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PART II
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PILOT PRODUCTION, FABRICATION AND EVALUATION OF PROMISING TITANIUM ALLOYS

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WRIGHT AIR DEVELOPMENT CENTER
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Carpenter Litho & Prtg. Co., Springfield, O.
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FOREWORD

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I. INTRODUCTION

This report summarizes accomplishment under Air Force Contract No. AF 33(616)-2060, "Pilot Production of Promising Elevated Temperature Titanium-Base Alloys". The purpose of the current extension of this program was to produce approximately 300 pounds of a single titanium-base alloy for evaluation by jet engine manufacturers. The alloy was to be selected as the most promising from those being developed under Air Force Contract No. AF 33(038)-22806 sponsored by the Materials Laboratory at the Armour Research Foundation. The period covered by this report is from 1 April 1955 to 31 August 1957. Work of the previous contract period was reported in WADC TR 54-546 (November 1955).

II. PREPARATION OF ALLOY

A. Materials

The materials used in the preparation of 300 pounds of Ti-7Al-3Mo alloy are listed in Table I along with their analyses. Prior to melting, the titanium sponge was screened to remove all of the -20 mesh fraction, passed through a magnetic separator, and finally dried in a circulating air furnace held at 250°F for 3 hours. An average Brinell hardness of 114 was obtained on four 100-gram arc-melted samples. A portion of the aluminum and all the molybdenum used in the preparation were added as a master alloy. This master alloy was prepared by arc melting 200-gram buttons of nominally 78% molybdenum and 22% aluminum. The buttons were extremely friable and were easily crushed. The -8 +28 mesh fraction was used in making additions. Chemical analyses of a number of samples were in the range 22.99 to 23.20% aluminum, the average being 23.1%.

B. Melting

The alloy was prepared by the double arc melting process. This process and the equipment were described in the report for the previous period, WADC TR 54-546. Approximately 360 pounds of alloy were initially nonconsumable electrode arc melted into ingots weighing 11 pounds each. Ingots of this size were forged into convenient lengths of 1-1/2 in. diameter electrodes for remelting. The forged electrodes were centerless-ground, removing approximately 0.040 in. from the diameter, and screwed together for remelting. Remelting of the electrodes was performed in the consumable electrode arc melting furnace. It was intended to produce three 100-pound ingots. However, inadequate contact pressure on the electrode caused the cessation of operation after only 30 pounds of the first ingot were melted. After this difficulty was corrected, operations resumed and three additional ingots weighing 73, 101 and 114 pounds were obtained. After scalping, the ingots weighed 27, 68, 97 and 102 pounds, respectively. Analyses were taken from the scalpings and are given in Table II.

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TABLE I

MATERIALS

Material	Source	Form	Purity	Impurities, %
Titanium	E. I. duPont de Nemours	Sponge	114 Bhn	0.049 C, 0.133 Fe, 0.083 Mn, 0.011 N
Aluminum	Aluminum Co. of America	Granulated shot	99.8%	0.12 Fe, 0.07 Si
Molybdenum	Fansteel Metallurgical Corp.	Sheet	99.9+%	- - -

TABLE II

CHEMICAL ANALYSES OF Ti-7Al-3Mo ALLOY HEATS

Heat No.	Ingot Weight (lb)	Scalped Ingot Weight (lb)	Chemical Content (%)					
			Al	Mo	C	H	N	O
653	30	27	7.30 7.20	2.93 2.84	0.030	---	0.009	---
656	73	68	6.93 6.96	3.53 3.36	0.038	---	0.018	---
657	101	97	7.01 7.06	3.20 3.25	0.035	---	0.007	---
658	114	102	7.13 7.07 6.78	3.34 3.17	0.049	0.0072*	0.011	0.082*

* Analysis by Republic Steel Corporation, Massillon, Ohio.

C. Forging

Forging of the electrodes and the final ingots to 3-1/2 in. square billets was performed at the Lawndale Forging and Tool Works under the direct supervision of Foundation personnel. Drop forges with flat and swaging dies were used. The ingots were heated in an electric furnace to the forging temperature of 2050°F. The 3-1/2 in. square billets were shipped to Republic Steel Corporation, Massillon, Ohio, for rolling to bar. However, the size of equipment at Republic Steel prevented them from handling anything less than three feet long. Therefore, the 27-pound ingot (Heat No. 653) was returned to the Foundation. This ingot was forged to 1-1/4 in. square at 2000°F and finished to 5/8 in. round at 1800°F. The 68-pound billet (Heat No. 656) was forged to 2-1/2 in. square at Republic Steel Corporation to extend the length to the required minimum.

D. Rolling

All of the billets were thoroughly conditioned and supersonically tested by the Republic Steel Corporation prior to rolling. After testing, the billets were preheated for 2 hours at 1550°F, and then raised to 2000°F. The total time in the furnace for each billet was approximately 3 hours.

Dimensions of rolled bar obtained were 38 ft of 0.940 in. round (Heat No. 657), 30 ft of 1.222 in. round (Heat No. 658), and 30 ft of 0.625 in. round (Heat No. 656). These bars were centerless-ground to 0.875, 1.0156 and 0.575 in. round, respectively. The removal of 0.207 in. of stock from the 1.222 in. diameter bar was necessitated by the presence of two seams which ran the length of the rod. It is believed that these seams were the result of lack of experience in rolling this alloy. The alloy rolled with greater ease than anticipated and, since high roll pressures were used, the material lapped over on the corners to form seams which were not apparent until the grinding operation.

III. SUMMARY OF STEERING COMMITTEE MEETINGS

Steering committee meetings were held May 25, 1955; January 11, 1956; and February 26, 1957. The first meeting was held at the Foundation. Its purpose was to familiarize jet engine manufacturers' representatives with promising titanium-base alloys for use at elevated temperature, and to select an alloy for fabrication into jet engine parts for testing and evaluation. The second meeting was held at Thompson Products, Inc. The purpose of this meeting was to iron out procedural difficulties arising from changes in personnel and organization at Thompson Products. The final meeting was also held at Thompson Products after the forging process had been worked out and Thompson was ready to mass-produce the required blades. The purpose of this meeting was to review the steps in the manufacture of the blades and to reach an agreement on heat treatment and heat treatment procedures.

Participants of the May 25, 1955 meeting were:

Materials Laboratory, WADC - Lt. G. Hahn

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

Curtiss-Wright Corp., Wright Aeronautical Division - Mr. L. Luini

General Electric Co. (AGT Division) - Mr. G. Wile

Republic Steel Corp. - Mr. V. Whitmer

Thompson Products, Inc. - Mr. K. Bartlett

Westinghouse Electric Corp. (AGT Division) - Mr. W. Hazelton

Armour Research Foundation - Dr. E. H. Schulz, Mr. R. A. Lubker, Drs. D. J. McPherson and F. A. Crossley, Messrs. W. F. Carew and B. R. Rajala

The general objective of the program was to fabricate some 300 pounds of a promising titanium-base alloy into jet engine parts for evaluation. Fabrication was to be supervised by Foundation personnel for quality control. It was generally agreed that such supervision would be greatly facilitated by using a single vendor. The representatives of the jet engine manufacturers were asked to select parts for which forging dies were available and which they would be interested in evaluating.

It was generally agreed that alloys much stronger than those presently available, and useful to temperatures of 1000°F, were needed. It was considered that the Ti-7Al-3Mo alloy offered promise of meeting some anticipated and some actual needs. This alloy was the unanimous selection for the program. Compressor blades were concluded to be the most satisfactory parts that could be made.

Mr. Whitmer offered the services of the Republic Steel Corporation for rolling the bar stock. Mr. Bartlett offered the services of Thompson Products for manufacturing the compressor blades. These services were gratefully accepted.

Following this meeting, the jet engine producers participating in the program were surveyed by letter to determine the following:

(1) Part number, location of dies, and number of blades desired for evaluation.

(2) Type of testing planned.

(3) Bar stock desired.

The results of this survey are summarized in Table III.

In the fall of 1955 Mr. Bartlett left Thompson Products and a reorganization involving the department formerly under his supervision was effected. As a result of these changes it was deemed advisable to have a meeting at Thompson Products to discuss details of the blade forging program. The meeting took place on January 11, 1956 at the Coit Road Works. Present at the meeting were:

TABLE III

RESULT OF SURVEY FOR BLADE AND BAR STOCK REQUIREMENT

Company	Blade Designated	Number Desired	Testing Planned	Bar Stock Desired	
				Length, ft	Diameter, in.*
Allison Div. General Motors	J-35, 2nd stage	20-35	Bench	30	5/8
Curtiss-Wright Corp.	J-67 high pressure compressor 7th stage rotor 203069	20-118	Bench & engine if sufficient number available	10	1/2
General Electric (AGT Div.)	J-47, 4th stage No. 508E 143(?)	15-40	Bench	none	
Materials Laboratory	none			15	1/2
Pratt & Whitney	J-57, 7th stage	15	Bench	none	
Westinghouse Electric Corp. (AGT Div.)	none			15 ea. or 22.5 ea.	5/8, 7/8, 1; 7/8, 1

* Bar diameters given as centerless-ground.

Materials Laboratory, WADC - Lt. D. Wruck

Thompson Products, Inc. - Messrs. R. Paetz and E. Pekarek

Armour Research Foundation - Drs. D. Levinson and F. Crossley and Mr. B. Rajala

It was agreed that the best procedure from the standpoint of time, economy and conservation of material was to divide the program into two phases. The first phase was to consist of making a single blade configuration for evaluation of forgeability and reproducibility, simultaneously making thorough process development. About 100 blades were to be made. The second phase was to consist of making the remaining three blade configurations for the other participating engine companies. Since the J-57 7th stage blade was currently in production at Thompson Products, it required the least effort, time and cost to fabricate from the experimental Ti-7Al-3Mo alloy. Therefore, it was selected for the first-phase production.

Because of the organizational changes, the Thompson representatives did not believe that the company could forge the blades gratis as offered by Mr. Bartlett and were unable to make a definite commitment regarding their participation in the program at the close of the meeting. Lt. Wruck was requested to investigate the possibility of obtaining Air Force funds for subsidy. It was agreed to urge the participating engine companies to help relieve the financial burden by accepting forged blades and, when desired, doing the necessary root machining themselves.

