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SST Technology
Follow-On Program—Phase II
DEVELOPMENT OF IMPROVED TITANIUM 6AL-4V MILL PRODUCTS

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D6-60276

May 1974

FINAL REPORT

Task 1

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16. Abstract

In the SST prototype program, wide variations in mechanical and fracture properties of Ti-6Al-4V mill products were found. During DOT/SST Phase I follow-on work, these variations were shown to be related to composition, crystallographic texture, and microstructure. The Phase II follow-on program applied this technology as a basis to develop new material specifications for high toughness Ti-6Al-4V material. Specifications were prepared for sheet, plate, extrusions, bar, and forgings. The specifications emphasized tighter controls on composition, crystallographic texture, and microstructure, as well as minimum requirements for stress corrosion resistance. Verification testing was conducted on mill products procured to the requirements of the new specifications. The materials exhibited excellent fracture characteristics, with slight loss in tensile strength. Minor modifications to the specifications were incorporated as a result of verification test data.

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SYMBOLS AND NOMENCLATURE

AST	advanced supersonic transport
DCB	double cantilever beam stress corrosion specimen
I_L	texture intensity factor for longitudinal orientation
I_{ST}	texture intensity factor for short transverse orientation
I_T	texture intensity factor for transverse orientation
K_c	plane stress fracture toughness
K_{Ic}	plane strain fracture toughness
K_Q	mixed-mode fracture toughness (thick gage)
K_{scc}	threshold stress intensity level for stress corrosion in 3.5% NaCl (thin gage)
K_{Iscc}	threshold stress intensity level for stress corrosion in 3.5% NaCl (thick gage)
K_{SL}	stress intensity factor sustained at specified level for 20 minutes in aqueous 3.5% NaCl
R	minimum to maximum stress ratio in a fatigue test
RA	percent reduction in area in a tension test
R/t	ratio of bend radius to material thickness in the formability test
TD	transverse direction texture
TUS	ultimate tensile strength
TYS	0.2% offset tension yield strength
α	peripheral angle in pole figure
d2a/dN	crack growth rate (crack extension per cycle) in a fatigue test
σ_g	maximum gross area stress
ϕ	radial angle in pole figure
ΔTUS	transverse minus longitudinal tensile ultimate strength
ΔTYS	transverse minus longitudinal yield strength

1.0 INTRODUCTION

Titanium alloys are potentially the most efficient primary structural material for airframes over a temperature range from -100° to 800°F. Their use has been hampered, however, by procurement problems involving wide variations in mechanical and fracture properties. Titanium mill products procured for the American SST prototype (Ref. 1, 2, 3, 4, 5, and 6) demonstrated property variations as great at 600%. For example, the stress corrosion resistance (K_{scc}) of Ti-6Al-4V sheet varied from 22 to 150 ksi $\sqrt{in}$. Similar data for plate material are shown in Figure 1-1.

The degree of property variations and causes of variations were extensively investigated during the SST prototype development program and Phase I of the DOT/SST technology follow-on program. The large quantities of Ti-6Al-4V products procured for the SST prototypes (nearly 1.2 million pounds) provided a unique opportunity to accurately delineate the major metallurgical variables causing property variations. Results of these investigations demonstrated that alloy composition, crystallographic texture and microstructure are the primary causes of property variations.

The objective of Phase II of the DOT/SST technology follow-on was to incorporate the titanium technology generated by Phase I into the industrial state of the art. To achieve this goal, new Ti-6Al-4V mill product specifications were prepared based on this new technology; verification test materials were procured and evaluated. (The specifications included new controls on texture, microstructure, composition and stress corrosion resistance.) This document summarizes the specification preparation, verification-material procurement, and mill product evaluation.

The improved Ti-6Al-4V mill products developed by the DOT program were designed for aircraft components requiring high toughness, stress corrosion resistance and fatigue characteristics. Structure requiring high tension and compression strengths should be fabricated from other titanium alloys which provide higher strength.

