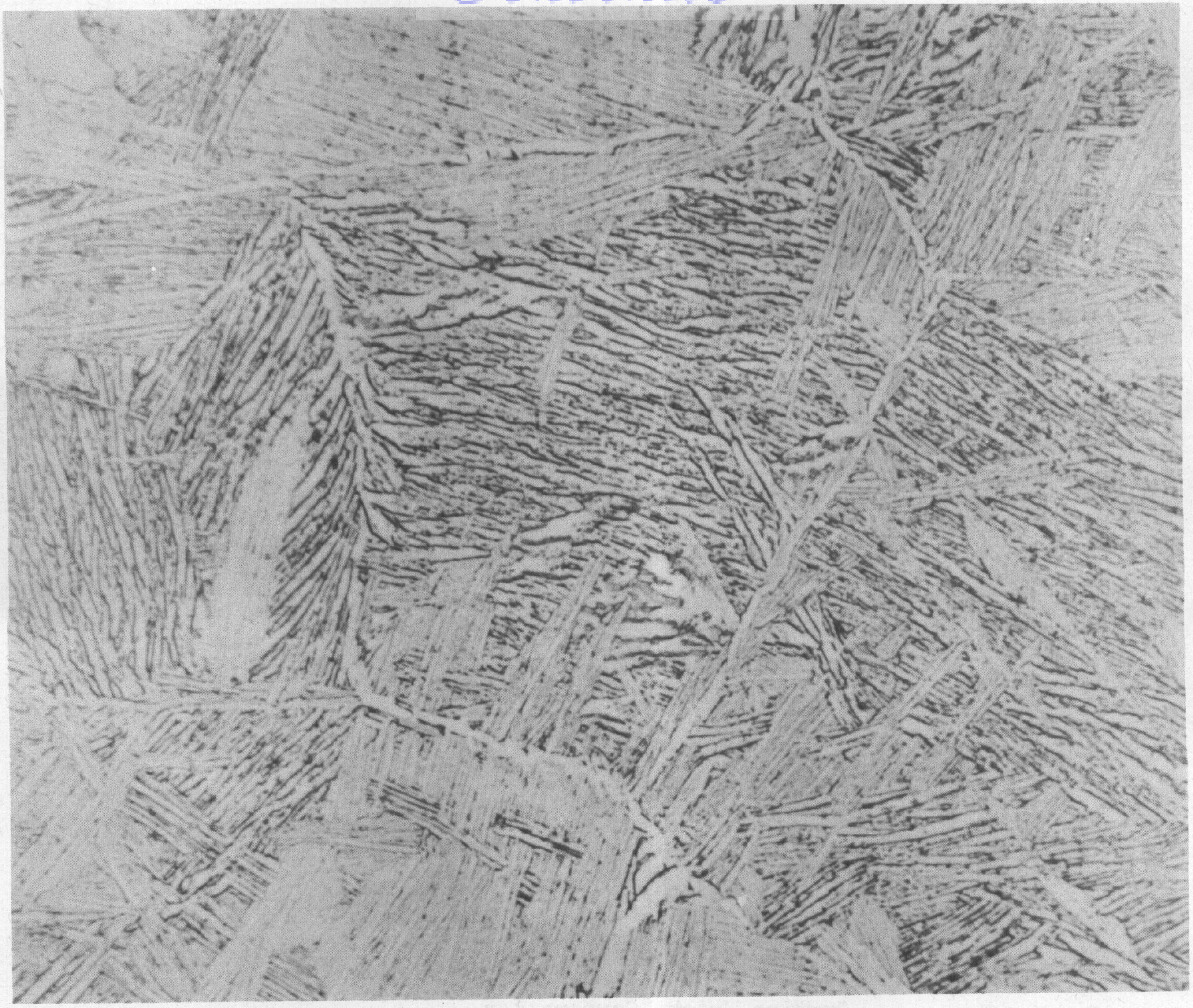


FIG. I

CREEP DATA FROM Ti-6Al ALLOY BARSTOCK

COMPOSITION: 0.043C, 6.29 Al, 0.006N, Ti BALANCE
CONDITION: FORGED AND STRESS-RELIEVED AT 1200 °F, 1 HOUR, AC
HARDNESS: RC 32-34



X 500

Fig. 2

Microstructure of longitudinal section of Ti-6% Al bar stock.

Etchant: 1 HF, 12 HNO_3, 87 H_2O

APPENDIX II

REPORT NO. 1 ON TESTS AND EVALUATION OF Ti-6% Al ALLOY

L. A. Luini

Curtiss-Wright Corporation
Wright Aeronautical Division
Wood-Ridge, New Jersey

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I. INTRODUCTION

The information contained within this report concerns the effect of temperature on the microstructure hardness and tensile properties of Ti-6% Al bar stock at temperatures up to 1000°F. This material was received in the as-forged condition from Armour Research Foundation.

II. DISCUSSION OF RESULTS

The 6% aluminum titanium alloy is predominantly an alpha phase alloy with a small percentage of a secondary phase. The structure consists of a Widmanstätten distribution of alpha plates separated by a secondary phase, Figure 1. Deformation is evidenced by the disrupted appearance of the alpha plates in the as-received condition. Severe segregation is prevalent and confuses the interpretation of the phase distribution with reference to heating temperature. Some difference in the configuration of the alpha plates is noticed with the structures heated up to 1800°F as outlined in Table I. Specimen A6, Figure 2A, heated at 1400°F is an example of extreme contamination. This structure is characterized by coarse grains and contains no evidence of working. The Widmanstätten alpha is observed in specimen A7 air cooled from 1400°F, Figure 2B. Grain boundaries are distinctly outlined with a layer of alpha and there is no evidence of working. Heating to 1600°F shows the worked alpha plates and some recrystallization. As shown in Figure 3, distinct grain boundaries traverse the former grains. The former alpha plates are seen to extend continuously through the new grain boundaries. In these areas of recrystallization most of the secondary phase is dissolved. At 1800°F some localized solution of alpha is noticed. The structure remains predominantly the original Widmanstätten alpha separated by a secondary phase, Figure 4. On water quenching the secondary phase is clear, while on air cooling it is a dark precipitate similar to that of the as-received structure.

The hardness of the alloy has a maximum change of 25 points VHN between the solution temperature of 1200°-1800°F. A peak hardness is recorded on air cooling from 1400°F, Figure 5. The water quenched hardness is generally lower. Hardness values for individual specimens have deviations up to 25 points VHN.

The data indicates that the structure of the alloy is stable from the standpoint of structure and grain size. Within the temperature limits of 1200°-1800°F the original alpha Widmanstätten plate structure is retained. At the higher solution temperature the secondary phase appears to remain clear on water quenching and reverting to the dark structure on air cooling. Recrystallization structures, Figure 3, and coarse Widmanstätten structures, Figure 2A, are believed to be the result of segregation or contamination.

The tensile properties of the alloy with reference to temperature show the characteristic drop in strength with increasing temperature, Figure 6. Within the temperature range from room temperature to 1000°F the loss in strength is approximately 45,000 psi. The elongation remains fairly constant at 18% and drops to 16% at 800°F.

These properties are superior to the commercially pure all alpha grade titanium alloys. While the room temperature strength of 120,000 psi is inferior to the alpha-beta grades as C-130 AM, the hot strength of the all alpha grade is superior. At 1000°F the 0.2% yield strength of C-130 AM is 40,000 psi, compared to 60,000 psi for the 6% Al alloy.

TABLE I

MICROSTRUCTURE OF ARMOUR Ti-6% Al ALLOY

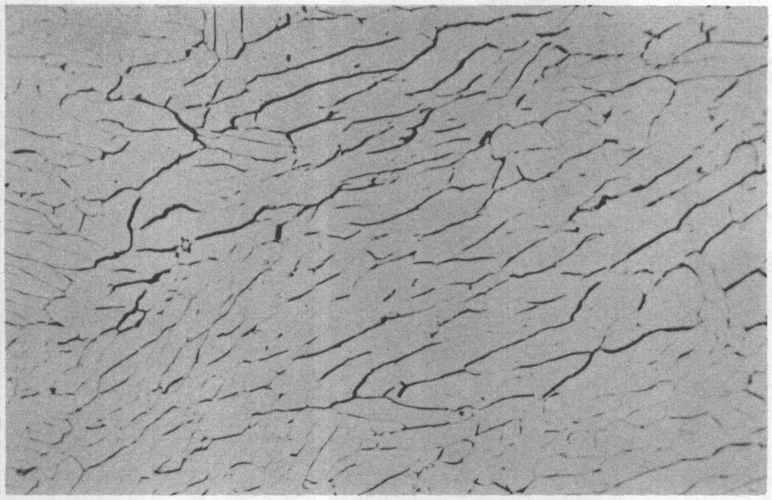
Specimen	Treatment Temp. °F	Time hrs.	Quench	Structure
A-1	As received			Alpha phase, Widmanstätten weave pattern. Worked. All specimens have this basic structure with the listed modifications.
A-2	1200	2	WQ	Acicular Widmanstätten-Contaminated-No work.
A-3	1200	2	AC	Basic Widmanstätten alpha.
A-4	1300	2	WQ	Basic Widmanstätten alpha.
A-5	1300	2	AC	Basic Widmanstätten alpha.
A-6	1400	2	WQ	Acicular Widmanstätten-Contaminated-No work.
A-7	1400	2	AC	Alpha at grain boundaries. No signs of work. Coarse grain.
A-8	1500	2	WQ	Some clear g.b.* Some recrystallization.
A-9	1500	2	AC	Recrystallized structure. Irregular patches of light etching structure.
A-10	1600	2	WQ	Recrystallized structure.
A-11	1600	2	AC	Recrystallized structure.
A-12	1700	2	WQ	Coarse grain. Old structure and new structure. Segregation banding.
A-13	1700	2	AC	Widmanstätten weave alpha and patches of light etching structure.
A-14	1800	2	WQ	Recrystallized structure. Patchy structure and Widmanstätten alpha.
A-15	1800	2	AC	Widmanstätten alpha. Secondary phase heavier.

* g.b. - grain boundaries.

TABLE II

FATIGUE PROPERTIES OF ARMOUR Ti-6% Al ALLOY

R. R. Moore Type	Treatment	6×10^7 Endurance Limit psi	Endurance Ratio	Root Diameter
Notch	Ground notch	13,000	.105	.340-.342
Notch	Machined notch	25,000	.201	.328-.340



X 400

Fig. 1

Armour Ti-6% Al alloy as received.