It developed that $12,500 would have to be supplied to Thompson Products for the first phase of the program. This money was supplied by the Materials Laboratory through their contract with the Foundation. Pratt and Whitney initially requested 15 blades for bench testing; therefore, they were contacted to determine if they were willing to accept a larger number of blades for extensive evaluation including engine testing should preliminary results justify such. Pratt and Whitney graciously assented to this plan.

The meeting on February 26, 1957 at Thompson Products, Coit Road Works, was attended by the following persons:

Materials Laboratory, WADC - Lt. M. Grahm

Thompson Products, Inc. - Messrs. R. Paetz, E. Pekarek and W. Weddle

Armour Research Foundation - Dr. F. Crossley

The steps in the manufacture of blades were reviewed and sample pieces from each stage of fabrication were examined. Thompson personnel were very pleased with their preliminary experiences with the alloy and anticipated no difficulties in manufacturing the blades. It was agreed to heat treat the blades as follows: solution-treat at 1560°F in argon, air-cool and age at 1020°F for 24 hours in air. The time of the solution treatment was not set at this meeting, since it was desired to make it as short as possible. Thompson was requested to solution-treat tensile test specimens for times varying from 1/4 to 1 hour and age. The time of the solution treatment was to be selected after an appraisal of the tensile test data. Subsequent to the meeting this was done, and 1/2 hour was selected as the time.

IV. SUMMARY OF MATERIAL PREPARED AND DISTRIBUTED

Organizations which received material during the previous contract period (see Table V, WADC TR 54-546) but did not send reports of their evaluations were contacted for these reports. The only reports received were from Eaton Manufacturing Company. It was discovered that two billets which had been sent to the Republic Steel Corporation for rolling to bar for eventual distribution to Curtiss-Wright, General Electric, and Pratt and Whitney were never rolled because the identification papers had been misplaced. These billets remain at Republic Steel as of this writing. No reports were received on the Ti-6Al-4V alloy distributed. This alloy became commercial during the previous contract period. The volume of literature now available on this alloy makes the experience obtained with the limited quantities supplied under this program of little consequence.

Eaton Manufacturing Company made preliminary tests on Ti-7Al-3Mo alloy strip supplied. The results are given in Appendix I. The evaluation was stopped when their chemical analyses indicated a considerable off-analysis condition (5.66% Al, 2.31% Mo). However, no check was made with the Foundation at this time. Later, the Foundation obtained a sample of the material for analysis. The results obtained were 6.98% Al and 2.99% Mo, which checked with the original analyses made by the Foundation of 6.92% Al and 3.16% Mo. The Eaton report showed the strip to have a basically Widmanstätten structure (see Figure 2). Since the material was rolled at a nominal temperature of 1750°F, an equiaxed structure was expected. It appears that insufficient cold work was introduced to obtain complete recrystallization of the structure to the fully equiaxed condition.

Material distributions under the current contract are summarized in Table IV. The status of evaluation is also indicated in the table. The Johnston and Funk Titanium Corporation reported the 9/32 in. diameter hot-rolled Ti-7Al-3Mo alloy rod was experimentally converted to wire as small as 0.020 in. This wire was processed using the same lubricants, die design, speeds, and schedules that are standard with Johnston and Funk for titanium alloys. No breakage was experienced and no center condition was encountered. No problems in supplying production quantities of wire from bar and rod stock now on hand are anticipated.

The Materials Laboratory reported the following analysis for their material (Heat No. 656): 6.25% Al, 3.99% Mo, 0.03% C, 0.10% O, 0.017% N and 0.0038% H. The aluminum result is low and the molybdenum result is somewhat high compared to Foundation analyses of 6.94% Al, 3.44% Mo. Heat treated properties for a solution treatment of 1800°F-1 hour-water quenched were as follows:

TABLE IV

DISTRIBUTION OF Ti-7Al-3Mo ALLOY BAR STOCK DURING CURRENT CONTRACT PERIOD

Recipient	Dimensions: Dia. as Centerless Ground, in.	Dimensions: Length, ft	Purpose	Status of Evaluation
Allison Div., GM Attn. P. E. Hamilton	0.575	--	----	Nothing has been done and a low priority has been given this work.
Curtiss-Wright Corp., Attn. E. Lee	0.5	10	Mechanical properties	Will test fall, 1957.
Johnston & Funk Titanium Corp., Attn. E. R. Funk	0.5	5	Draw to wire	Successfully drawn to wire as small as 0.020 in.
Materials Laboratory, Attn. H. J. Middendorp	0.5	15	Heat treatment and mechanical properties	In progress.
Thompson Products, Attn. E. Pekarek	0.940 1.0156	13 25	Forge to J-57 7th stage blades	Completed successfully.
Westinghouse (AGT Div.) Attn. M. Parrish	0.575 0.875	22 23	Heat treatment and stability. Applicability for through bolts.	In progress.

Aging Temp (°F)	Time (hr)	UTS (psi)	0.2% YS (psi)	% RA	% El
1000	6	202,000	195,000	16	8
1100	6	192,000	184,000	29.3	10

Tests of creep and stress stability are in progress.

Thompson Products was eminently successful in forging the Ti-7Al-3Mo bar rolled by Republic Steel to J-57 7th stage compressor blades. Their report is given in Appendix II. Properties obtained for blades were excellent. The endurance limit of blades bench-tested at room temperature was 75,000 psi--5000 psi higher than for Ti-6Al-4V blades of the same configuration. The heat treatment, 1560°F-1/2 hour-air cooled, 1020°F-24 hours, selected for evaluation of the blades produced the following tensile properties: 170,000 psi ultimate tensile strength; 167,000 psi 0.2% offset yield strength; 49% reduction of area; and 16% elongation. A total of 140 acceptable blades were made. Fifty-five blades were semi-finished and heat treated for bench testing and metallurgical evaluation. The remaining 85 blades were withheld for finishing pending the preliminary bench evaluation of the 15 blades received by Pratt and Whitney.

The blades were manufactured according to the following schedule.

ROUTING

J-57 7th Stage Blades
Ti-7Al-3Mo Alloy

(1) Cut stock -- Cutomatic -- 1.015 in. dia. x 2-1/4 in. long
0.940 in. dia. x 2-5/8 in. long

(2) Burr ends of slugs

(3) Stress-relieve slugs -- 1250°F-1 hour-air cool (no atmosphere)

(4) Tumble blast -- 80 grit steel shot

(5) Heat and point -- 1750°F-15 minutes-air
Slug was dipped in Apex 1052 precoat
Fiske's BMI No. 4 Grade 2 used on dies

(6) Tumble blast -- 80 grit steel shot

(7) Polish cone section to remove defects -- 60 grit paper

(8) Tumble blast -- 80 grit steel shot

(9) Heat and extrude -- 1750°F-15 minutes-air
Slug was dipped in Apex 1052 precoat
Fiske's BMI No. 4 Grade 2 used on dies

(10) Tumble blast -- 80 grit steel shot

(11) Polish stem, neck, and head of extrusion -- 60 grit paper-endless belt-dry

(12) Stress-relieve extrusions -- 1250°F-1 hour-air cool (no atmosphere)

(13) Heat and blockdown -- 1700°F-10 minutes-air
Extrusions coated with Apex 1052
Acme JK die compound on dies

(14) Saw flash

(15) Table blast -- Zirconite sand

(16) Micropolish -- 100 grit paper-oil used

(17) Bench polish radius and adjacent airfoil -- 150 grit paper-dry

(18) Local repairs

(19) Micropolish repair -- 100 grit paper-oil used

(20) Stress-relieve -- 1200°F-1 hour-air cool (no atmosphere)

(21) Table blast -- Zirconite sand

(22) Heat and Coin

(23) Stress-relieve -- 1200°F-1 hour-air cool (no atmosphere)

Tentative Schedule

The next steps would be performed upon approximately 45 blades:

(24) Saw flash

(25) Solution treat in argon -- 1560°F-1/2 hour-air cool

(26) Age harden -- 1020°F-24 hours

(27) Table blast -- Zirconite sand (0.2 mil off surface)

(28) If necessary heat to 1200°F and restrike

(29) Table blast -- Zirconite sand

(30) Acid etch and inspect for defects

(31) Inspect for size, form, twist, bow -- correct bow and twist

(32) Cut off tong hold

(33) Snag grind edges (remove pimple and blend root flash)

(34) Finish micropolish airfoil -- 150 grit paper-oil used (0.5 mil off surface)

(35) Polish airfoil fillet and packing height-150 grit paper-dry

(36) File and blend L.E. and T.E. and tip

(37) Ship samples to Armour, WADC, and P & W

An initial shipment of 15 blades to Pratt and Whitney was made. Initial bench test results of Pratt and Whitney confirmed the data obtained by Thompson Products. Pratt and Whitney has ordered the root machined on the 85 blades remaining at Thompson Products for engine evaluation.

Westinghouse plans to evaluate the Ti-7Al-3Mo material for through-bolt application. Initial concern is stability of the as-received and heat-treated conditions. The determination of these stability data are awaiting the availability of test facilities.

V. STABILITY OF HIGH STRENGTH HEAT TREATMENT

Harvey Machine Company demonstrated that tensile strengths of about 200,000 psi with about 30% reduction of area could be obtained by applying to equiaxed microstructures the heat treatment: 1800°F-1 hour-water quench, 1000°F-2 hours, to the Ti-7Al-3Mo alloy.(1) The data obtained by the Materials Laboratory given on page 10 confirm this. Workers at the Foundation suspected that structures produced by such a heat treatment would be unstable under conditions of elevated temperature creep. In order to have an unequivocal evaluation of stability at 800°F, some extruded rods of Ti-7Al-3Mo alloy were obtained from Thompson Products. Duplicate specimens were given the 1800°F-1 hour-water quenched plus 1000°F-2 hours heat treatment, and the heat treatment applied to blades distributed for initial evaluation. Also, since recent work had shown the Widmanstätten structure to be more creep resistant at 1000°F than equiaxed structures,(2) a pair of specimens were heat treated to produce a Widmanstätten structure and also tested. All of the specimens were exposed to stresses of 60,000 and 70,000 psi at 800°F for 300 hours. The results are tabulated in Table V. After exposure the specimens given the high strength heat treatment fractured in a brittle manner without yielding. The β grains were light etching in the unexposed specimens. In the exposed specimens they were partially dark etching, for the most part at grain edges, indicating progress in the aging reaction during the exposure. Apparently, continued aging of the β phase during exposure resulted in a brittle condition.