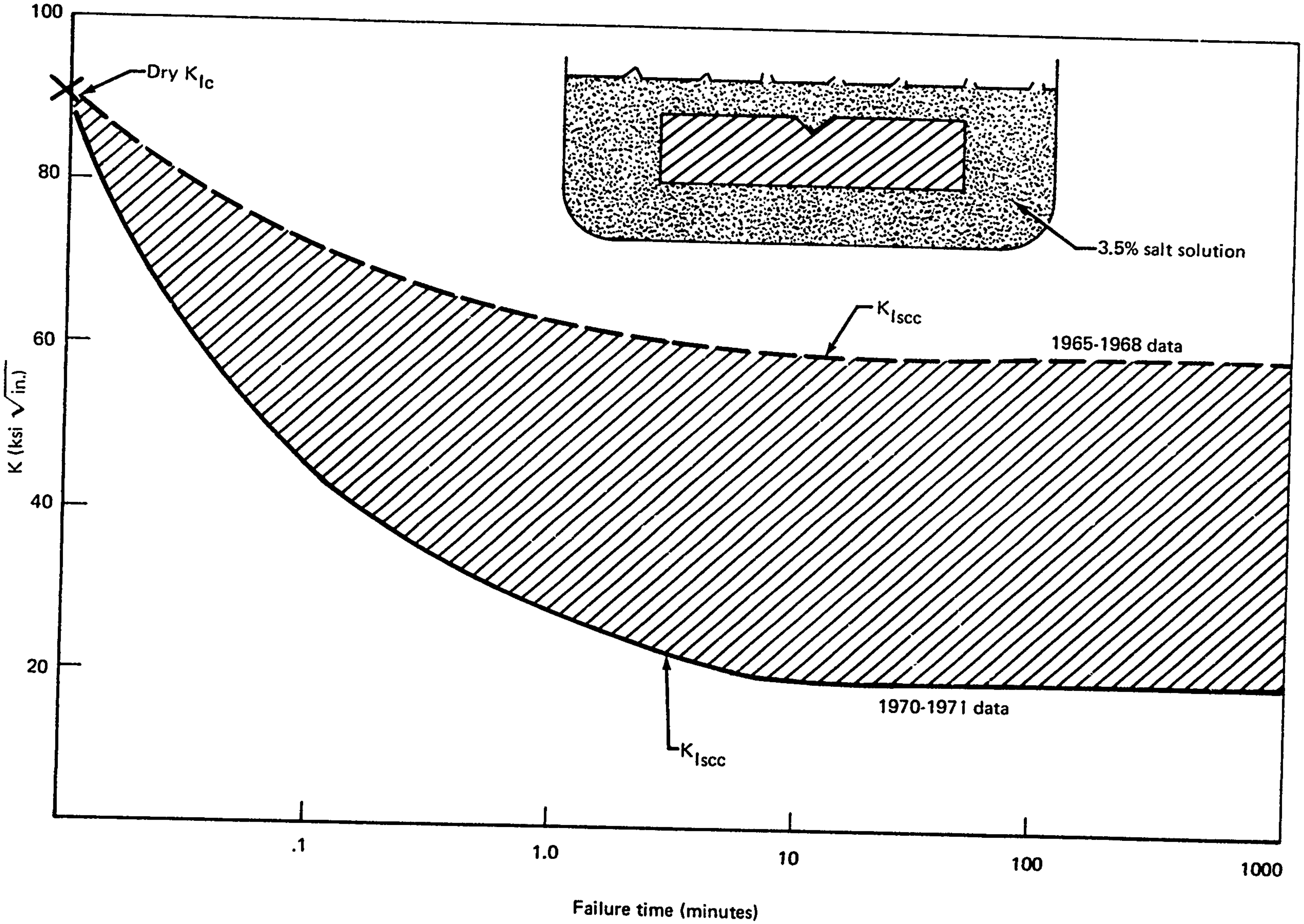


FIGURE 1-1.—STRESS CORROSION CHARACTERISTICS OF Ti-6Al-4V PLATE PROCURED FOR THE SST DEVELOPMENT

2.0 SPECIFICATION DEVELOPMENT

Material specifications for improved Ti-6Al-4V mill products were prepared incorporating the titanium technology generated by the preceding programs (Ref. 2), and tested in accordance with the procedures outlined in Appendix A. The primary goal of each specification was to establish requirements which would provide material with consistently high fracture toughness and stress corrosion resistance. It was recognized, however, from test data of previous developmental programs, that the attainment of high-fracture characteristics would be achieved at a minor loss in tensile properties. New specifications were prepared for Ti-6Al-4V mill product forms including sheet, plate, extrusions, bar and forgings. The specifications were entitled "AST" specifications to distinguish them from Boeing or other existing industry materials specifications. Specification numbers and titles are listed in Table 2-1. Copies of the latest versions of the specifications are contained in Appendices B through E.