Kellers Etch.

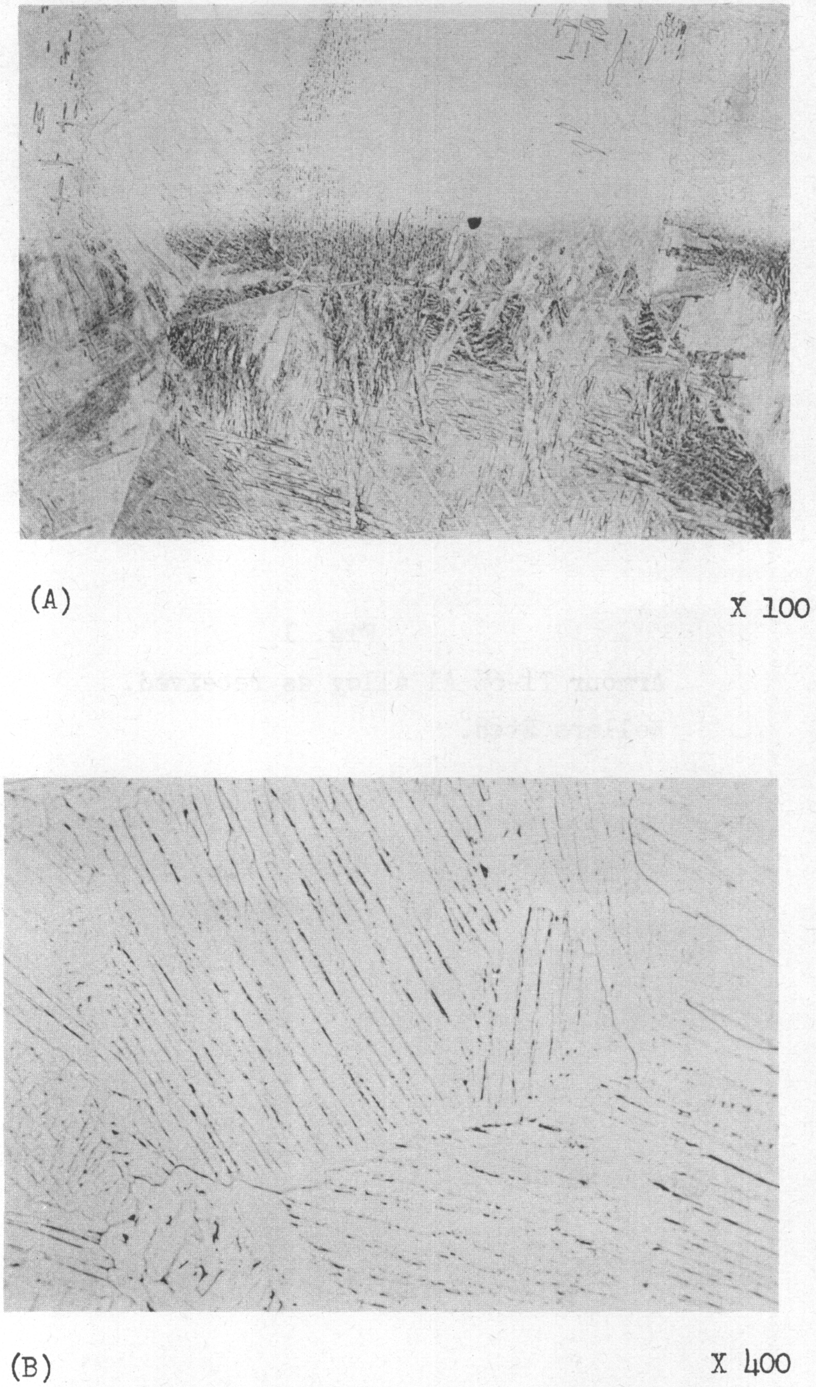
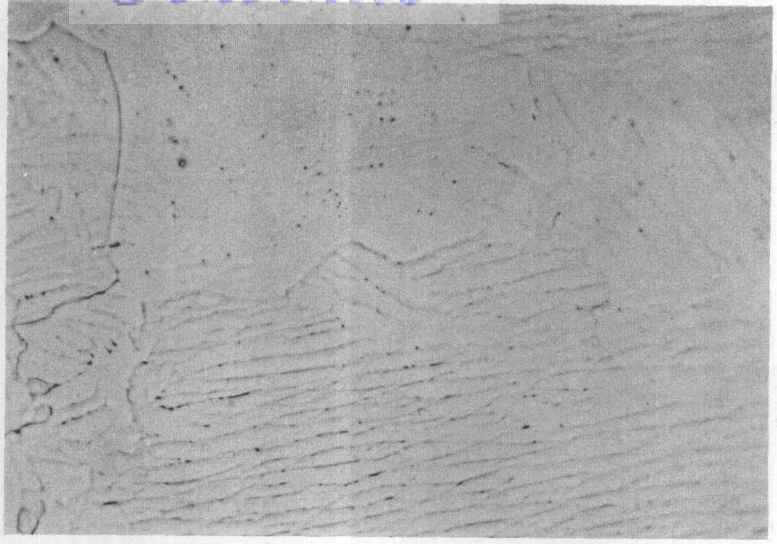


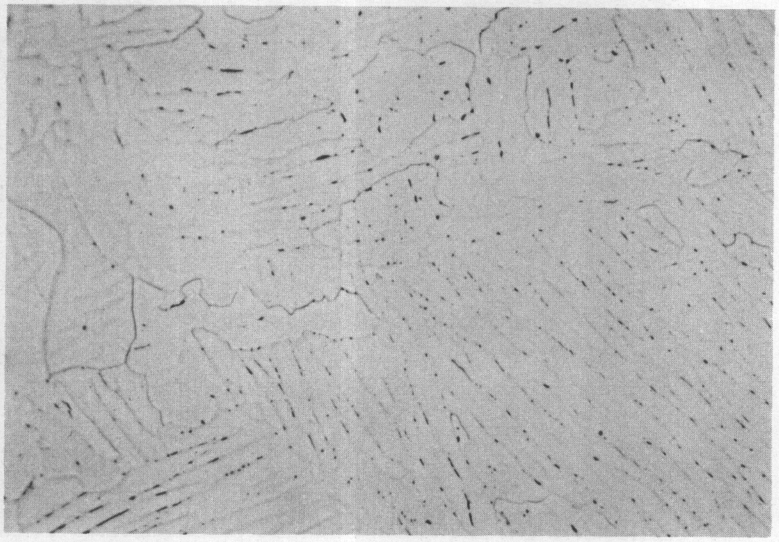
Fig. 2

Armour Ti-6% Al alloy after 1400°F-2 hours,
(A) water quenched, (B) air cooled.

Kellers Etch.



(A) X 400

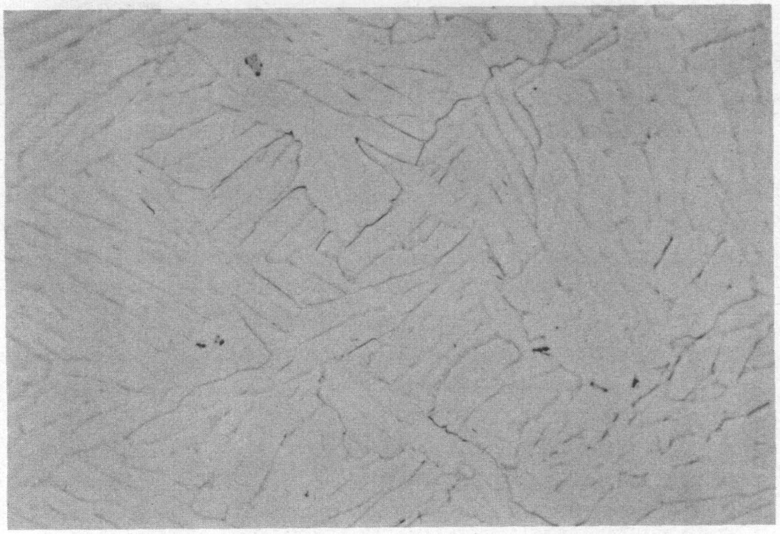


(B) X 400

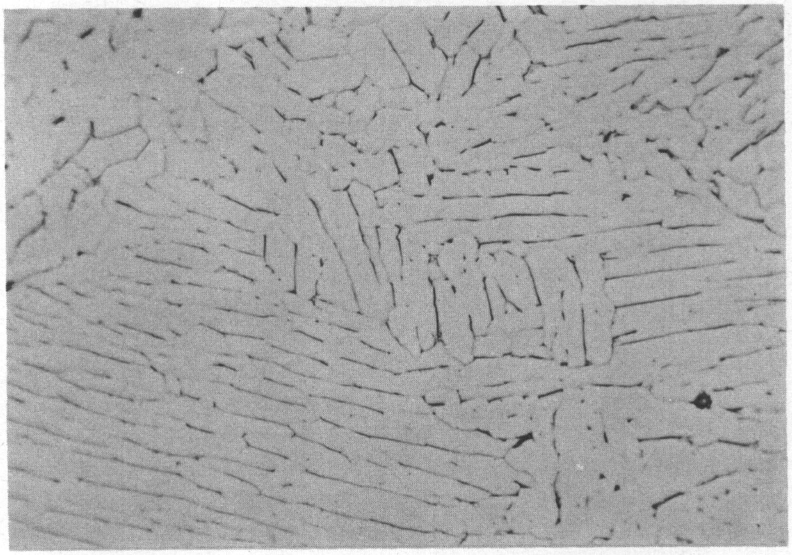
Fig. 3

Armour Ti-6% Al alloy after 1600°F-2 hours,
(A) water quenched, (B) air cooled.

Kellers Etch.



(A) X 400



(B) X 400

Fig. 4

Armour Ti-6% Al alloy after 1800°F-2 hours,
(A) water quenched, (B) air cooled.

Kellers Etch.