Unfortunately, there was not sufficient material to test a specimen heat treated 1900°F-1/2 hour-air cooled, 1020°F-24 hours before exposure. Judging

TABLE V

STABILITY DATA FOR Ti-7Al-3Mo ALLOY

		Exposure Conditions				Tensile Properties					
						Before Exposure			After Exposure		
Heat Treatment	Structure*	Temp °F	Stress psi	Time hr	Def, %	UTS, psi	RA %	El %	UTS, psi	RA %	El %
1560°F-1/2 hr-AC,	E	800	70,000	300	0.81	170,000	49.0	16.0	178,000	46.0	18.0
1020°F-24 hr-AC			60,000	300	0.39	170,000	49.0	16.0	164,000	34.0	19.0
1900°F-1/2 hr-AC,	W	800	70,000	300	0.20	---	--	--	157,000	8.0	4.0
1020°F-24 hr-AC			60,000	300	0.21	---	--	--	159,000	10.0	8.0
1800°F-1 hr-WQ,	E	800	70,000	300	0.32	211,000	11.5	6.0	172,000	0.0	0.0
1000°F-2 hr-AC			60,000	300	0.14	211,000	11.5	6.0	166,000	0.0	0.0

* E - equiaxed, W - Widmanstätten.

from the fineness of the Widmanstätten structure, it is entirely possible that the ductility values after exposure are representative of those before exposure.

Creep data obtained from these stability tests are plotted in Figure 1. The curves A and B are for equiaxed structures and curve C is for the Widmanstätten structure. Under 70,000 psi stress the order of increasing creep resistance appears to be: A - medium strength equiaxed, B - high strength equiaxed, and C - medium strength (fine) Widmanstätten. The data suggest that this order might be different under a stress of 50,000 psi. Data for the Ti-6Al-4V alloy were included for comparison.(3) Note that the data for the Ti-6Al-4V alloy are for 750°F. Under the same stresses the Ti-7Al-3Mo alloy shows greater creep resistance at 800°F than the Ti-6Al-4V alloy at 750°F.

VI. SUMMARY AND CONCLUSIONS

Three hundred pounds of Ti-7Al-3Mo alloy ingots were prepared by the Foundation. Approximately 185 pounds were rolled to bar by the Republic Steel Corporation and 25 pounds were forged to rod by the Foundation. Distribution of bar stock was made to the following organizations: Allison Division of General Motors; Curtiss-Wright Corporation; Johnston and Funk Titanium Corporation; Materials Laboratory, Wright Air Development Center; Thompson Products, Inc.; and Westinghouse, Aircraft Gas Turbine Division.

As of this writing, Allison has done nothing with their material. While they desire to do some testing, a low priority has been given to evaluating this material. Curtiss-Wright plans to evaluate heat treatment, creep strength, and stability in the fall of 1957. Johnston and Funk has successfully drawn wire in sizes down to 0.020 in. diameter. Their standard practices were used and they anticipate no difficulties in making production quantities with the stock now on hand. Lt. Gegel of the Materials Laboratory is evaluating the relationship of heat treatment, elevated temperature strength, and stability.

Thompson Products was highly successful in forging J-57 7th stage compressor blades from bar stock. No special precautions were necessary. Extruding and forging were done in the temperature range 1650°-1750°F. Preliminary evaluations by Thompson Products and Pratt and Whitney were very promising. The endurance limit for blades bench tested at room temperature was 75,000 psi--5000 psi higher than for Ti-6Al-4V blades of the same configuration. Tensile properties obtained for a blade heat treated 1560°F-1/2 hour-air cooled, 1020°F-24 hours were: 170,000 psi ultimate tensile strength; 167,000 psi 0.2% offset yield strength; 49% reduction of area; and 16% elongation. Pratt and Whitney is preparing to make an engine evaluation of the blades.

Westinghouse is planning to evaluate the material for through-bolt application. Heat treatment, strength and stability will be investigated.

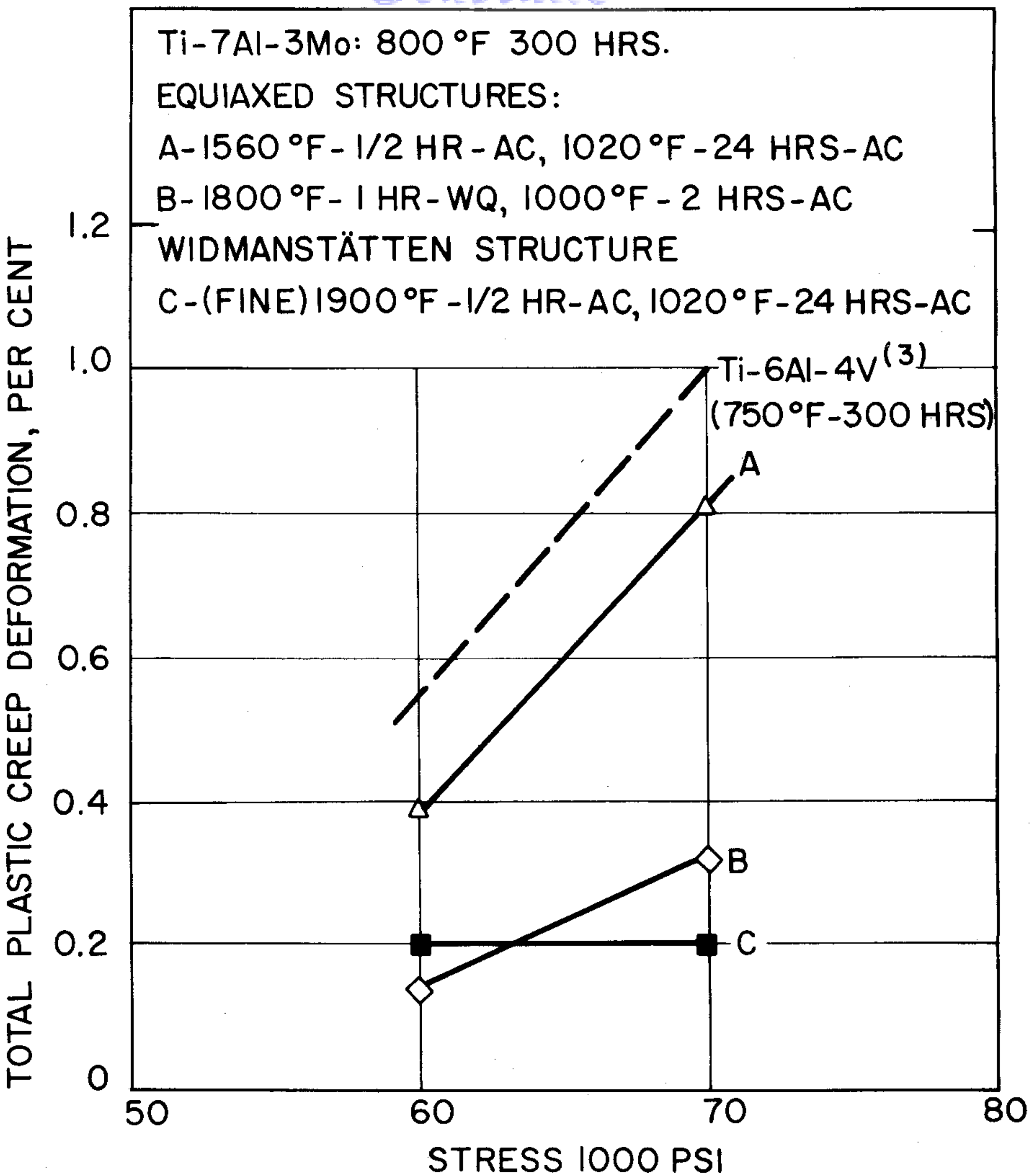

FIG. 1 - CREEP DATA FOR Ti-7Al-3Mo ALLOY AT 800 °F

In general, mechanical properties and pilot evaluations of the Ti-7Al-3Mo alloy to date highly recommend it as a new member of the family of commercial titanium-base alloys. In recognition of this, Cramet, Inc. produced between 1500 and 2000 pounds of the Ti-7Al-3Mo alloy for commercial sale. Also, Rem-Cru Titanium, Inc., has announced the availability on an experimental basis of their version of this alloy.(4) The Rem-Cru version has a slightly modified composition, viz., 6-1/2% aluminum, 3-3/4% molybdenum.

APPENDIX I

SUMMARY OF REPORTS ON TESTS OF Ti-7Al-3Mo ALLOY STRIP

Eaton Manufacturing Company
Aircraft Division
Battle Creek, Michigan

I. INTRODUCTION

Hardness and tensile tests were made on Ti-7Al-3Mo alloy strip manufactured by Armour Research Foundation.

II. DISCUSSION OF RESULTS

Chemical analysis of the material by National Spectrographic, Inc. gave the following: 5.66% Al, 2.31% Mo, 0.037% C, 0.0097% H, 0.24% Fe, and 0.010% N.* Tensile specimens were tested in duplicate in the as-received condition and in two heat treated conditions. After each thermal treatment hardness was measured on the Rockwell C scale. The hardness and tensile test results are given in Tables VI and VII, respectively. The microstructure for the as-received condition is shown in Figure 2. Microstructures for the heat-treated conditions are shown in Figures 3 and 4.

A slug was heated in a lead pot at 1650°F and one end was upset. Microstructures of longitudinal and transverse sections of the unforged and forged ends are shown in Figures 5 and 6, respectively. The working produced refinement of the α needles. A hardness survey showed that the forged end was R_c 40-41 compared to R_c 34-35 for the unforged portion. A 2-hour anneal at 1300°F softened the forged end to R_c 36 but produced no change in microstructure.