TABLE 2-1.—LIST OF AST Ti-6Al-4V MATERIAL SPECIFICATIONS [a]

Number	Title
AST-1	Titanium alloy 6Al-4V sheet
AST-2	Titanium alloy 6Al-4V beta processed plate
AST-3	Titanium alloy 6Al-4V beta processed bar and forgings
AST-4	Titanium alloy 6Al-4V beta processed extrusions

[a]AST=Advanced Supersonic Transport

Since the major metallurgical variables affecting fracture and stress corrosion resistance were previously determined to be composition, texture and microstructure, the new specifications contained requirements to control these variables.

The standard Ti-6Al-4V composition was modified by lowering the ranges for both oxygen and aluminum contents. Linear regression analyses conducted in Phase I indicated that oxygen at 0.11 wt.% maximum and aluminum at 6.2 wt.% maximum would substantially improve environmental fracture characteristics. The selected AST specification composition limits are listed in Table 2-2 along with the existing military specification requirements.

2.1 TEXTURE

Control of basal plane crystallographic texture was established for the various mill product forms. Beta processing was specified for plate, bar, forgings, and extrusions to control the crystallographic texture. Beta processing, particularly beta annealing, was found

TABLE 2-2.—COMPOSITION LIMITS FOR Ti-6Al-4V PER AST AND MILITARY SPECIFICATIONS

Document	Alloying elements (weight %)						
	O_2	Al	V	Fe	N_2	C	H_2
AST specifications (Final proposed limits)	0.08 - 0.11	5.7 - 6.2	3.6 - 4.4	0.25 Max	0.03 Max	0.05 Max	0.0125 Max
Mil-T-9046G (Oct. 12, 1970)							
Composition 6 (Std composition)	0.20 Max	5.5 - 6.75	3.5 - 4.5	0.30 Max	0.05 Max	0.08 Max	0.015 Max
Composition 7 (ELI composition)	0.13 Max	5.5 - 6.75	3.5 - 4.5	0.25 Max	0.05 Max	0.08 Max	0.0125 Max

to randomize texture in Ti-6Al-4V during alloy development efforts for the SST program. Previous test results (Ref. 3) demonstrated a good correlation between texture and differences in tensile properties with grain direction. Therefore, the texture of sheet and plate was also monitored by specifying a maximum for the difference in longitudinal and transverse tensile properties.

2.2 MICROSTRUCTURE

The transformed beta microstructure was selected for thick-section mill products to assure high toughness where good formability was not necessary. The beta processed micr structures were controlled by specifying grain size and morphology. Sheet microstructure was specified to consist of equiaxed primary alpha grains in a matrix of transformed beta. The range for the percentage of primary alpha was specified at 10% minimum and 60% maximum by area. The alpha-beta microstructure was specified for sheet to ensure good formability.

In addition to the controls on metallurgical variables, an environmental fracture test was required to assure high levels of fracture properties. The test specifies that precracked specimens must withstand relatively high sustained loads in the presence of saltwater. Required endurance time without failure is 20 minutes.

These specially developed specification requirements, in addition to the usual requirements typically specified in military specifications, result in Ti-6Al-4V mill products possessing high fracture toughness and environmental resistance.

3.0 MECHANICAL, FRACTURE, AND METALLURGICAL CHARACTERIZATION TESTING

Standard test specimen configurations and test procedures were used wherever possible in order to facilitate comparison with other data sources. Exceptions to this occurred when insufficient material necessitated the use of a smaller or non-standard sample or when comparison with a specific data source which used non-standard specimens was considered beneficial.

Ultimate tensile strength, 0.2% offset tensile yield strength, percent elongation in 2 in. or 4 in., and percent reduction in area data were generated using standard flat and round test coupons.

Several fracture toughness testing configurations and procedures were used, including four-point loaded notched bend specimens, center-notched panels, and compact tension specimens. The choice of specimen configuration was generally related to material thickness and grain direction to be tested. Stress corrosion susceptibility tests were conducted using the same notched specimen configuration as used for fracture toughness testing, with the addition of wedge-loaded and double-cantilever beam specimens.

Appendix A shows details of particular test specimen configurations, procedures employed and analyses.