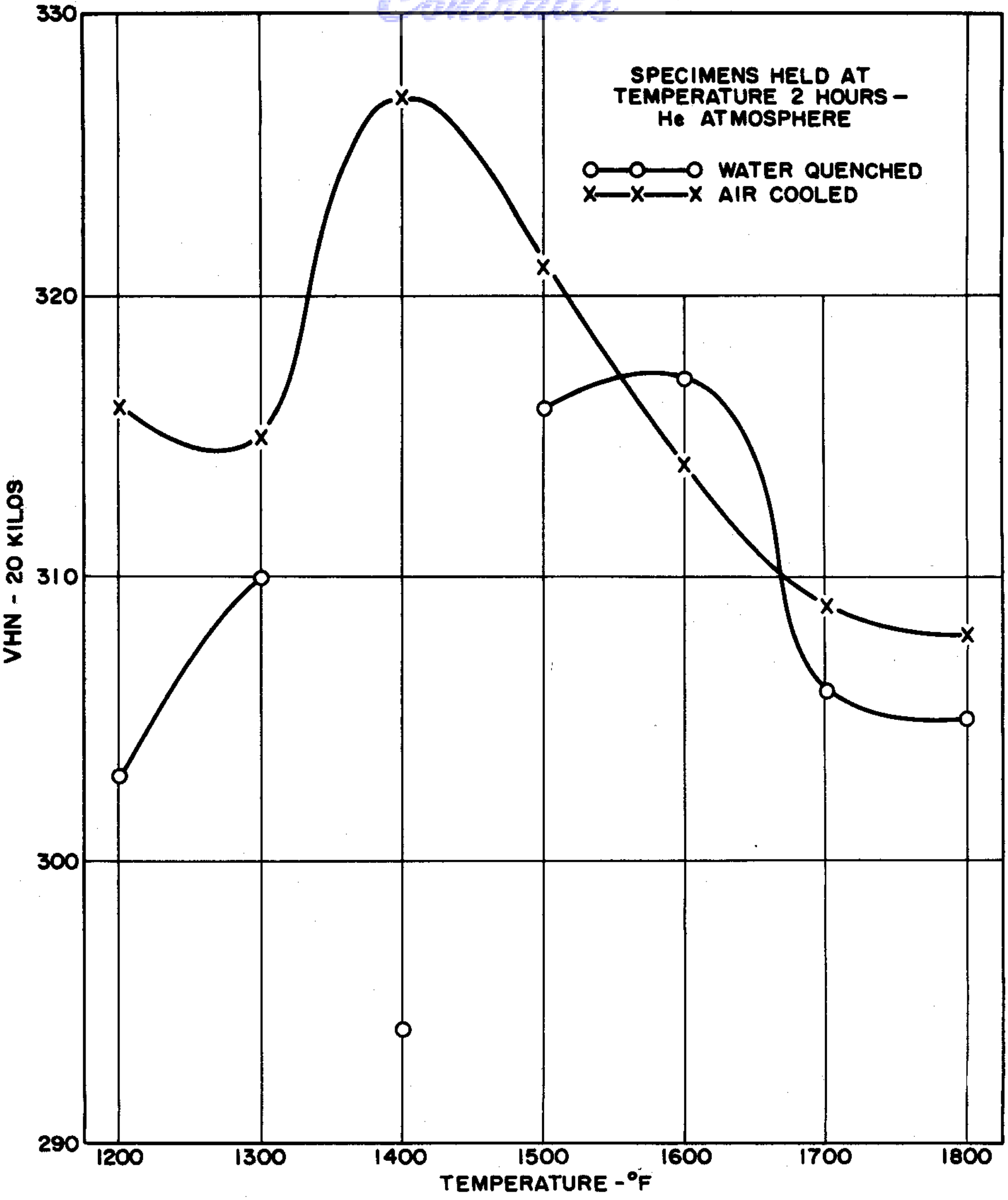


FIG. 5 - EFFECT OF ANNEALING TEMPERATURE ON THE HARDNESS OF ARMOUR Ti-6% Al ALLOY

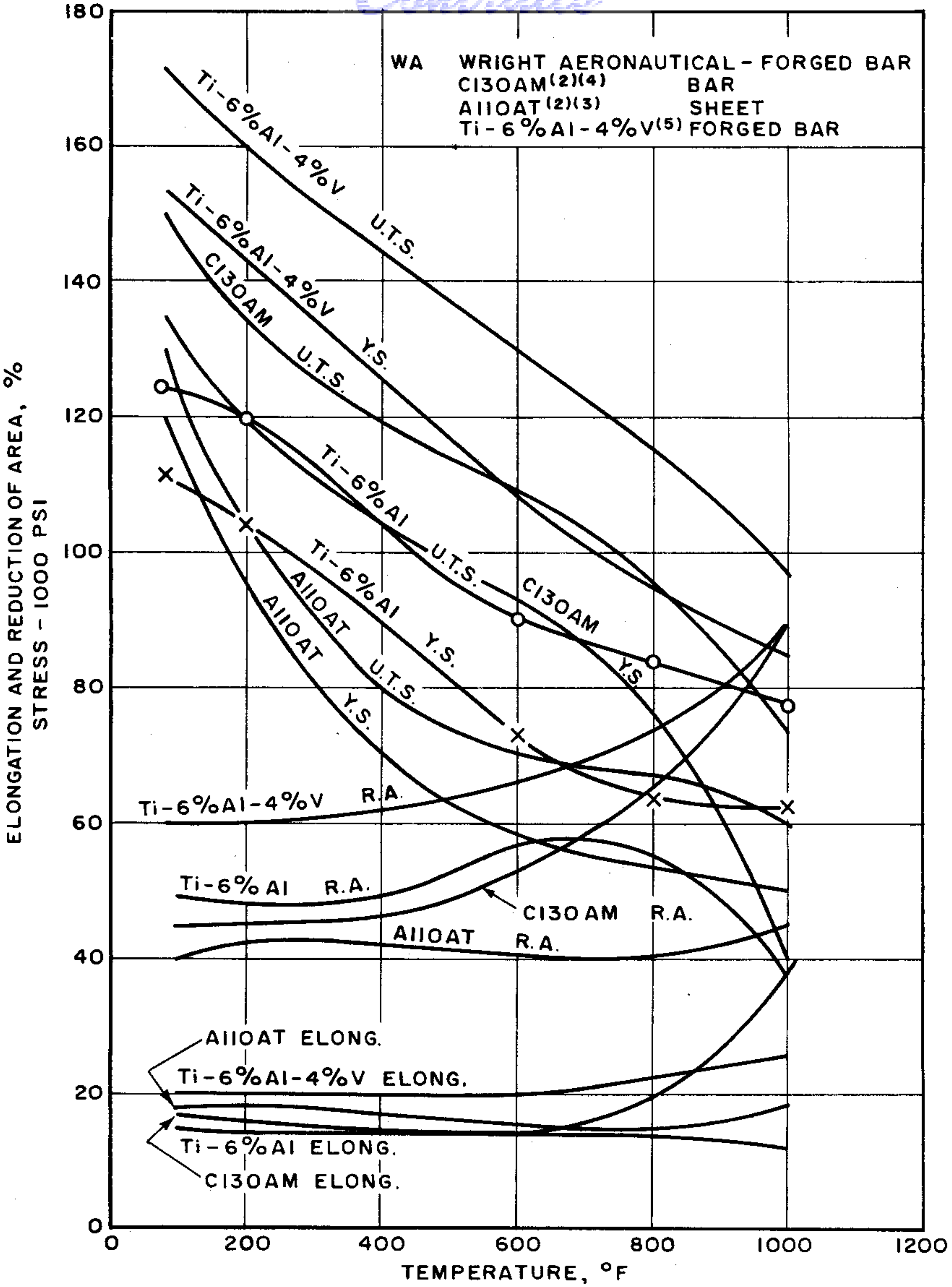


FIG. 6 - SHORT TIME TENSILE PROPERTIES VS. TEMPERATURE ARMOUR Ti-6% Al, A110AT, C130AM AND Ti-6%Al-4%V

APPENDIX III

REPORT NO. 2 ON TESTS AND EVALUATION OF Ti-6% Al ALLOY

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I. INTRODUCTION

The information contained within this report concerns the tests performed on the Ti-6% Al alloy received from Armour Research Foundation. The forging and fatigue tests were performed on bar stock; tensile, weld-bend and formability upon 0.062 in. thick hot rolled and annealed sheet.

II. DISCUSSION OF RESULTS

A. Bar Stock

1. Fatigue

The notch and standard fatigue data are presented in Figures 1 and 2, respectively. The notch fatigue limit for the ground notch condition is 13,000 psi and the notch fatigue limit after stress relieving at 1200°F for 5 hours and air cooled is 15,000 psi. The stress relieved machined notch fatigue limit is 15,000 psi. The standard fatigue limit is 55,000 psi. The above data were obtained with 9/16 in. diameter stock ground and polished. The machined notch fatigue limit obtained from 5/8 in. diameter bar stock is 26,000 psi.

2. Forging

Several compressor blades were randomly forged by a vendor having no previous forging experience with the alloy. A forging temperature of 1500°F was used, although the solution temperature data indicated 1900°F would be appropriate. Cracks developed at the edges and all portions of the die were not filled, see Figure 3. The surface imperfections and structural inhomogeneities of the bar stock were transmitted to the blades. The as-received bar stock had a poor hot rolled surface and the size required for forging did not permit sufficient centerless grinding to remove all surface defects.

B. Sheet - .062 in. Thick Hot Rolled Annealed

1. Surface Condition

The surface texture was uniformly rough with an orange peel pattern, Figure 4. The texture consisted of ridges of metal running transverse to the rolling direction. The two slopes of these ridges were not equal and one slope was greater than the other in one direction. It appears that the metal accumulated in lumps ahead of the rolls to form numerous ridges on the surface. Mill representatives reported the sheet rolling temperature was 1500°F. Oxidation, scaling or large grain size may contribute to this surface condition.

2. Sheet Tensile

The tensile properties show a decrease with increasing test temperatures from room temperature to 1000°F, Figure 5. The strength drops from 138,000 psi at room temperature to 93,000 psi at 400°F. Testing at above 400°F, the rate of strength loss is decreased and the strength at 1000°F is 62,000 psi.

Compared to the bar stock, the sheet has higher room temperature strength but lower strength at higher temperatures. It is significant that the microstructure of the bar stock shows a coarse lamellar type structure, while the sheet stock shows a fine grained equiaxed structure with a dispersed second phase, Figure 6.

3. Weld Bend

The bend test results of arc-welded and annealed sheet are listed in Table I. Bending to complete fracture occurs with specimens annealed at 700° and 900°F. With the higher annealing temperatures the fracture is not spontaneous and the bend radius decreases as the annealing temperature is increased. Annealing at 1100° and 1200°F results in a bend radius of approximately 3.2 T. Annealing at 1400° and 1500°F results in a smaller bend radius of 2.7 T. In the as-welded condition the fracture is not spontaneous and is fairly ductile.