III. CONCLUSIONS

The as-received material shows a lower YS/TS ratio (compared to heat-treated material) which may be favorable to rolling.

Strength levels are improved after solution treatment and age hardening; however, tensile ductility is lowered.

Hardness is higher after duplex heat treatment.

The as-received material differs from Ti-6Al-4V alloy in that the β and α phases are massive. This implies that the β transus is higher--approximately 1900°F as compared to 1800°F.

Solution treatment at 1550°F for 4 hours results in more massive α. Since α is the strengthener of the alloy, this may explain its better creep properties.

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* Foundation analyses averaged 6.98% Al, 2.99% Mo.

The age-hardened condition of the alloy differs from the as-received in more random distribution of the α phase.

IV. CONTRIBUTING PERSONNEL

Laboratory reports on chemistry, forging and metallography were requested by D. Dunham and reported by W. Gee, Van Asperen and P. M. Settanni, respectively. Mechanical tests were conducted by N. Walters and reported by P. M. Settanni.

TABLE VI

HARDNESS OF Ti-7Al-3Mo ALLOY AFTER THERMAL TREATMENT

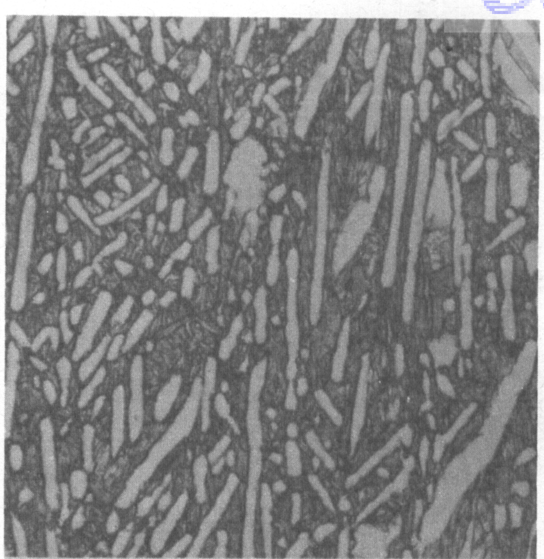
Special Test No.	As-Received Hardness, R_c	Heat Treatment For Forging	Hardness R_c	Solution Treatment	Aging Treatment	Hardness R_c
S-341	35.5-36	----	---	----	----	---
S-342	36.5	----	---	----	----	---
S-343	35.5-36.5	1700°F-8 min-AC	35.5-36.5	----	1000°F-24 hr	36.5-37.5
S-344	36.5	1700°F-8 min-AC	35.5	----	1000°F-24 hr	36.5-37
S-345	36.5	1800°F-8 min-AC	35	1560°F-4 hr-AC	1025°F-24 hr	37.5
S-346	36.5	1800°F-8 min-AC	35.5	1560°F-4 hr-AC	1025°F-24 hr	37.5-38

TABLE VII

MECHANICAL PROPERTIES OF Ti-7Al-3Mo ALLOY*

Heat Treatment	Test No.	Ultimate Tensile Strength (psi)	Yield Strength (0.2% Offset) psi	Elongation (in 4D) %	RA %	Ratio YS/UTS	Rockwell Hardness C Scale	Fracture Cup
As-received	T-377	156,300	132,800	13.4	37.6	0.84	36	60° V
	T-373	153,300	131,200	13.0	32.8	0.855	36.5	45° shear
1700°F-8 min-AC, 1000°F-24 hr	T-378	159,500	143,300	12.8	29.4	0.745	37.5	60° V
	T-375	156,000	140,400	12.8	33.6	0.895	37	1/4
1800°F-8 min-AC, 1560°F-4 hr-AC, 1025°F-24 hr	T-379	160,100	143,300	14.4	25.1	0.885	37.5	60° V
	T-376	163,000	146,400	13.6	24.3	0.895	38	45° shear

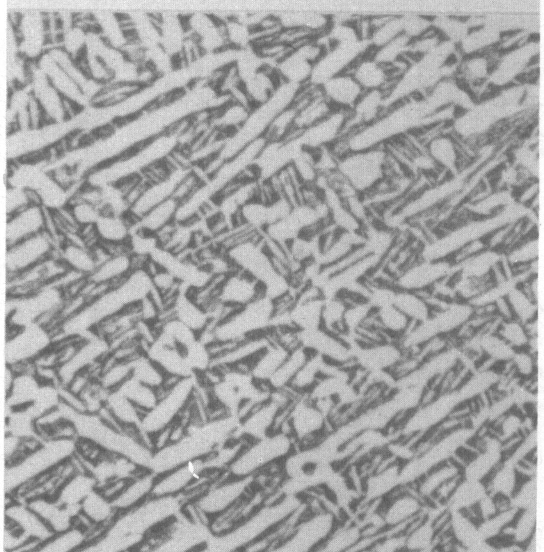
* Tests conducted on duplicate specimens.



Micrograph 782 X 1000
Specimen 2508

Fig. 2

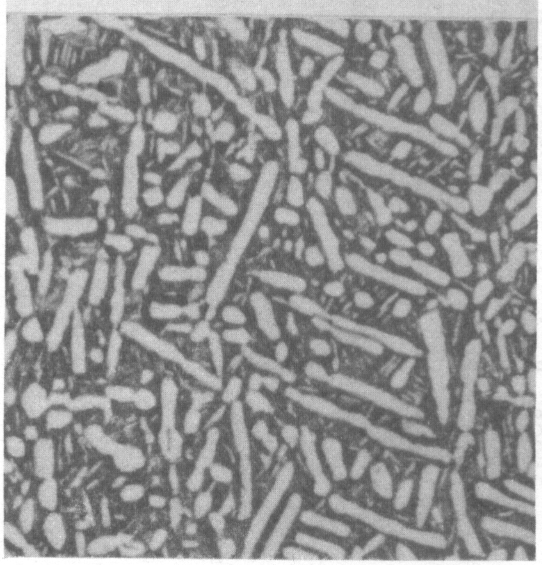
As-received microstructure of Ti-7Al-3Mo alloy. White massive area is α phase. Dark area is β phase. Hardness is R_c 35-36.



Micrograph 784 X 1000
Specimen 2509

Fig. 3

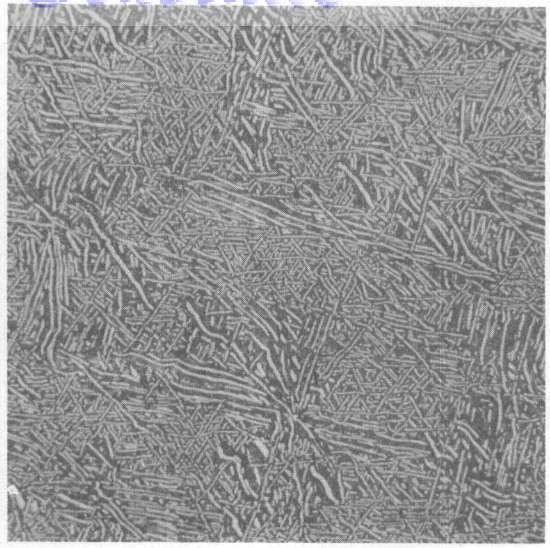
Ti-7Al-3Mo given 8 minutes at 1800°F-air cooled. Solution heat treated at 1560°F for 4 hours-air cooled plus age hardened at 1025°F for 24 hours. Alpha (white) phase more prominent and precipitation shown after age hardening. Hardness is R_c 37.5.



Micrograph 783 X 1000
Specimen 2507

Fig. 4

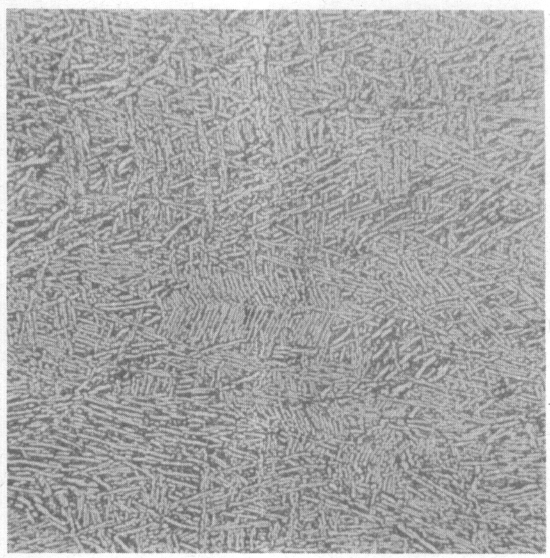
Ti-7Al-3Mo given 8 minutes at 1700°F-air cooled. Age hardened at 1000°F for 24 hours. Spheroids of α resulting from precipitation treatment. Hardness R_c 36.5-37.



Micrograph 756

Fig. 5

Unforged end of Ti-7Al-3Mo alloy showing random distribution of α needles (light areas) and β (dark areas). Hardness of this structure is R_c 34-35.



Micrograph 757

Fig. 6

Forged end of Ti-7Al-3Mo alloy showing refinement of α needles as a result of mechanical working. The random distribution does not change. Hardness of this structure is R_c 40-41.

Etchant: 1.5% HF, 1.5% HNO_3, balance water.

APPENDIX II

THE PILOT PRODUCTION, FABRICATION AND EVALUATION OF THE Ti-7Al-3Mo ALLOY COMPRESSOR BLADES

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I. INTRODUCTION

Ti-7Al-3Mo is a promising new titanium alloy in which the various builders of aircraft gas turbine engines have manifested an interest. This interest was first demonstrated in the steering committee meeting held at Armour Research Foundation in Chicago in May 1955. This committee included representatives of Pratt and Whitney, General Electric, Allison Division of General Motors, Westinghouse, Wright Aeronautical, Materials Laboratory of WADC, Republic Steel, Thompson Products, and Armour Research Foundation. The Ti-7Al-3Mo composition was chosen as the most promising of a group of alloys being developed by Armour under WADC Contract No. AF 33(038)-22806 titled "Titanium Alloys for Elevated Temperature Application".