Metallurgical characterization testing for each material included analyses for chemical composition, basal plane crystallographic texture, microstructure and macrostructure. These metallurgical variables were previously shown (Ref. 2) to be the major factors influencing mechanical and fracture properties. Test techniques and procedures are described in detail in Appendix A.

4.0 VERIFICATION TEST PROGRAM

The specification requirements proposed to assure high fracture toughness and stress corrosion resistance in Ti-6Al-4V mill forms were verified by material testing. Sheet, plate, bar and extrusions were procured to the new specifications and evaluated for mechanical, fracture, and metallurgical characteristics. The evaluation tests and results are discussed for each form.

4.1 SHEET

Two full-size sheets (36 by 96 in.), one 0.050 in. thick and one 0.150 in. thick, were specially produced by Timet to the requirements of AST-1, high toughness Ti-6Al-4V sheet. The 0.050-in.-thick sheet was produced from an 1800-lb ingot specially melted for this program. The 0.150-in.-thick sheet was made from a standard-size ingot (28-in. diameter, 7000 lb) which was originally produced for weld wire.

Thermomechanical processing from ingot to sheet was done in the conventional manner, except for the smaller ingot used for the 0.050-in. sheet (heat V-4826). The smaller ingot (16-in. diameter) was upset forged 35% at 2050° F, cross forged to 12- by 16-in. cross-section at 2000° F, and then cut and one end forged to sheetbar, 3.25 in. by 24 in. by length at 1850° F. The sheetbar was cross-rolled to sheet starting at 1750° F. The majority of the cross-rolling was done at temperatures below 1700° F.

The 0.150-in. sheet was cross-rolled from 3.25- by 16-in. sheetbar at 1600° F. The sheetbar was forged from 15-in.-square billet at 2100° F, with final forging at 1850° F to 3.25 in. by 16 in. by length. After final rolling, the sheets were duplex-annealed (1625° F, 7 min air cool and 1350° F, 4 hr air cool). Finishing of the sheets consisted of belt sanding and light pickling. Mechanical and fracture tests were conducted by the producers, in addition to the determination of microstructure.

Verification testing of the sheet at Boeing included metallurgical characterization and the evaluation of tensile properties, fracture toughness, stress corrosion resistance, and environmental fatigue crack growth. Chemical composition, microstructure, and basal plane texture were analyzed to characterize the important metallurgical features. Analytical procedures are described in Appendix A.

4.1.1 Composition

Boeing chemical analyses of the two sheets compared favorably with the analyses conducted by Timet, Table 4-1. The oxygen contents determined at Boeing, however, were lower for both sheets. Assuming that averaging of the two values would approach the true oxygen content, both sheets would represent lean compositions with respect to the AST-1 specification ranges. Note that the reported aluminum content for the 0.050-in. sheet varied greatly between test laboratories. The Timet value of 5.6% aluminum, 0.1% above the specification minimum, is more likely to be closer to the true value since the mechanical properties were also unexpectedly low. The aluminum content for the 0.150-in. sheet, 5.8%, was typical for the AST-1 specification requirements. The iron content of both sheets was

TABLE 4-1.—CHEMICAL COMPOSITIONS OF VERIFICATION TEST—Ti-6Al-4V SHEET

Sheet thickness (in.)	Heat	Test lab (a)	Alloying elements (weight %)						
			O_2	Al	V	Fe	N_2	C	H_2
0.050	V4826	Ti. et	0.090	5.6	4.0	0.05	0.007	0.025	0.0092
		Boeing	0.055	6.07	4.34	0.07	0.004	0.020	0.0074
0.150	G8080	Timet	0.070	5.8	4.1	0.04	0.010	0.023	0.0071
		Boeing	0.050	5.8	4.35	0.08	0.009	0.030	0.0047
Initial AST-1 Reqm'ts	—	—	0.07 - 0.11	5.5 - 6.0	3.6 - 4.4	0.25 Max	0.03 Max	0.05 Max	0.0125 Max

consistently low and demonstrated that the sheets represented lean compositions. The lower nitrogen content of the 0.050-in. sheet (0.0055%) compared to that of the 0.150-in. sheet (0.0095%) would also contribute to lower mechanical properties. The remaining alloying constituents, vanadium, carbon, and hydrogen are typical for Ti-6Al-4V compositions.