The bend tests indicate that the weld has satisfactory bend ductility as welded; however, the condition is unstable and is subject to brittleness when heated to 700°-900°F. Annealing at 1100°F appears to be the lowest temperature permissible for a ductile weld. Annealing at 1400°-1500°F produces the best bend ductility.

4. Formability

Sheets of 3-3/4 and 3-1/2 in. wide stock were rolled into 5 in. diameter cylinders then welded, annealed and expanded radially until fracture. The formability of this particular batch of sheet is poor. Fracture occurred when the cylinder was cold rolled. Hot rolling at 800°F was necessary to form the cylinder. Radial expansion of the cylinder resulted in a brittle fracture away from the welded seam (Figure 7).

III. SUMMARY

The overall results including fatigue, formability, uniformity and surface condition, appear poor. However, the material shows indications of faulty processing. The notch fatigue results of the two batches of bar stock indicate that the notch fatigue properties of the alloy should be as good as the results obtained with the 5/8 in. diameter bar stock. The prevalence of surface seams of one of the 9/16 in. diameter bar stock indicates rolling difficulty. The lamellar type fracture of a sheet bend specimen, the clumping of material on the surface to form a rough texture, and the poor cold forming characteristics (approximately 40 T) indicate that the processing temperatures were too low. The blade forgings indicate that limited shaping can be accomplished at 1500°F.

The combination of the tensile properties, grain size stability, weldability and notch fatigue indicates that the alloy has potential as a welding alloy with superior elevated properties over the commercially pure grades. Laboratory study of the processing techniques for both bar and sheet stock is necessary for additional development of the alloy.

TABLE I

ARMOUR Ti-6% Al ALLOY ARC WELDED BEND TEST ANNEALED 2 HOURS AT INDICATED TEMPERATURES - AC

Specimen	Annealing Temp., °F	Thick-ness in.	Bend Radius in.	R/t	Average	Fracture Location*	Remarks
A-1	700	.043	.280	6.5	5.1	HAZ	Brittle fracture.
A-2	700	.037	.137	3.7		W	Brittle fracture.
A-3	900	.046	.230	5.0	4.5		Metal separated into 2 layers at weld fracture.
A-4	900	.053	.205	3.9		W	Brittle fracture.
A-5	1000	.045	.197	4.4	5.5	W	
A-6	1000	.035	.230	6.6		W	
A-7	1100	.047	.120	2.6	3.1	HAZ	
A-8	1100	.043	.154	3.6		B.M.	
A-9	1200	.048	.222	4.6	3.9	W	Weld faulty-was cracked.
A-10	1200	.047	.155	3.3		W	
A-11	1400	.047	.103	2.2	2.7	HAZ	
A-12	1400	.048	.147	3.1		W	
A-13	1500	.050	.133	2.7	2.7	W	
A-14	1500	.049	.133	2.7		W	
A-15	1600	.051	.175	3.4	3.3	W	
A-16	1600	.043	.133	3.1		W	
A-17	As weld	.047	.155	3.3	3.5	W	
A-18	As weld	.050	.199	3.8		B.M.	
A-19	As weld	.052	.178	3.4		W	
A-20	As weld	.051	.181	3.5		HAZ	Brittle fracture.