After lengthy negotiations it was established in June 1956 that ingots furnished by Armour would be rolled to 1 in. diameter and 1.250 in. diameter bar stock by Republic Steel Corporation and that the smaller diameter stock would be utilized in the manufacture of a pilot lot of Pratt and Whitney J-57 7th stage compressor blades at Thompson Products. This particular design was chosen in order to take advantage of available forging tooling and to reduce the cost of the program. It was understood that if the initial evaluation of the parts was encouraging arrangements would be made to provide Pratt and Whitney with finished blades for engine testing.

Armour Research Foundation Purchase Order No. A-23858 was issued to the Jet Division of Thompson Products, Inc., to cover this work. It was amended in February 1957 to show the following breakdown of parts required:

1.	Pratt & Whitney bench testing	-	15 pieces
2.	Pratt & Whitney engine evaluation	-	60 pieces
3.	Materials Laboratory, WADC	-	4 pieces
4.	Armour Research Foundation	-	12 pieces
5.	Thompson Products, Inc.	-	12 pieces
	Total	-	103 pieces

II. DISCUSSION OF RESULTS

A. Material

Approximately 25 feet of 1.016 in. diameter and 13 feet of 0.940 in. diameter centerless ground bar stock were received from Republic Steel Corporation, Massillon, Ohio. Visual inspection of the as-received bar stock revealed a few seams in the 0.940 in. bar stock; no seams were observed in the 1.016 in. diameter stock. Both sizes of bar stock were rolled to considerably larger diameters, but processing difficulties at Republic necessitated grinding undersize to eliminate seams.

No complete chemical analysis was carried out on the as-received bar stock, but determination of aluminum and molybdenum verified the reported Armour results.

B. Extrusion Temperature Survey

Armour Research Foundation reported that the tensile properties, particularly ductility, of this alloy can be correlated with the microstructure. Therefore, a survey was undertaken to ascertain the forging temperature which would yield blade forgings with optimum tensile properties. Bar stock was extruded to 0.460 in. diameter after heating for 20 minutes at each of the following temperatures: 1600°, 1650°, 1700°, 1750°, 1800°, 1850°, and 2000°F. Tensile and metallographic specimens were prepared from the extrusions as extruded and heat treated 1560°F-1 hour in argon-air cool + 1020°F-24 hours in air-air cool.

The results of room temperature tensile tests are given in Table VIII and illustrated graphically in Figures 9 and 10. Variations in extrusion temperature did not yield any great differences in tensile properties. The above-mentioned heat treatment generally resulted in a slight decrease in ultimate strength, with little effect upon the elongation or reduction of area. The microstructures of the extrusions are discussed in the Metallography section of this report.

An extrusion and forging temperature range of 1650°-1750°F was selected after consideration of the following:

1. Tensile properties of extrusions
2. Microstructure of extrusions
3. Die life
4. Oxygen contamination

C. Manufacture of Blades

The major forging and finishing steps utilized in manufacturing these experimental semi-finished blades are illustrated in Figure 7. The blades were manufactured by a forging practice which consists of extruding bar stock, then flattening the extrusion between contoured dies. Previously this forging tooling had been used for the manufacture of the same parts from Ti-6Al-4V alloy.

The extruding and forging was performed at the upper limit of the 1650°-1750°F range established by the extrusion temperature survey. The Ti-7Al-3Mo alloy forged readily. No difficulties were encountered, nor was it necessary to observe any special precautions during processing. Nearly all of the few irreparable defects encountered were attributed to seams in the 0.940 in. diameter bar stock.

A total of 140 acceptable blade forgings were recovered. Of this number, 55 were given the following heat treatment prior to semi-finishing for fatigue testing and metallurgical evaluation:

Solution: 1560°F-30 minutes in argon-air cool
Age: 1020°F-24 hours in air-air cool

This heat treatment is similar to one reported by Armour to impart excellent ductility and stability to the Ti-7Al-3Mo alloy. The 1 hour solution heat treatment in vacuum recommended by Armour was revised because of the delays which would inevitably occur when attempting to air quench from a vacuum. The solution treatment time was reduced to 30 minutes to minimize oxygen contamination. The 30-minute solution heat treatment was evolved from microstructure and tensile property investigations which are discussed in the Metallography and Mechanical Properties sections of this report.

Pending results of fatigue tests at Pratt and Whitney, a total of 85 blade forgings are being held in the coined and trimmed condition for finishing to PWA Print No. 251807. This design will allow engine testing.

The blades for fatigue testing and metallurgical evaluation were finished by a procedure which avoided the considerable expense and delay involved in procurement of the necessary machining tooling which locates from a broached root.

The machined blades were stress-relieved at 1000°F for 2 hours, vapor blasted, and etched in an aqueous solution of 30% HNO_3-2% HF.

The blades were PEP Zyglo sound. Radiographic inspection indicated no voids within the blades. However, small high density indications appeared on the X-ray negatives of almost all of the semi-finished blades. These spots probably result from tungsten inclusions in the material which may have occurred in the initial melting operation.

D. Metallography

The microstructure of the as-received bar stock is shown in Figure 8. The bar stock exhibits a basketweave alpha-beta structure.

The microstructures of the bar stock extruded at 1600°, 1650°, 1700°, 1750°, 1800°, 1850°, and 2000°F as extruded and extruded and heat treated 1560°F-1 hour in argon + 1020°F-24 hours in air are illustrated in Figures 9 and 10, respectively. The bar stock extruded at temperatures of 1750°F and higher exhibits an unstable basketweave alpha-beta structure with primary alpha along the grain boundaries, the grain size decreasing with decreasing extrusion temperatures. Bar stock extruded at 1700°F and below exhibits a fine-grained structure consisting of a matrix of primary alpha in which equiaxed unstable beta is embedded. Bar stock extruded at 1850° and 2000°F and heat treated exhibits a more stable structure than does the as-extruded material. Material extruded at 1800°F and below and heat treated exhibits a fine-grained structure, consisting of a matrix of primary alpha in which equiaxed unstable beta is embedded.

The microstructures of airfoil sections of coined blades, as coined, coined and solution treated at 1560°F for both 15 and 30 minutes in argon, and aged at 1020°F for 24 hours are illustrated in Figure 11. The structure, in all three cases, consists of equiaxed unstable beta embedded in a matrix of primary alpha. There was no evidence of oxygen contamination, even in heat treated blades examined prior to stock removal by blasting or polishing.

The microstructure of a semi-finished blade solution treated at 1560°F-30 minutes in argon-air cool and aged at 1020°F-24 hours in air-air cool is illustrated in Figure 12. The microstructure in all sections of the blade consists of equiaxed unstable beta embedded in a matrix of primary alpha. No oxygen contamination was observed in any portion of the blade.

E. Mechanical Properties

The room temperature tensile and hardness properties of the as-coined blades and coined blades solution treated at 1560°F for both 15 and 30 minutes followed by aging at 1020°F for 24 hours are given in Table IX. For comparison, the room temperature tensile properties of the Ti-6Al-4V alloy, currently being used for the production of this part, are also given in Table IX. The 30-minute solution treatment resulted in a somewhat higher tensile strength than did the 15-minute solution treatment, and was therefore adopted for the blades which were semi-finished for fatigue strength and metallurgical evaluation. The 170,000 psi ultimate and 167,000 yield strength (0.2% offset) of the Ti-7Al-3Mo blades are considerably higher than the 135,000-140,000 psi ultimate and 125,000-130,000 yield strength (0.2% offset) of the production 7th stage blades of Ti-6Al-4V alloy.

The room temperature hardness of R_c 36 of the semi-finished blades approaches the maximum hardness at which broaching is feasible.

The tensile properties at 800°F of heat treated extrusions of Ti-7Al-3Mo are given in Table X. For comparison, the tensile strength reported by Rem-Cru Titanium for the Ti-6Al-4V alloy at 800°F is also given in this table. The 122,000 psi ultimate strength and 101,000 yield strength of Ti-7Al-3Mo alloy are considerably higher than the 102,000 psi ultimate and 90,000 yield strength (0.2% offset) reported for the Ti-6Al-4V alloy.

Room temperature fatigue tests were made on the heat treated semi-finished blades. A brief description of the fatigue testing machine is as follows:

> The root end of the blade is clamped in a vise and compressed air is directed through a nozzle at the tip end to excite the blade to vibration at its natural frequency. Strain gauges are attached to the blade in the high stress area and the stress calculated from the strain during vibration and the modulus of elasticity of the material. The fatigue strength is determined as the maximum stress at which failure does not occur after vibration for 10,000,000 cycles.

The results of the fatigue tests are illustrated graphically in Figure 13. The Ti-7Al-3Mo blades have a fatigue limit of approximately 76,000 psi which is somewhat higher than the 70,000 psi fatigue limit exhibited by the 7th stage Ti-6Al-4V parts produced by a comparable procedure.

In view of the excellent mechanical properties exhibited by the Ti-7Al-3Mo alloy, it would appear that this alloy has potential for use as a compressor blade material. No difficulties were encountered nor was it necessary to observe any special precautions in the processing of this alloy. Therefore, it is anticipated that the Ti-7Al-3Mo alloy would be readily adaptable to manufacturing procedures for the mass production of compressor blades.

III. SUMMARY

A pilot lot of Pratt and Whitney J-57 7th stage compressor blades was successfully manufactured by a precision forging technique. A total of 50 blades with the leading and trailing edges to size, but with tip and root unfinished, were manufactured. These parts were to be utilized for fatigue testing by Pratt and Whitney and metallurgical evaluation by Armour Research Foundation, Materials Laboratory WADC, and Thompson Products.

If required for engine testing, a total of 85 unfinished blade forgings are available for finishing to PWA Print No. 251807. Arrangements are to be worked out with Pratt and Whitney and Armour Research Foundation for the finish machining of these parts since they were not covered under this program.