4.1.2 Microstructure

Sheet microstructures, Figures 4-1 and 4-2, consisted of equiaxial and elongated primary alpha in a matrix of transformed beta (basketweave morphology). The amount of transformed beta was lower than desired. The estimated percentage (area of basketweave morphology) for the 0.050-in. sheet was 25% and for the 0.150-in. sheet was 20%. This type of microstructure results from duplex-annealing. The high temperature annealing step generally produces 50-90% beta at temperature. The composition of the beta is sufficiently lean that the beta transforms on cooling to a basketweave alpha-beta morphology. During cooling and the subsequent low temperature annealing at 1350°F, the primary alpha grows, resulting in a final percentage of primary alpha ranging from 10 to 60%. The first-step annealing used for these particular sheets was unusually low at 1625°F. This temperature was selected based on previous experience in attempting to anneal low-oxygen content material at 1725°F. Sheet produced from heat V-4826 was fully beta-annealed when heated at 1725°F. A beta transus evaluation of the material showed the beta transus to be approximately 1720°F. The first-step annealing temperature was reduced to 1625°F to assure that heating above the beta transus would not occur, taking into consideration the accuracy of the beta transus determination, furnace temperature tolerances, and possible variations in alloy composition throughout the sheet. The 1625°F temperature, however, did not produce the desired amount of transformed beta.

4.1.3 Texture

The crystallographic texture was determined for both sheets using the computerized basal plane X-ray pole figure technique developed by Boeing (Appendix A). The texture of