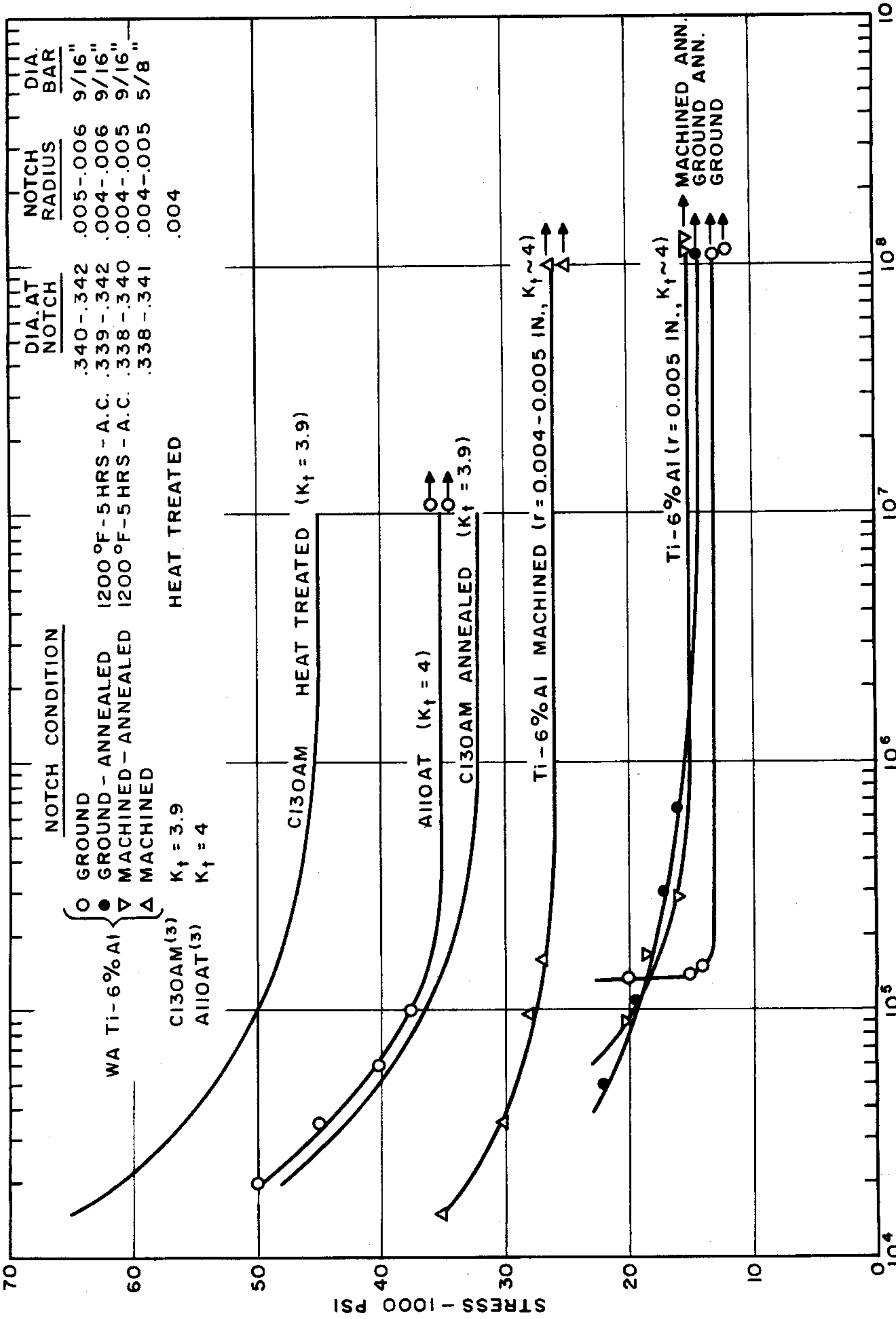


FIG. 1 - R.R. MOORE NOTCH FATIGUE Ti-6%Al, C130AM, A110AT

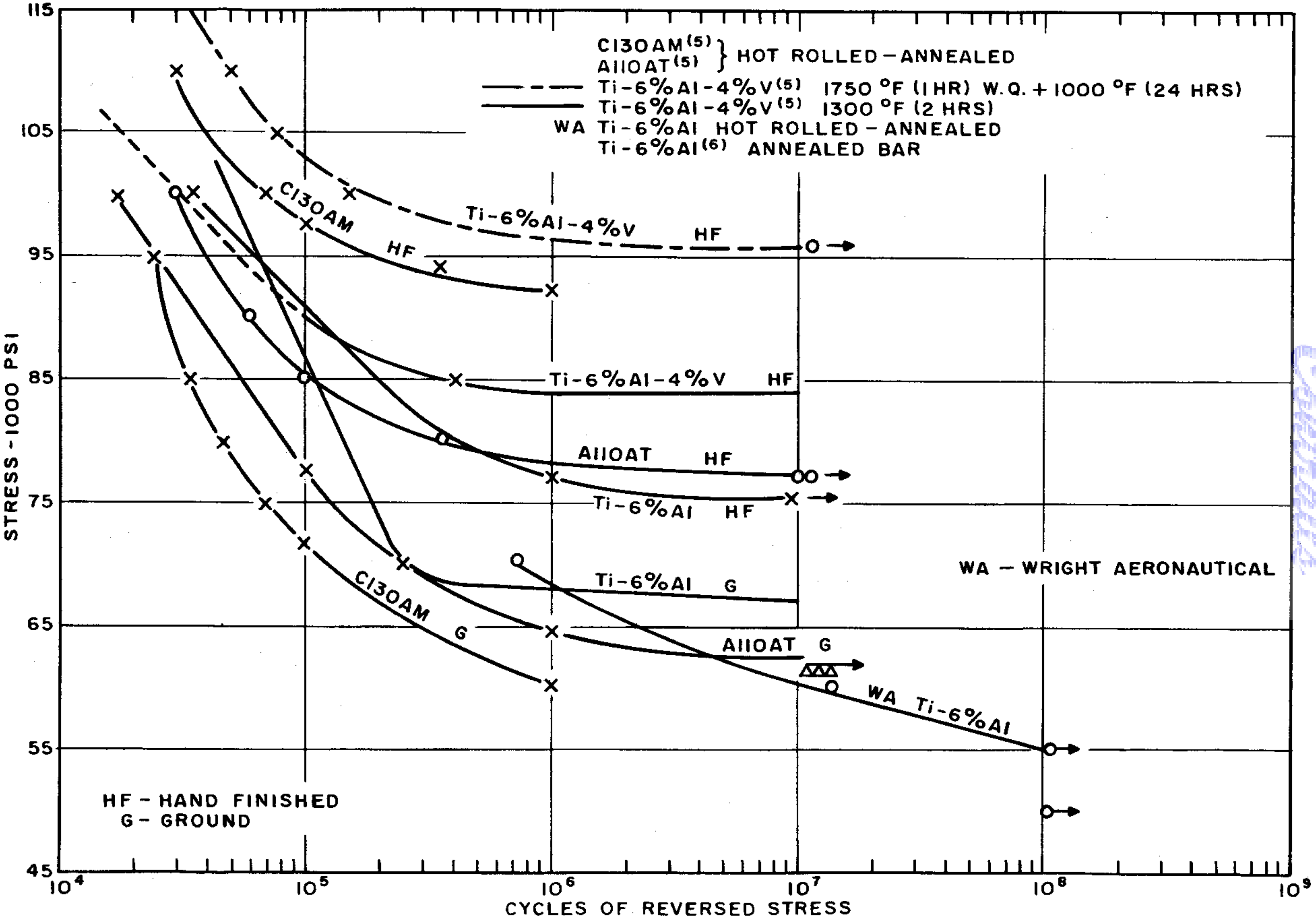


FIG. 2 - R.R. MOORE STANDARD FATIGUE

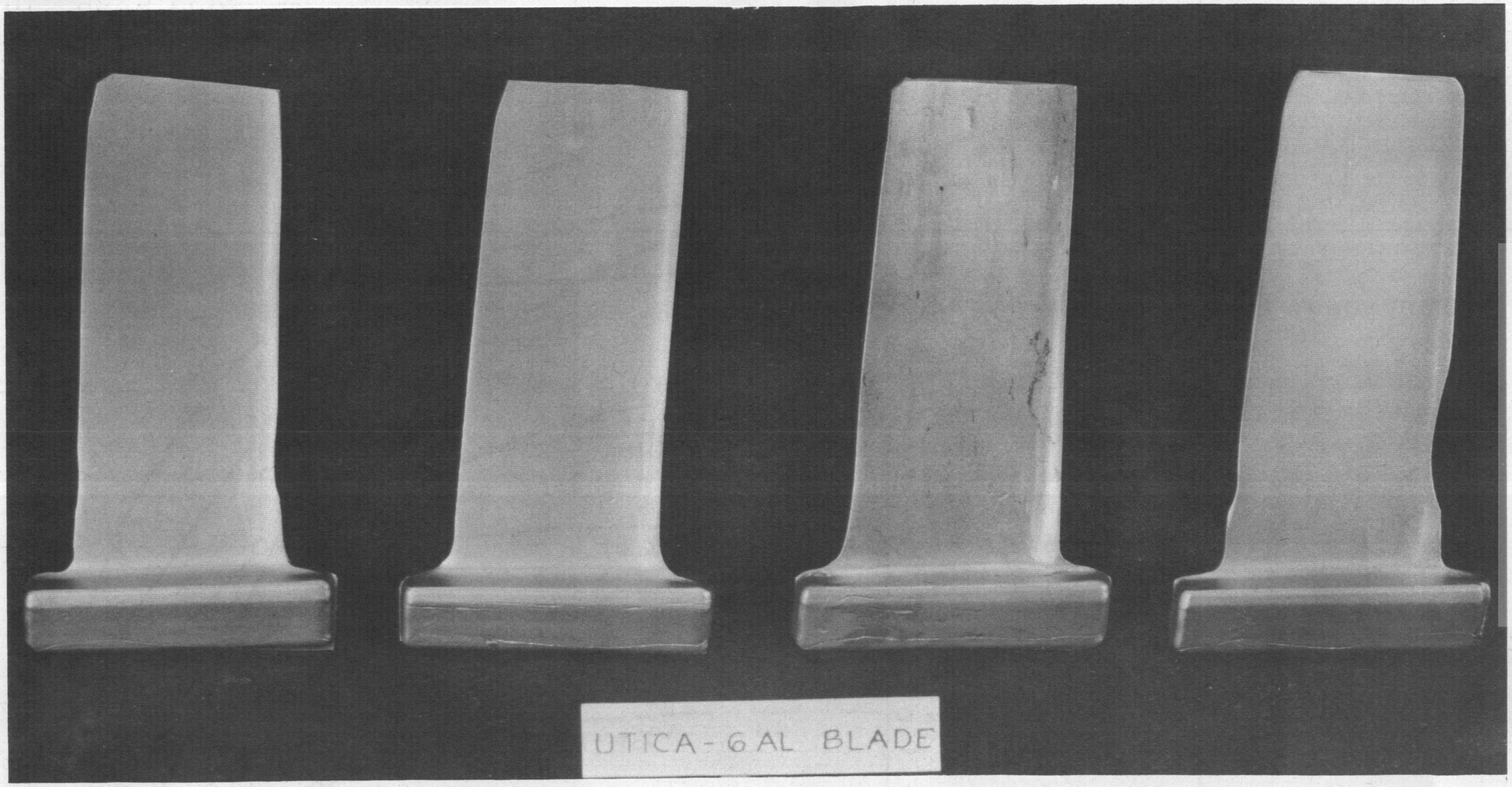
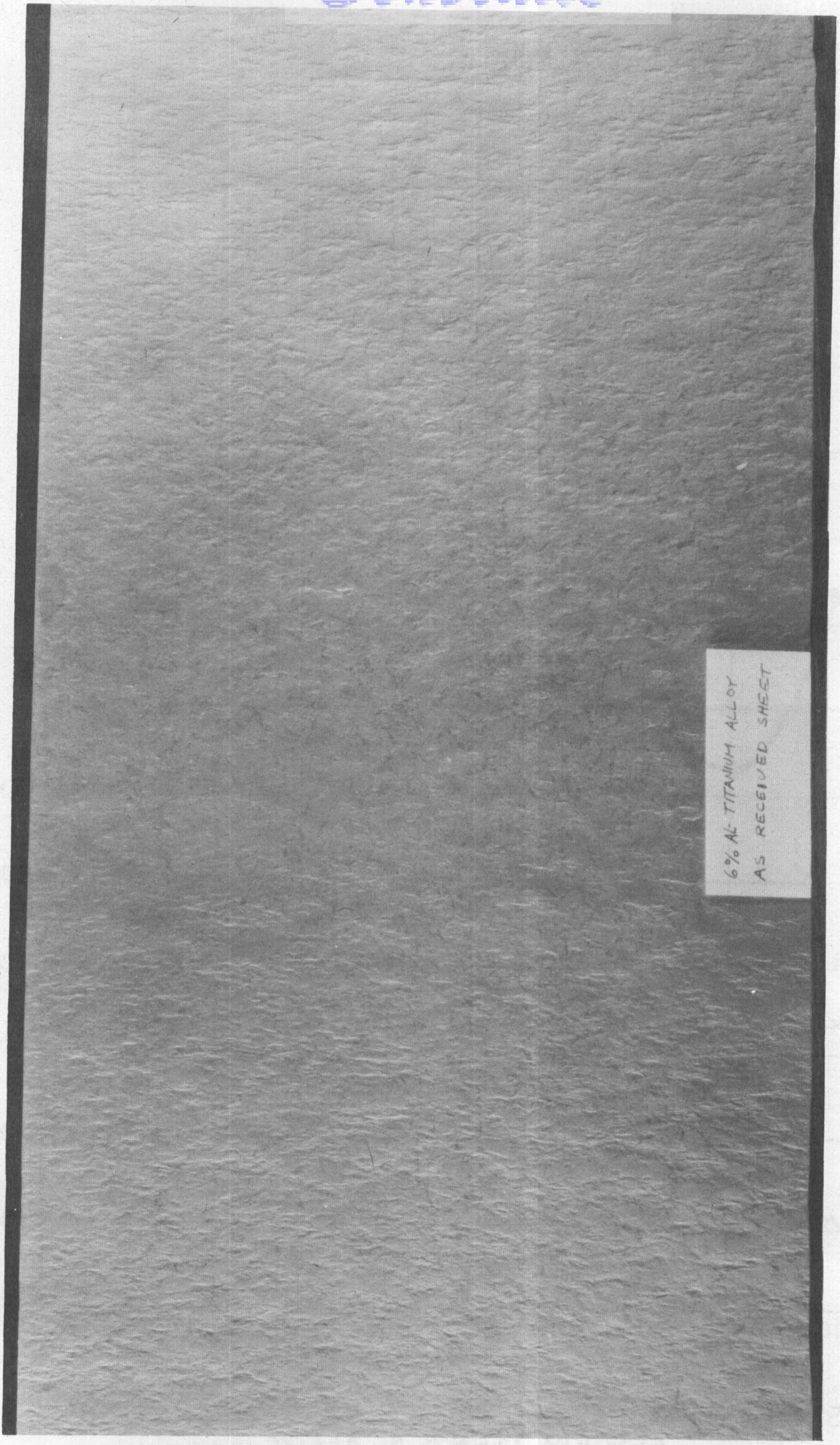


FIG. 3 - COMPRESSOR BLADES FORGED AT 1500°F SHOWING CRACKS AT EDGES, INCOMPLETE FILLING OF DIES, LAPS AT ROOT, AND MATERIAL INHOMOGENEITY



Mag: 0.5

Fig. 4

Surface of sheet showing orange peel texture.
Rolling direction is horizontal.