IV. CONCLUSIONS

(1) The results obtained on this program show the Ti-7Al-3Mo alloy to be readily adaptable to manufacturing procedures required for the quantity production of compressor blades. No difficulties were encountered, nor was it necessary to observe any special precautions in the processing of this alloy. The forging temperature range for this alloy is 1650°-1750°F.

(2) Metallographic examination showed that the Ti-7Al-3Mo alloy was not susceptible to oxygen contamination during processing.

(3) The room temperature tensile properties determined on heat treated blades of Ti-7Al-3Mo are commensurate with the properties reported by Armour for this alloy. The 170,000 psi ultimate strength and 167,000 psi yield strength of the Ti-7Al-3Mo blades are superior to the 135,000-140,000 psi ultimate strength and 125,000-135,000 psi yield strength of Ti-6Al-4V alloy currently required for the production of this part.

(4) The 122,000 psi ultimate strength and 101,000 psi yield strength determined on extruded bar stock of the Ti-7Al-3Mo alloy at 800°F are superior to

the 102,000 psi ultimate strength and 90,000 yield strength reported by Rem-Cru Titanium for the Ti-6Al-4V alloy.

(5) The average fatigue limit of the Ti-7Al-3Mo blades is 76,000 psi as compared with 70,000 psi obtained on Ti-6Al-4V parts manufactured by the same procedure.

TABLE VIII

ROOM TEMPERATURE TENSILE PROPERTIES OF Ti-7Al-3Mo
BAR STOCK EXTRUDED AT VARIOUS TEMPERATURES

	As Extruded*			Heat Treated**		
Extrusion Temp (°F)	Ultimate Strength (psi)	El %	RA %	Ultimate Strength (psi)	El %	RA %
1600	168,000	13.0	44.3	159,300	16.0	40.0
	170,900	15.0	50.8	162,800	16.0	41.5
1650	171,500	15.0	45.5	160,500	16.0	45.0
	166,300	15.0	51.3	162,100	15.0	45.5
1700	170,000	16.0	48.8	163,600	16.0	43.9
	173,500	17.0	51.2	163,400	18.0	45.5
1750	177,100	13.0	51.2	167,200	17.0	44.7
1800	174,900	15.0	33.3	168,500	11.0	15.4
	168,000	16.0	44.7	166,000	18.0	45.2
1850	164,400	17.0	46.0	171,900	15.0	42.1
	165,000	12.0	19.5	167,200	17.0	40.0
2000	186,000	10.0	25.8	158,800	13.0	27.3
	175,500	12.0	29.3	168,100	16.0	31.7

* Extruded to 0.460 in. diameter from 1.016 in. diameter bar stock.

** Extruded + 1560°F-1 hour in argon-air cool + 1020°F-24 hours in air-air cool.

TABLE IX

ROOM TEMPERATURE TENSILE
AND HARDNESS PROPERTIES OF COINED BLADES

Heat Treatment	Ultimate Strength (psi)	Yield Strength (0.2% Offset) psi	El %	RA %	Hardness Rc
As coined	169,900	163,200	17.4	50.8	37
1560°F-15 min in argon-AC + 1020°F-24 hr in air-AC	164,300 163,800	161,800 161,200	17.4 18.5	44.6 48.0	36
1560°F-30 min in argon-AC + 1020°F-24 hr in air-AC	171,100 168,600	168,700 165,200	17.4 15.2	49.9 47.9	36
Typical properties of Ti-6Al-4V blades manufactured by a comparable procedure	135,000-140,000	125,000-135,000	15-20	35-50	32-35

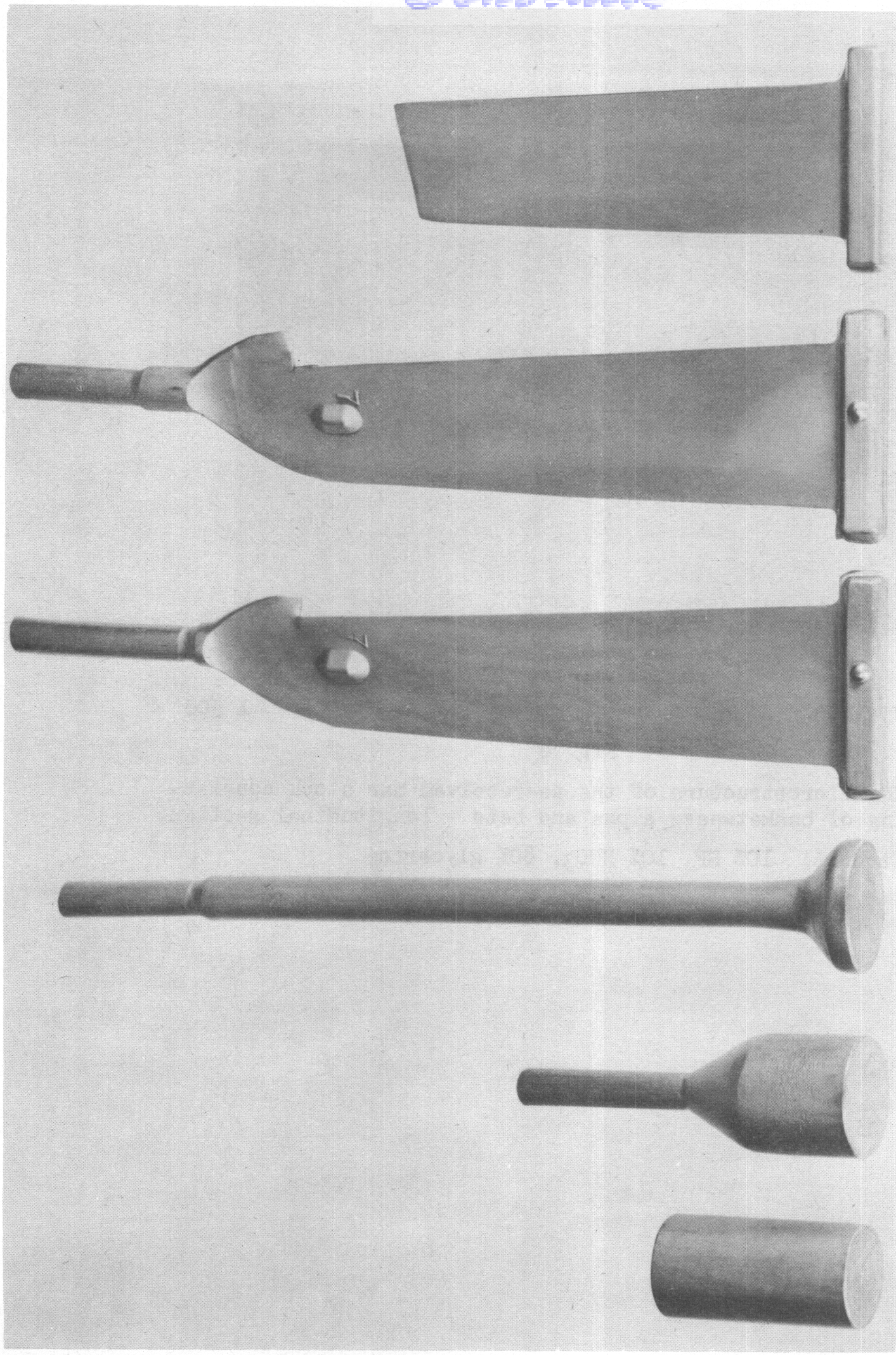
TABLE X

TENSILE PROPERTIES OF Ti-7Al-3Mo ALLOY AT 800°F

	Ultimate Strength (psi)	Yield Strength (0.2% Offset) psi	Elongation (%)	Reduction of Area (%)
(1)	121,500	101,700	21.1	60.8
(2)	123,200	101,200	22.0	62.5

Treatment: Extruded to 0.460 in. diameter from 1.016 in. diameter bar stock at 1750°F. Solution treated 1560°F-30 min in air-AC; aged 1020°F-24 hr in air-AC.

Note: Rem-Cru Titanium, Inc. reported the following properties for Ti-6Al-4V alloy at 800°F: 102,000 psi UTS; 90,000 psi YS (0.2% offset).