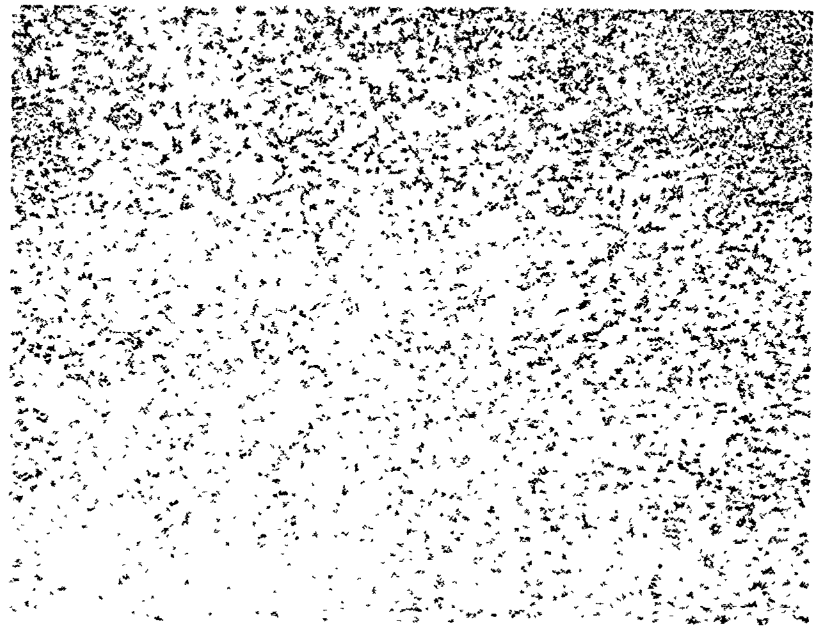


FIGURE 4-1.—EQUIAXED PRIMARY ALPHA IN DUPLEX ANNEALED 0.050 IN. Ti-6Al-4V SHEET—LONGITUDINAL ORIENTATION

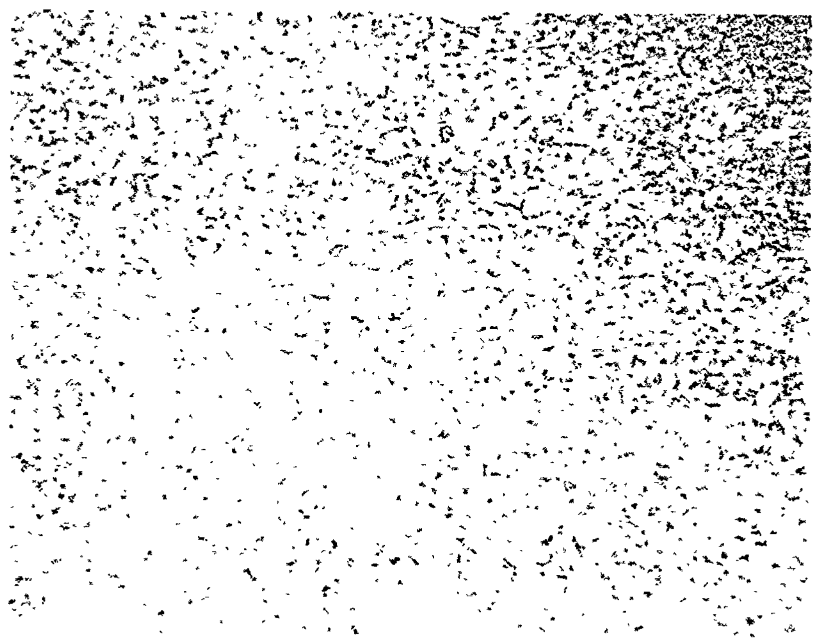


FIGURE 4-2.—EQUIAXED PRIMARY ALPHA IN DUPLEX ANNEALED 0.150 IN. Ti-6Al-4V SHEET—LONGITUDINAL ORIENTATION

the 0.050-in. sheet, Figure 4-3, was typical of cross-rolled Ti-6Al-4V in that the intensities of basal plane poles normal to the transverse and longitudinal grain directions were similar and the highest intensity of basal plane poles occurred normal to the sheet surface. Texture intensity factors calculated from the X-ray data for each grain direction, Table 4-2, show an identical trend. Texture intensity factor determination procedures are discussed in Appendix A.

The texture of the 0.150-in. sheet was significantly different from that of the thinner sheet, as shown in Figure 4-4. The majority of the basal plane poles are oriented toward the transverse direction and an absence of basal poles is observed in the longitudinal direction. Texture intensity factors listed in Table 4-2 show that over 50% of the basal poles are oriented in the transverse direction, compared to only 12% for the longitudinal direction. This is classified as a type "TD" texture.