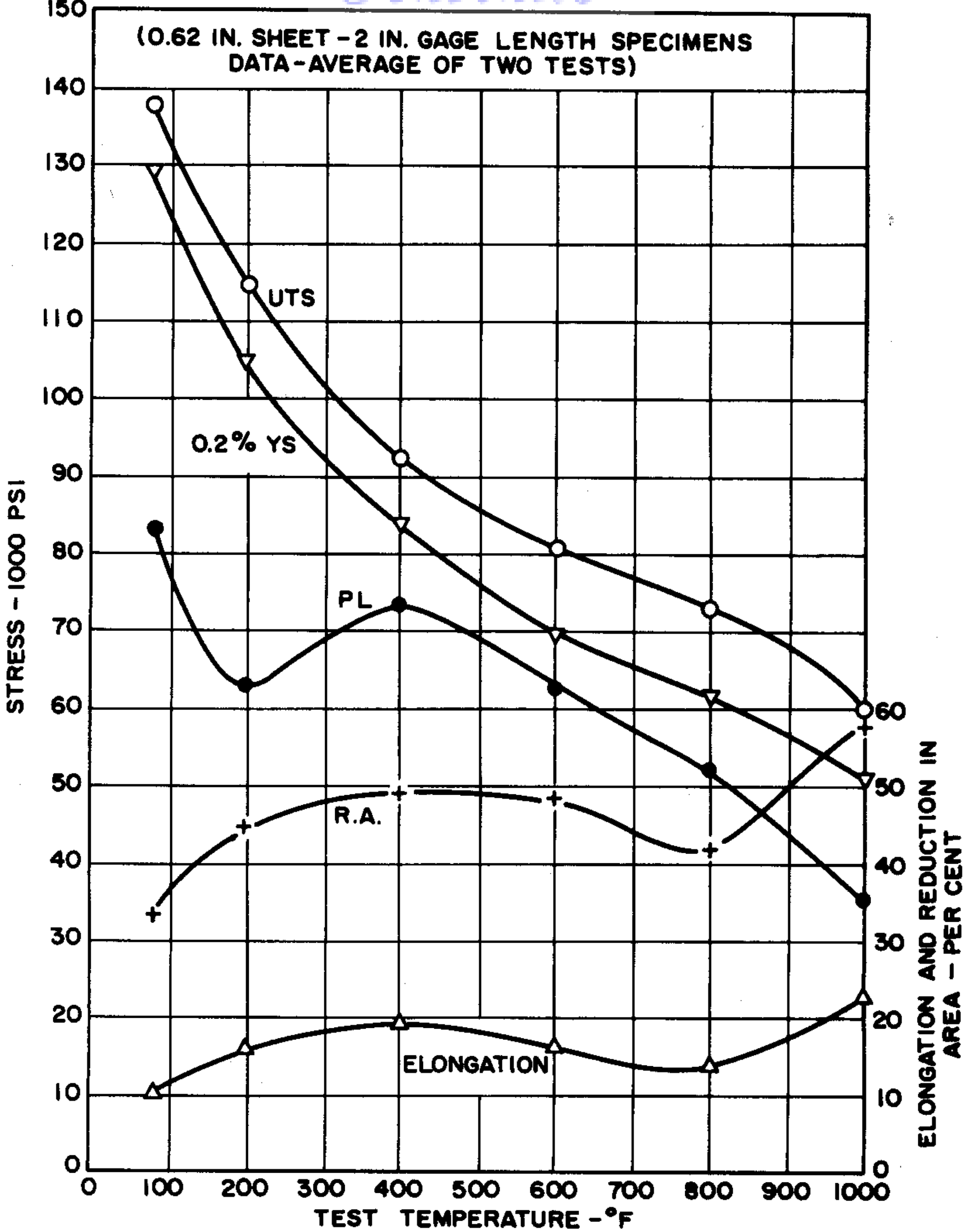
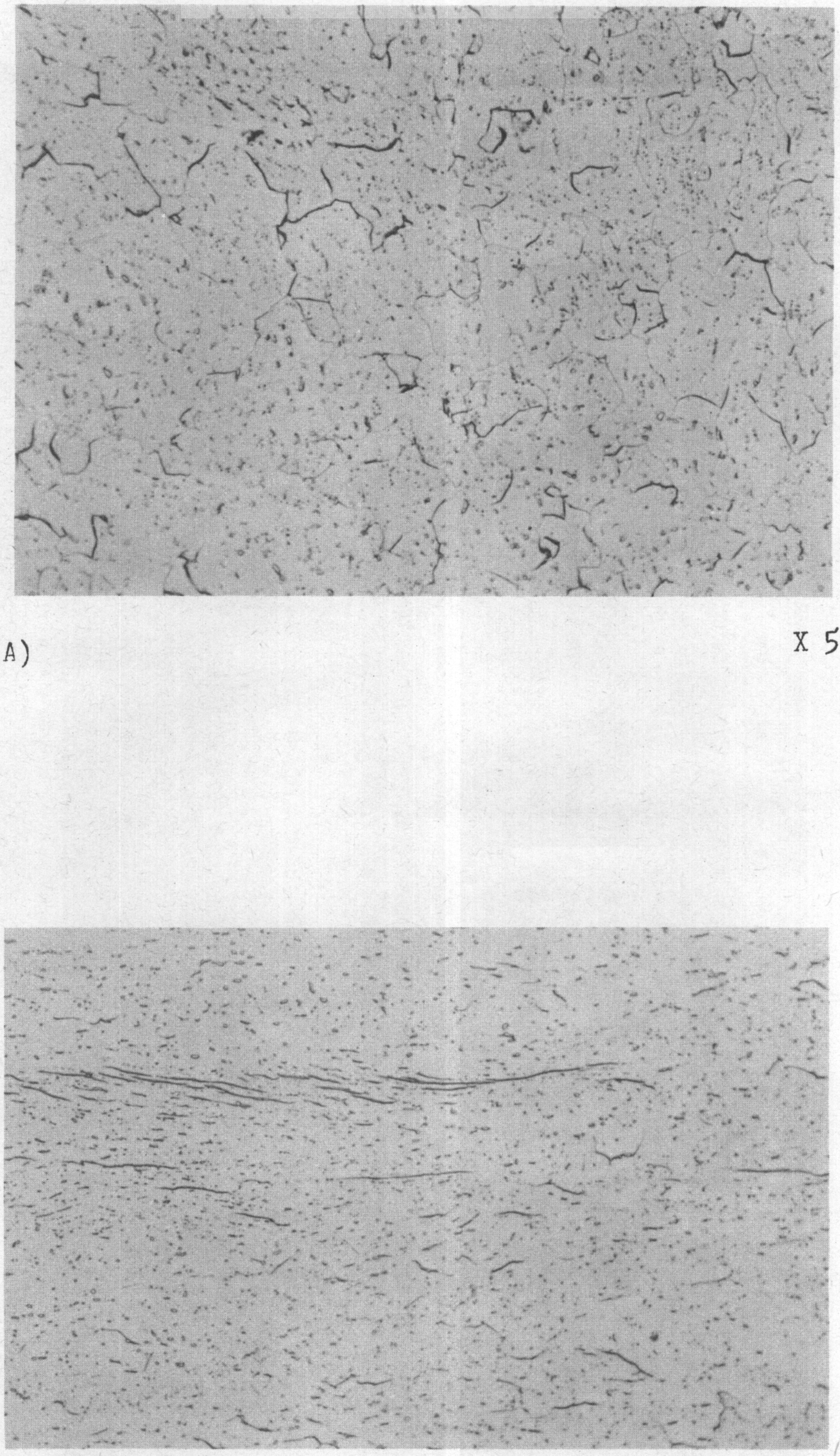


FIG. 5 - SHEET TENSILE PROPERTIES VS. TEMPERATURE
ARMOUR Ti - 6 % Al ALLOY



(A) X 500

(B) X 500

Fig. 6

Microstructure of Ti-6% Al sheet. (A) top view showing equiaxed structure and randomly dispersed second phase, and (B) side view showing second phase aligned in rolling direction.

Kellers Etch.

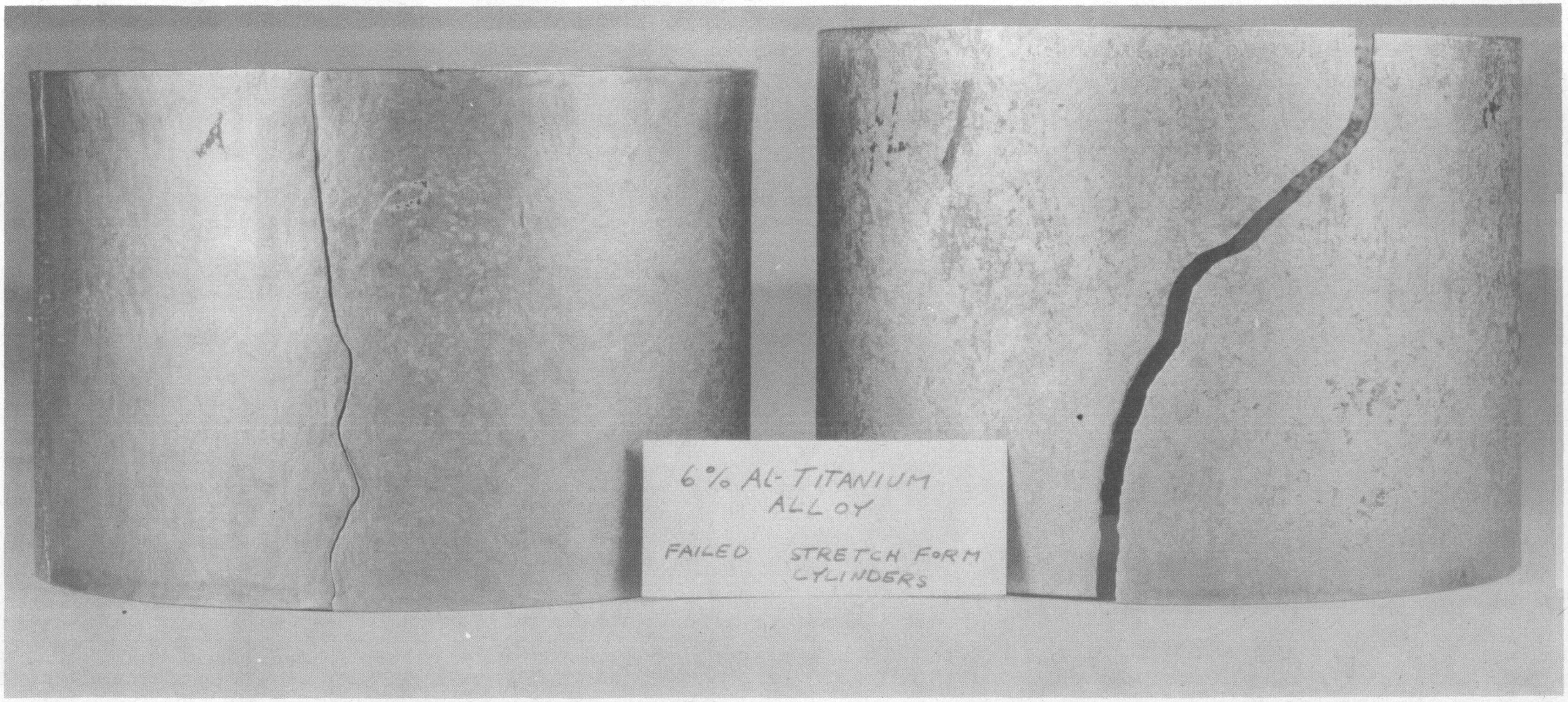


FIG. 7 - WELDED CYLINDERS AFTER RADIAL EXPANSION. CYLINDER AT LEFT IS SHORTER BY CONSTRUCTION. LEFT CYLINDER SHOWS SLIGHT DEFORMATION WHILE CYLINDER AT RIGHT SHOWS NO DEFORMATION.