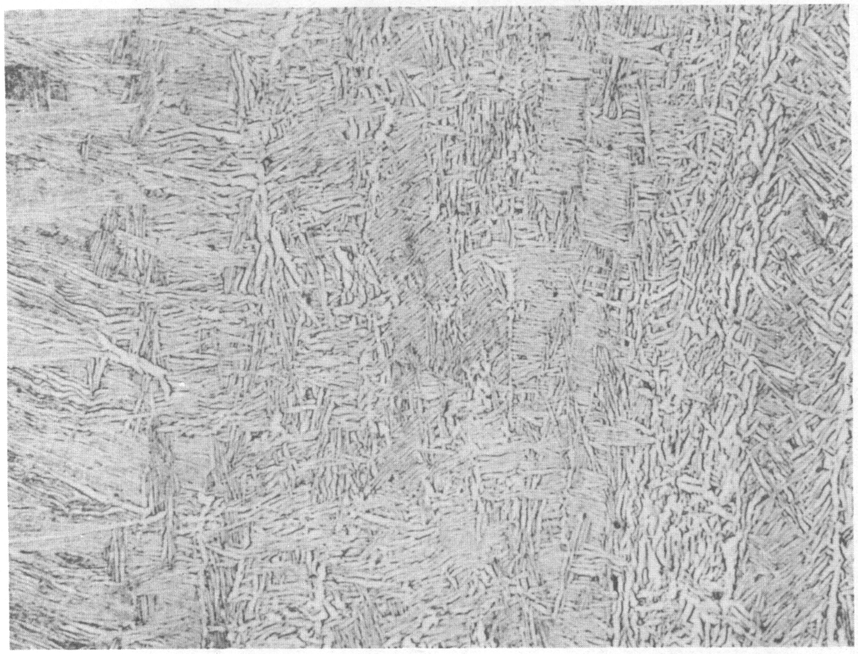


CP-1806

X 7

Fig. 7

STEPS IN MANUFACTURE OF SEMI-FINISHED BLADE

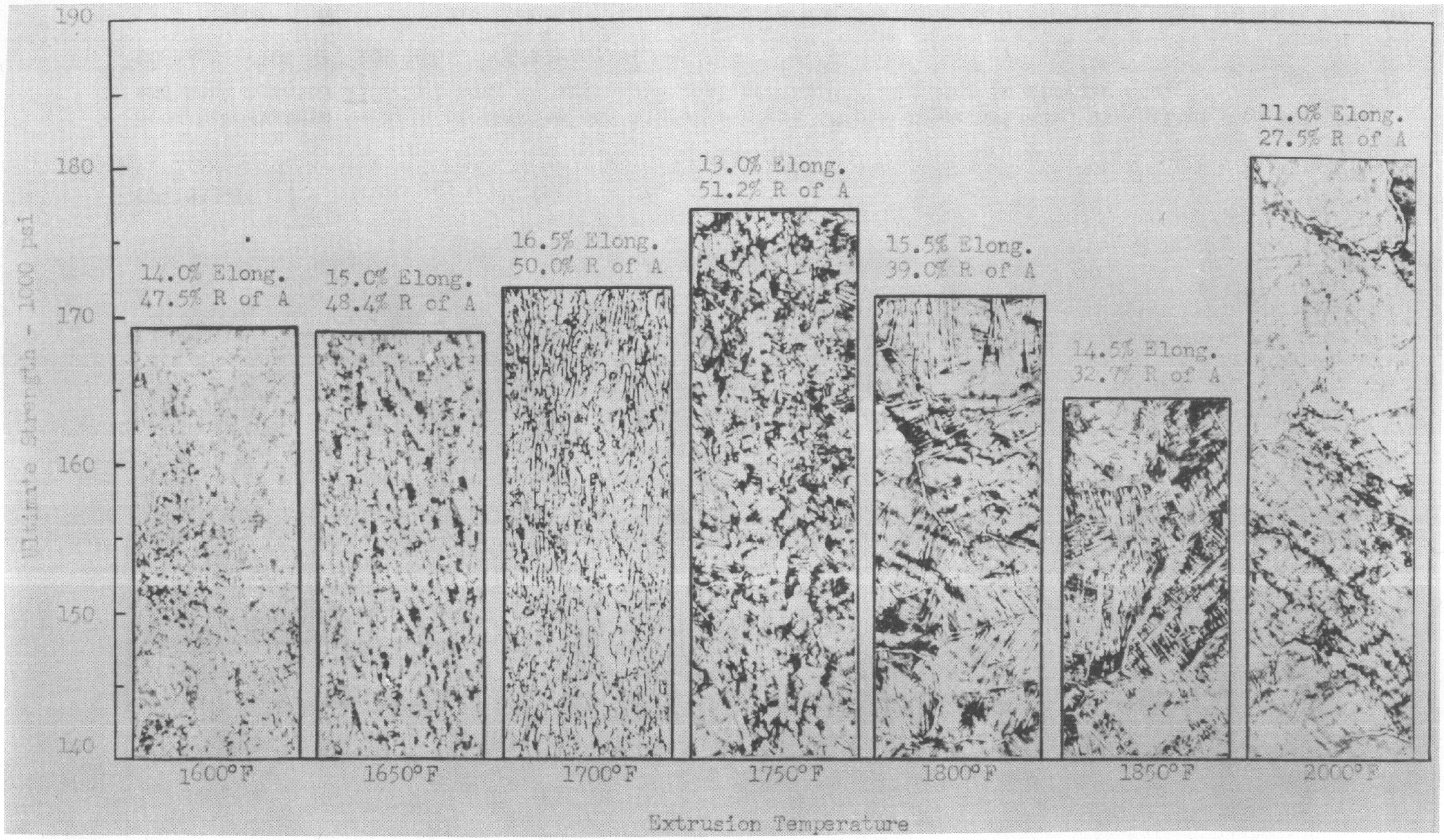


CP-1776 X 500

Fig. 8

The microstructure of the as-received bar stock consisting of basketweave alpha and beta - longitudinal section.

Etchant: 10% HF, 10% HNO_3, 80% glycerine.

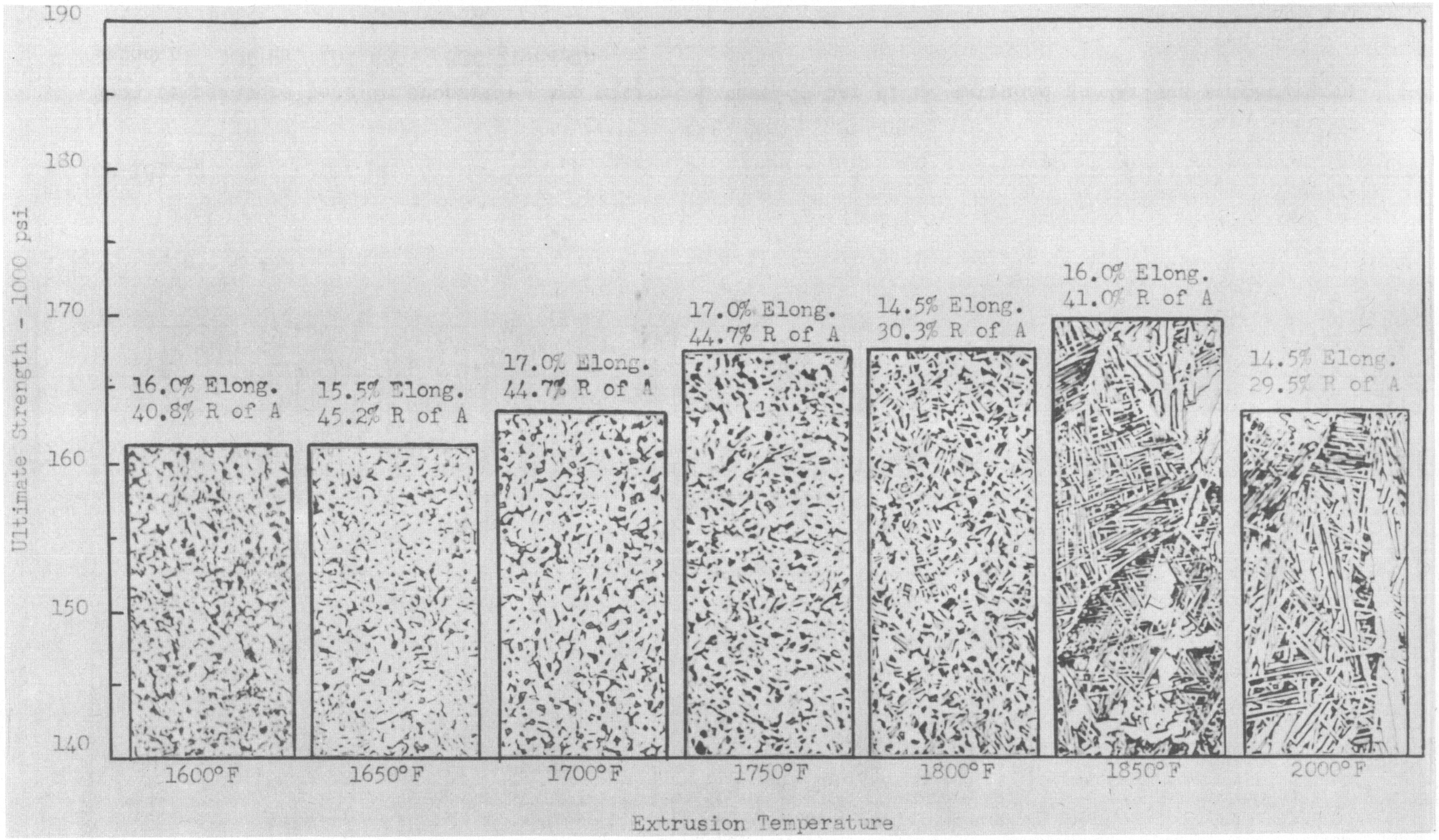


CP-1833-2 X 750

Fig. 9

Room temperature tensile properties and microstructure of bar stock extruded at various temperatures.

Etchant: 10% HF, 10% HNO_3, 80% glycerine.

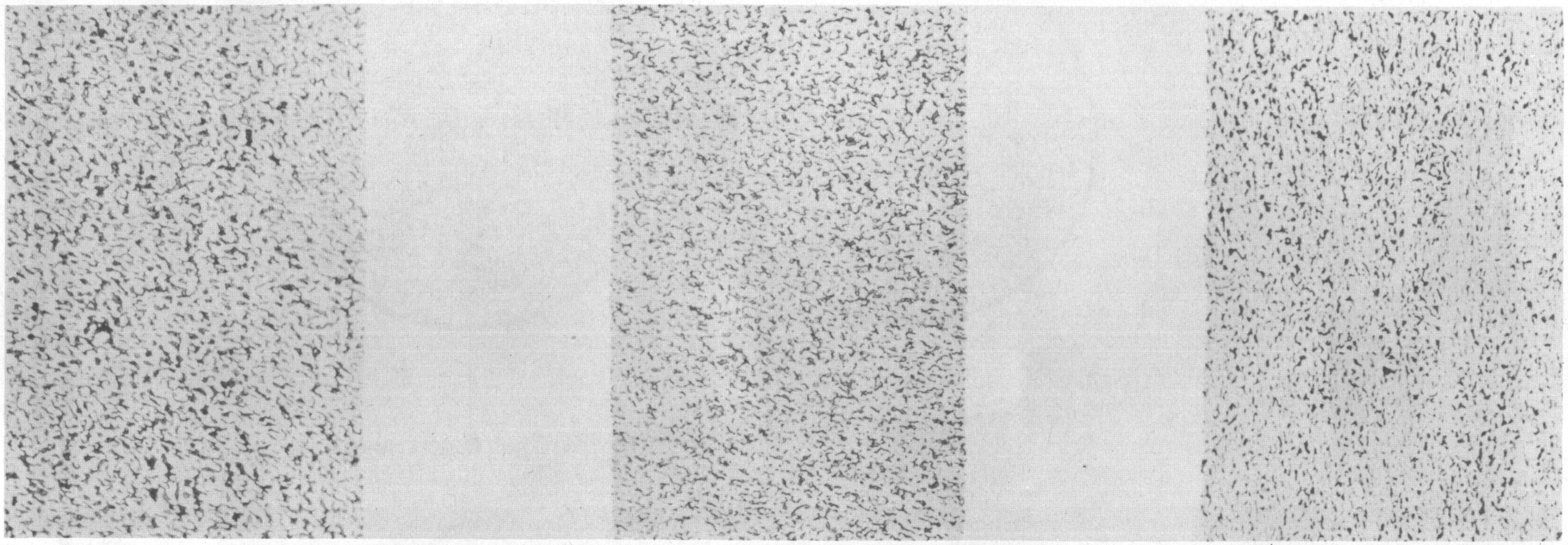


CP-1833-1 X 750

Fig. 10

Room temperature tensile properties and microstructure of bar stock extruded at various temperatures and heat treated 1560°F-1 hour in argon-air cool and 1020°F-24 hours in air-air cool.