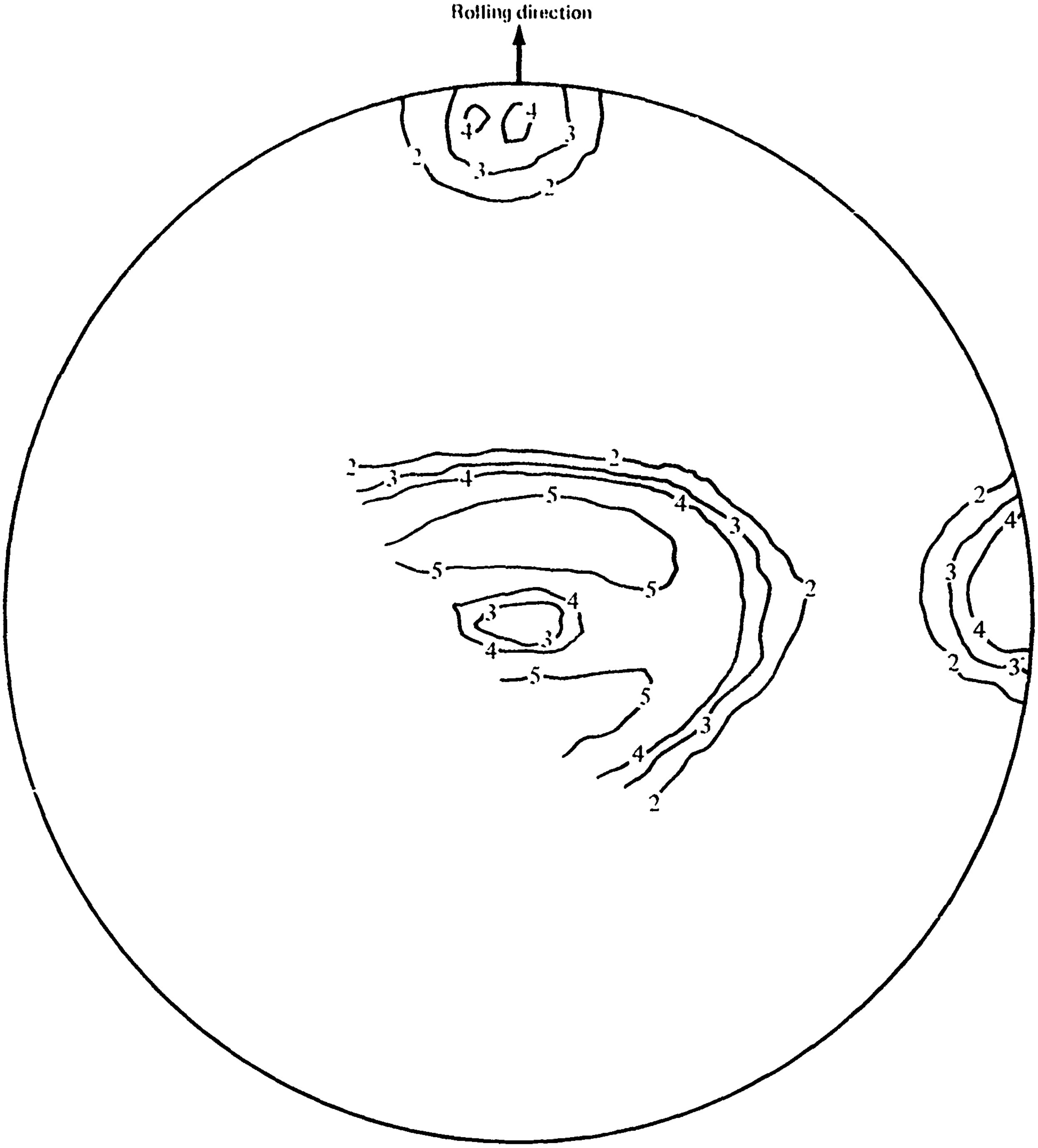
4.1.4 Mechanical Properties

The results of the tensile testing conducted by Boeing on the two sheets are listed in Table 4-3. The test results agree reasonably well with the supplier test values, except for those of the transverse grain direction. The Boeing tests demonstrated a yield strength equal to the ultimate tensile strength. Similar effects have been observed for highly basal textured Ti-6Al-4V, by Frederick (Ref. 1). The texture of the 0.150-in. sheet, however, was a transverse direction (TD) texture with the majority of the basal plane poles parallel to transverse direction. The difference between transverse and longitudinal yield strength data is consistent with earlier data (Ref. 2) for TD textures. Most of the tensile test values were lower than anticipated and did not meet the proposed specification requirements of 130 ksi for TUS and 120 ksi for TYS. Since the low tensile properties can be attributed to lean alloy composition and crystallographic texture, the specification requirements for TYS and TUS appeared optimistic and were subsequently reduced. Since basal textures are desirable from a fracture viewpoint and tighter ranges for alloy composition are impractical, reducing the specification tensile requirements was justified.