APPENDIX IV

REPORT ON TESTS OF Ti-6% Al ALLOY

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Herein reported are data obtained from tensile, stress-rupture, charpy impact and fatigue tests performed on specimens machined from a forged experimental test ring of Ti-6% Al alloy.*

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* (This report contained no discussion of the results.)

TABLE I

TENSILE RESULTS ON ARMOUR Ti-6% Al ALLOY

Test Bar Identification	Test Temp. °F	Ultimate Strength psi	0.2% Yield Strength psi	Elong. (% in 1 in.)	RA %
A-1	600	97,900	64,200	12.0	28.5
F-1	600	97,900	70,600	12.5	29.5
K-1	600	95,400	67,400	12.0	29.0
N-1	600	97,700	70,600	12.5	30.5
A-3	800	85,700	60,000	13.5	35.0
F-3	800	83,200	57,200	17.0	34.0
N-3	800	83,000	58,400	17.0	38.0
K-3*	550	97,600	73,300	13.5	29.0
A-5	1000	48,000	41,000	29.0	72.5
F-5	1000	49,000	42,500	28.0	70.5
K-5	1000	45,700	39,200	43.0	75.5
N-5	1000	49,600	43,800	66.0	75.5

* Pulled at 550°F by mistake.

TABLE II

STRESS-RUPTURE TESTS Ti-6% Al RING

Test No.	Load, psi	Temp., °F	Hours to Rupture	Elong. (% in 1 in.)
N-4	50,000	1000	15.9	36.5
N-2	45,000	1000	28.8	38.5
J-4	55,000	900	a	
J-2		900	a	
E-4	69,000	800	a	
E-2		800	a	
A-4	65,000	700	a	
A-2	50,000	700	2176.5	No rupture - Test interrupted and reloaded.

a - Test incomplete at time of writing.

TABLE III

TABULATION OF PHYSICAL PROPERTIES
GENERAL ELECTRIC PART 19-1/4 x 16-1/4 x 1-7/8 RING
SPECIFICATION ARMOUR Ti-6% Al ALLOY IMPACT VS. TEMPERATURE

Test Location	Test Temp., °F	V-Notch Charpy Impact Strength Foot-Pounds
B-1	-100	15
B-4	-100	15
F-1	70	17
F-4	70	18
K-1	200	20
K-4	200	20
O-1	300	21
O-4	300	21
B-3	400	25
B-6	400	25
F-3	500	25
F-6	500	26
K-3	600	27
K-6	600	27
O-3	700	31
O-6	700	29
P-1	800	30
P-4	800	27

TABLE IV

FATIGUE PROPERTIES (KROUSE ROTATING BEAM) 2000 CYCLES PER MINUTE
ARMOUR Ti-6% Al ALLOY

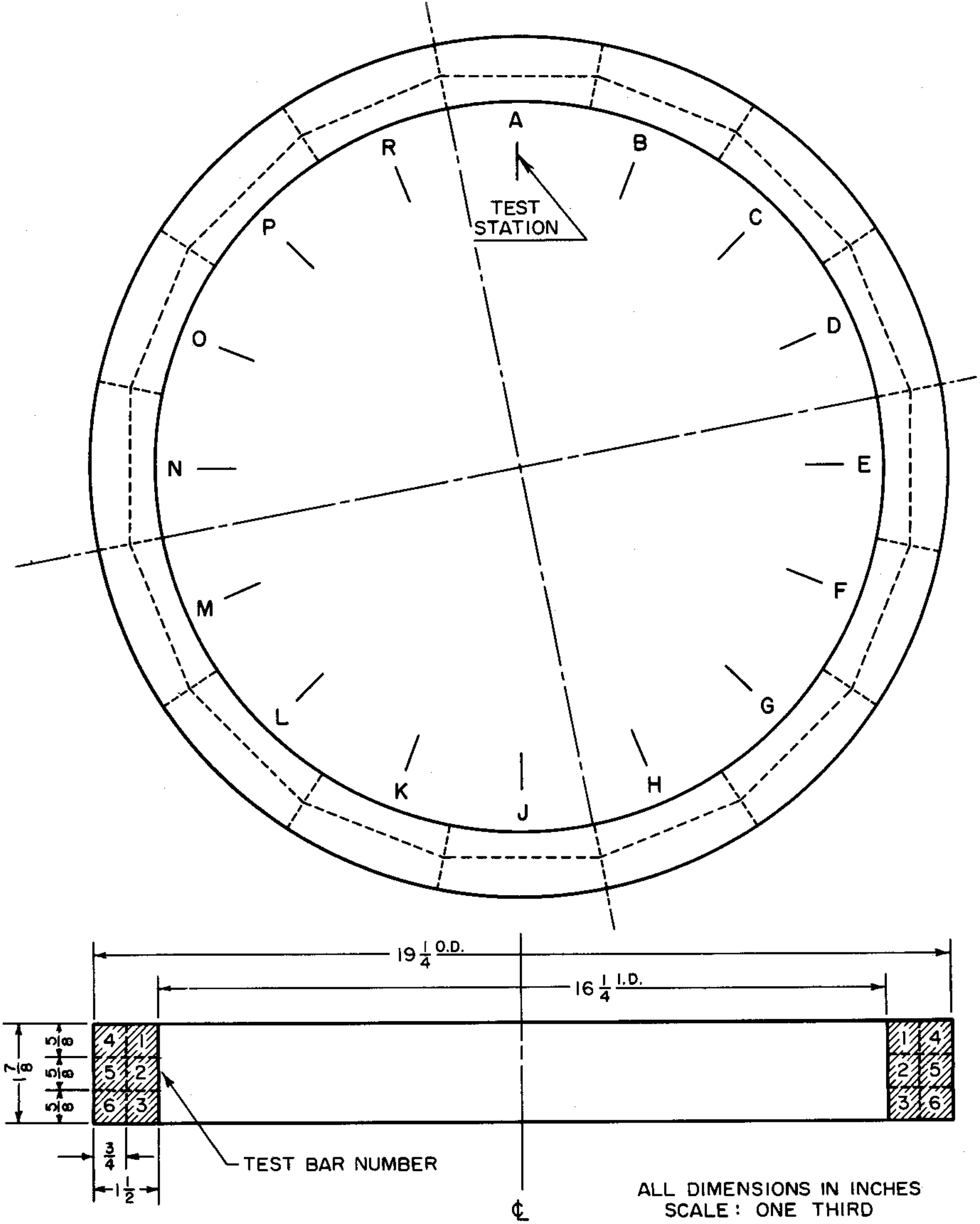
Test Location	Stress, psi	Cycles to Failure
B-2	100,000	11,200
B-5	100,000	7,000
F-2	90,000	12,900
F-5	90,000	18,700
K-2	80,000	33,900
K-5	80,000	24,100
O-2	70,000	66,700
O-5	70,000	32,600
C-1	65,000	82,600
C-2	65,000	10,666,000-->
G-1	65,000	120,500
G-2	67,500	15,093,200-->
C-3	62,500	160,000
C-4	69,000	49,200
G-3	60,000	14,286,900-->
G-4	68,500	10,193,400-->
L-3	61,000	16,716,800-->
L-4	68,000	29,600
L-1	62,000	104,926,000-->
L-2	66,000	80,380,000-->

--> Indicates no failure as removed.

TABLE V

GENERAL ELECTRIC EXPERIMENTAL RING
TEST PLAN Ti-6% Al ALLOY

Type of Test	Test Bar Size	Test Station	Location Test Bar Number	Test Conditions	
Tensile	0.252 dia.	A	1,3,5	To be tested by General Electric	
		E	1,3,5		
		J	1,3,5		
		N	1,3,5		
					Temp. °F
Charpy Impact	ASTM E 23-47 T	B	1,4		-100
		F	1,4		70
		K	1,4		200
		O	1,4		300
		B	3,6		400
		F	3,6		500
		K	3,6		600
		O	3,6		700
		P	1,4		800
Fatigue Krouse Rotating Beam	0.145			Stress, psi	CPM
	Smooth	B	2,5		
		F	2,5		
		K	2,5		
		O	2,5		
		C	1,2		
		G	1,2		
		L	1,2		
		P	1,2		
		C	3,4		
		G	3,4		
		L	3,4		
	Notched	P	3,4		
		C	5,6		
		G	5,6		
		L	5,6		
		P	5,6		
					Temp. °F
Stress Rupture	0.252 dia.				
		A	2,4		700
		E	2,4		800
		J	2,4		900
		N	2,4		1000