Etchant: 10% HF, 10% HNO_3, 80% glycerine.

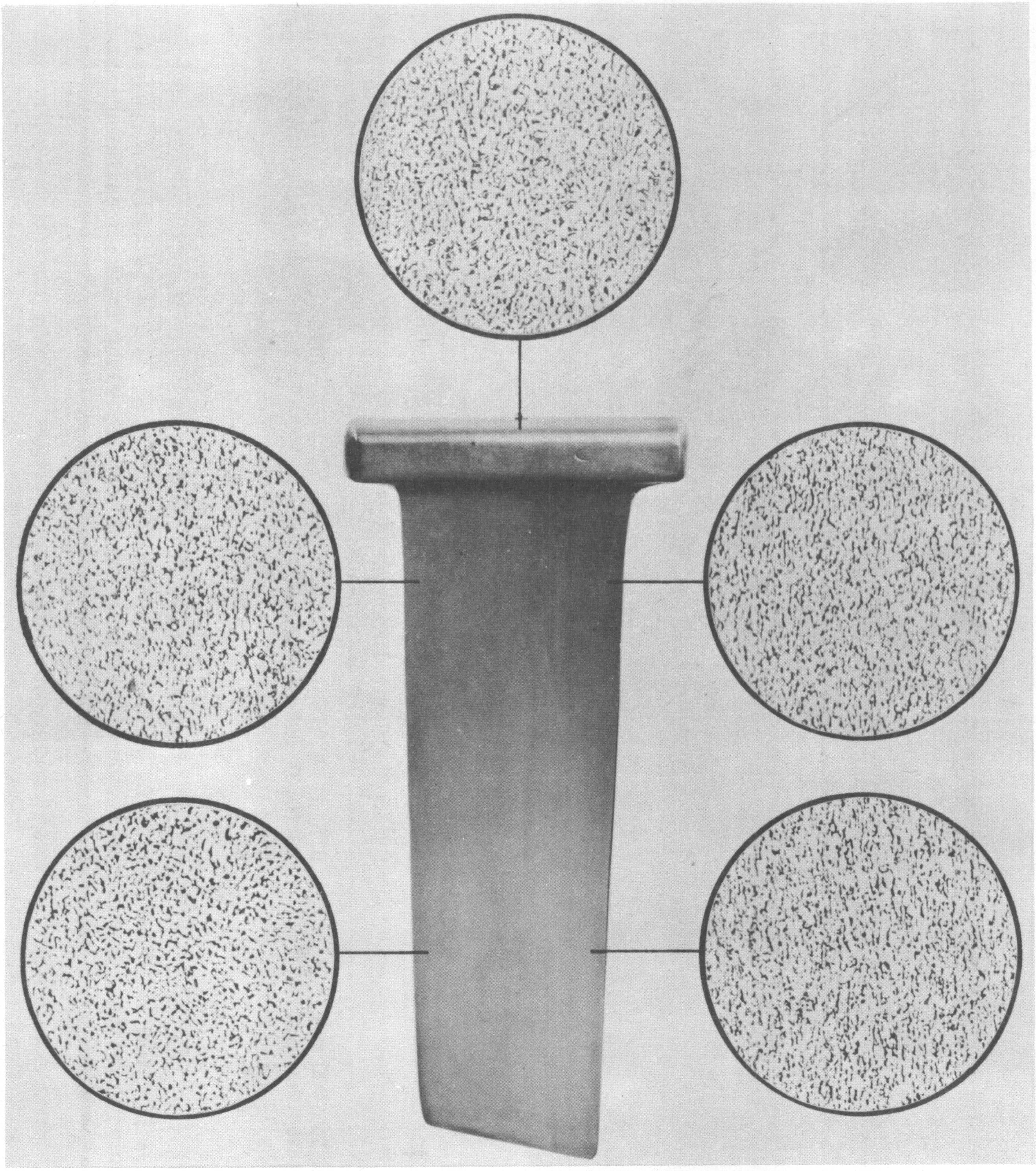


CP-1643		CP-1647		CP-1648	
As-coined		Coined + 1560°F-15 min in argon-AC 1020°F-24 hr in air-AC		Coined + 1560°F-30 min in argon-AC 1020°F-24 hr in air-AC	
UTS	169,900 psi	UTS	164,000 psi	UTS	170,000 psi
YS (0.2% offset)	163,200 psi	YS (0.2% offset)	161,500 psi	YS (0.2% offset)	167,000 psi
El	17.4%	El	17.9%	El	16.3%
RA	50.8%	RA	46.3%	RA	48.9%

Fig. 11

The microstructure and room temperature tensile properties of coined blades subjected to solution treatments of 15 and 30 minutes duration. In all cases, the matrix consists of primary alpha in which equiaxed unstable beta is embedded. X 500.

Etchant: 0.5% HF.



CP-1833 X 500

Fig. 12

The microstructure of a semi-finished blade. Solution treated 1560°F-30 min in argon-AC and aged 1020°F-24 hr in air-AC. The microstructure throughout the blade consists of a matrix of primary alpha in which unstable beta is embedded. Etchant: 10% HF, 10% HNO_3, 80% glycerine.

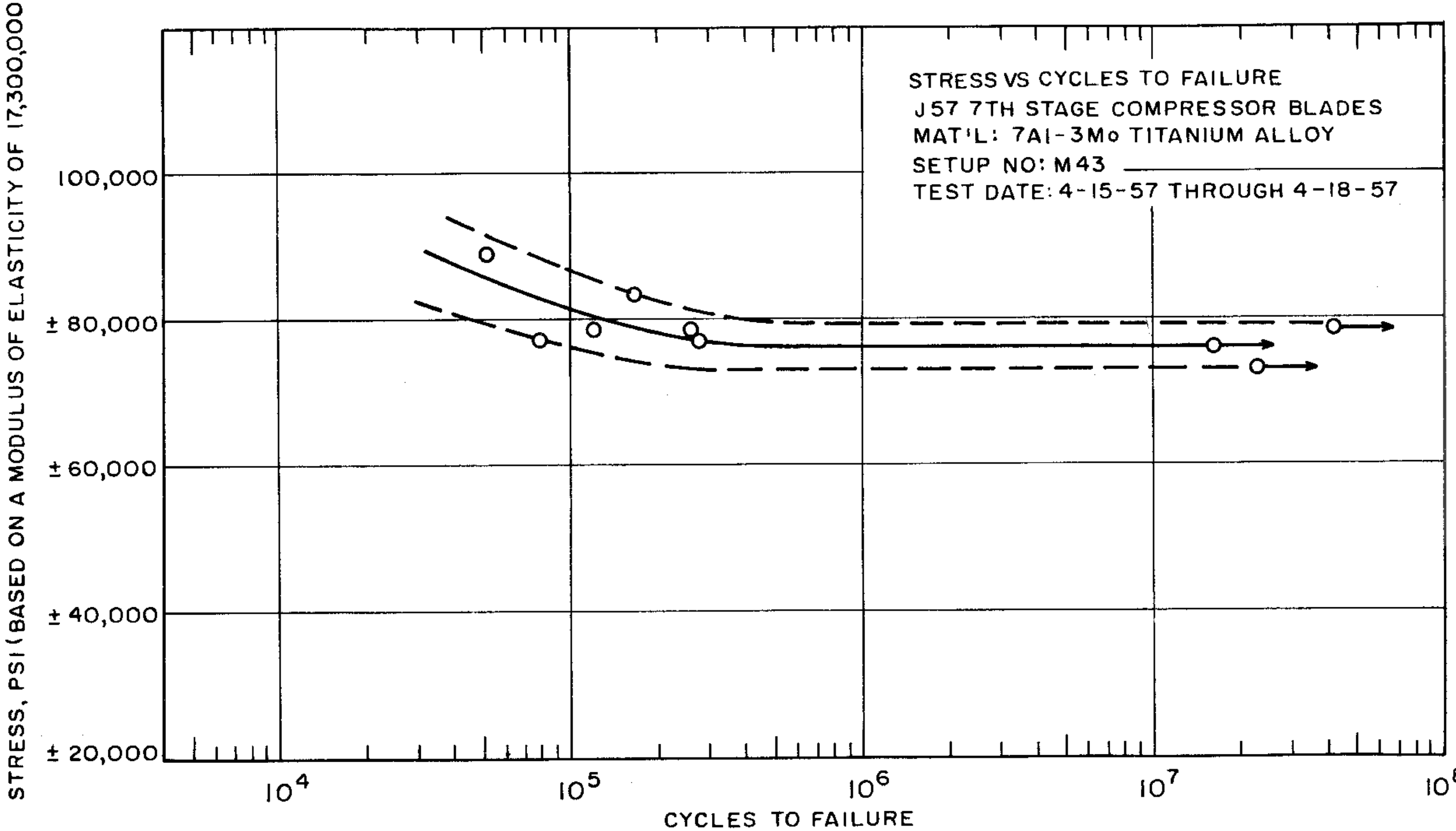


FIG. 13 - ROOM TEMPERATURE FATIGUE DATA FOR Ti-7Al-3Mo ALLOY J-57 7th STAGE COMPRESSOR BLADES UNDER COMPLETELY REVERSED STRESS

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