ALL DIMENSIONS IN INCHES
SCALE: ONE THIRD

GENERAL ELECTRIC EXPERIMENT RING TEST PLAN
TITANIUM 6% ALUMINUM ALLOY

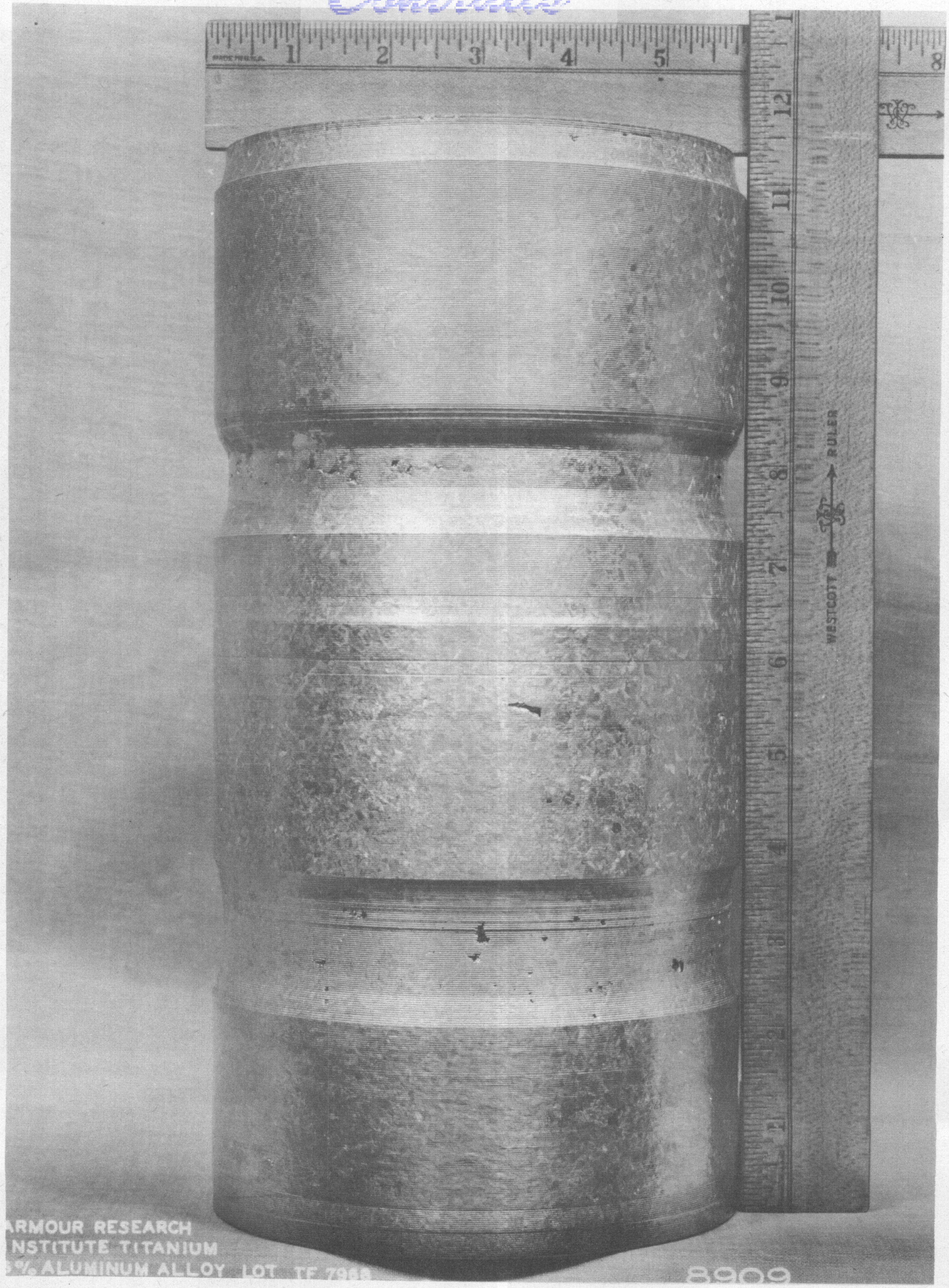


FIG. 2 - Ti-6% Al INGOT RECEIVED FROM ARMOUR RESEARCH FOUNDATION

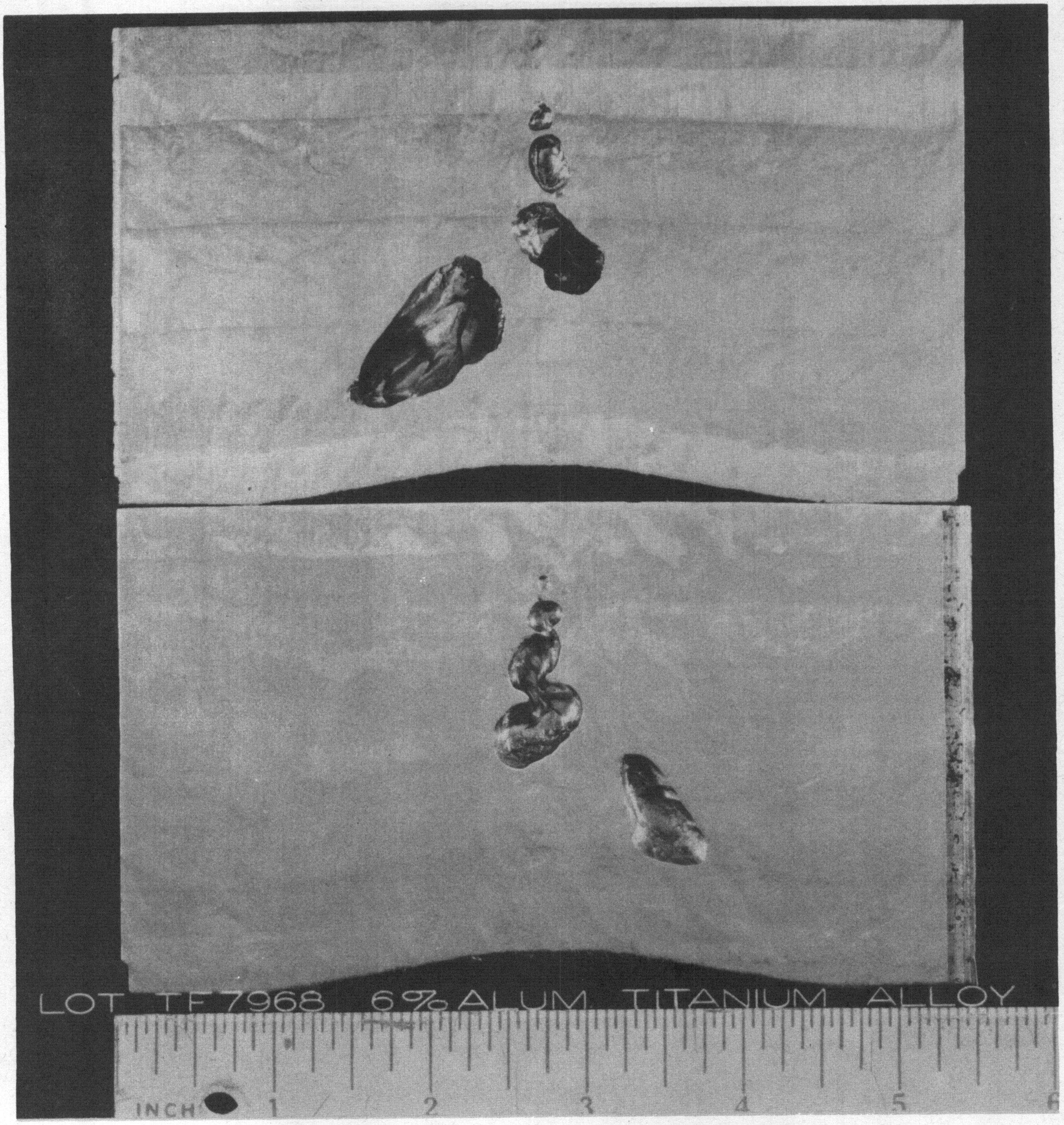


FIG. 3 - TOP OF Ti-6% Al INGOT SHOWING CAVITIES

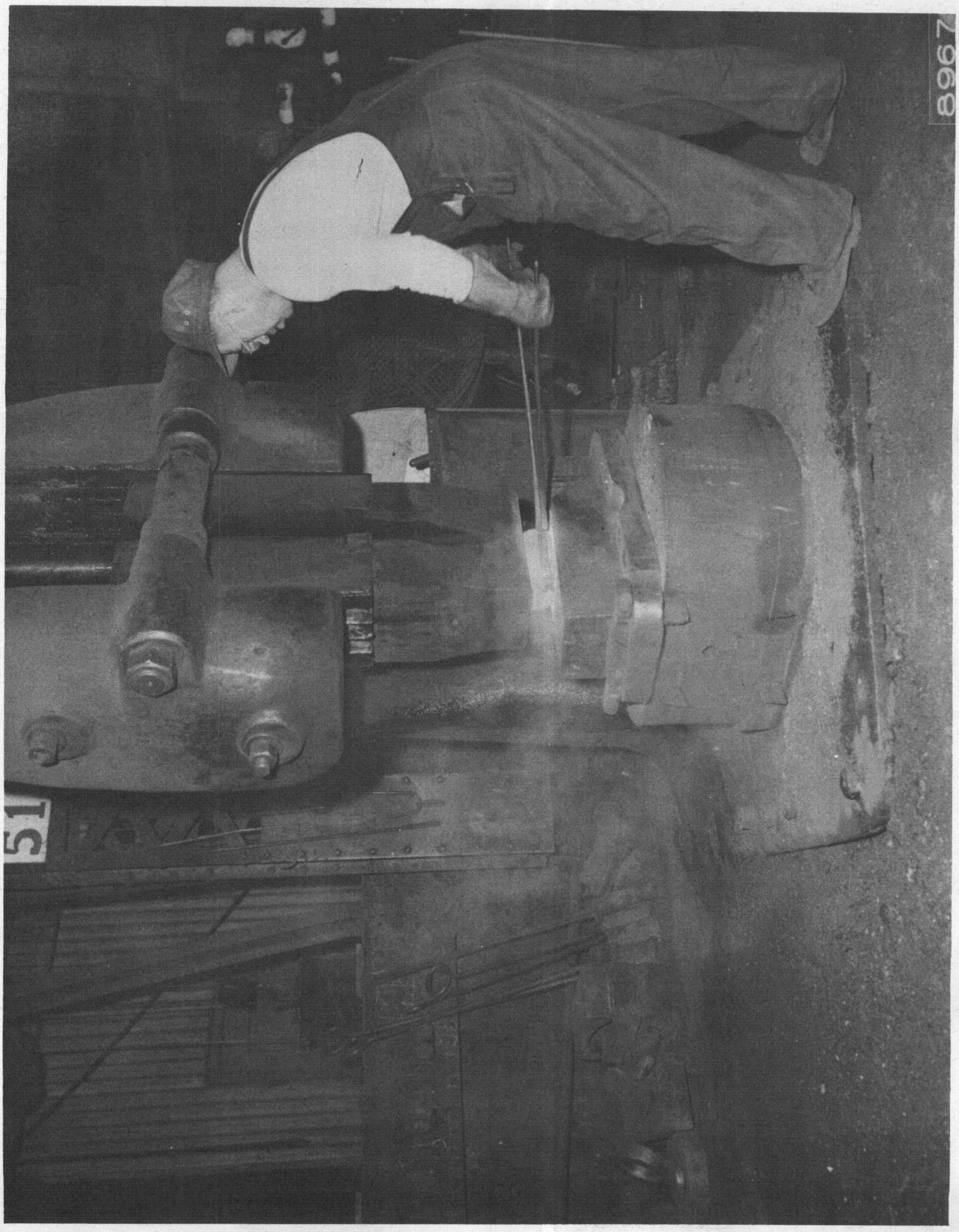


FIG. 4 - INITIAL FORGING TO PRODUCE RING

FIG. 5 - TITANIUM RING FORGINGS AT INTERMEDIATE STAGE IN FORGING OPERATIONS

FIG. 6 - TITANIUM RING FORGINGS

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