4.1.5 Fracture Properties

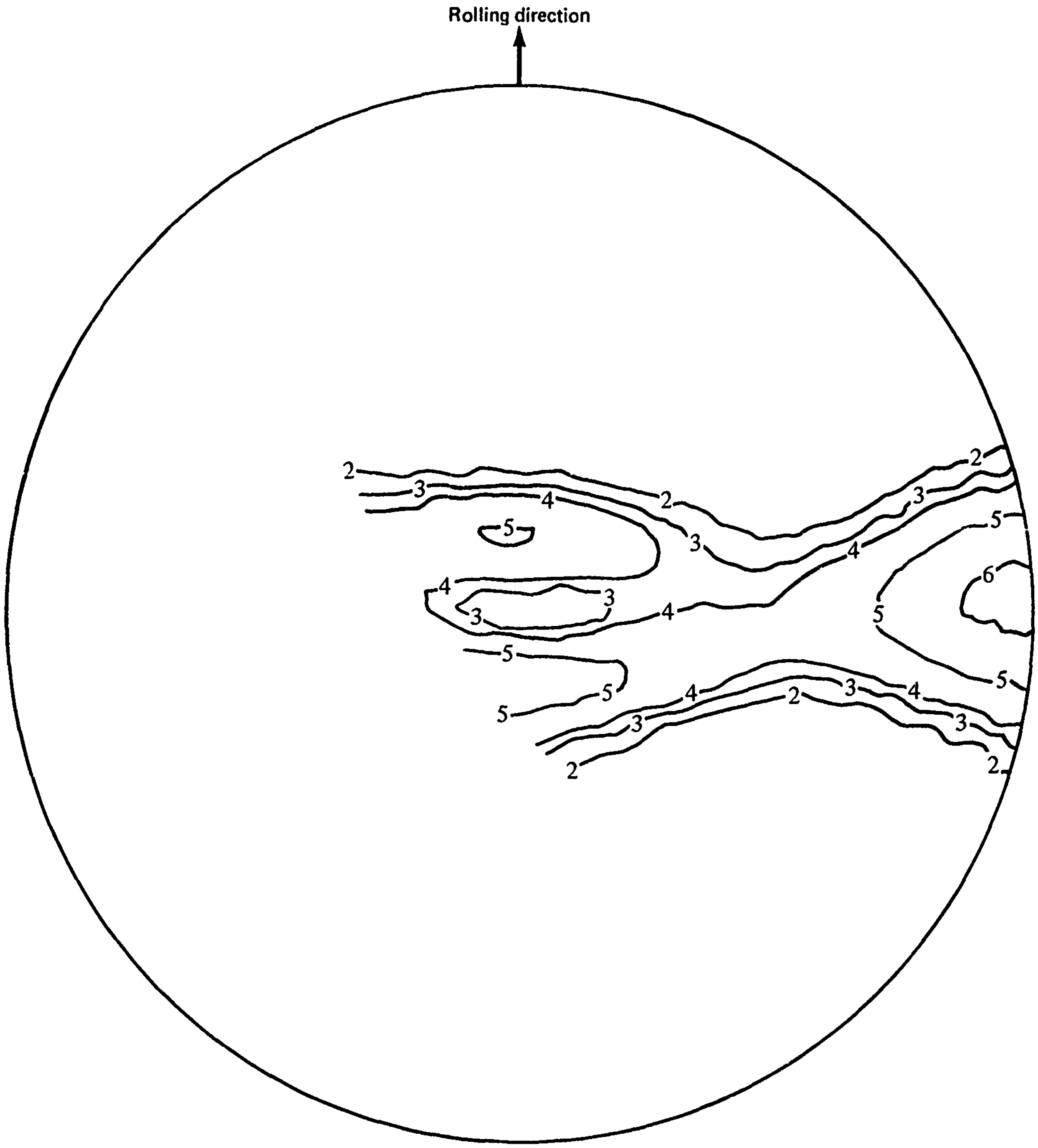
Sheet fracture characteristics were evaluated using 12-in.-wide center-notch panels. Cyclic fatigue crack growth was determined in air and saltwater (3.5%) at a frequency of 120 cpm. The ratio of minimum to maximum fatigue stress was 0.05. Buckling restraints were used to minimize out-of-plane deflections. Specimen details and test procedures are described in Appendix A.

The fracture toughness and stress corrosion test results for the 12-in.-wide center-notched panels are listed in Table 4-3. Both sheet materials exhibited excellent fracture characteristics, with the majority of K_c values approaching 200 ksi$\sqrt{\text{in}}$. One unusual feature was the 0.150-in. sheet transverse K_{SCC} value of 183 ksi$\sqrt{\text{in}}$. This high value resulted with the majority of the basal planes parallel to the stress corrosion crack propagation direction, in contrast to the trend established earlier for higher oxygen content Ti-6Al-4V sheet (Ref. 2).



Contour line	1	2	3	4	5
Times random intensity	0.5	1	1.5	2	4

FIGURE 4-3.—TEXTURE POLE FIGURE FOR DUPLEX ANNEALED 0.050 IN. Ti-6Al-4V SHEET SPECIMEN



Contour line	1	2	3	4	5	6
Times random intensity	0.5	1	1.5	2	4	

FIGURE 4-4.—TEXTURE POLE FIGURE FOR DUPLEX ANNEALED 0.150 IN Ti-6Al-4V SHEET SPECIMEN

TABLE 4-2.—TEXTURE INTENSITY FACTORS AND GRAIN DIRECTION FOR Ti-6Al-4V SHEET

Thickness (in.)	I_T (%)	I_L (%)	I_{ST} (%)
0.050	29	22	49
0.150	51	12	37

The environmental fatigue crack growth characteristics, summarized in Figure 4-5, show the effect of saltwater on crack growth rate characteristics. For comparison, the data is plotted with earlier data (Ref. 3) for duplex-annealed Ti-6Al-4V sheet procured for the SST prototypes. The newer sheet material offers marked improvement in fatigue crack growth in saltwater. The crack growth rates in air are only 3 to 5 times slower than in saltwater, Figure 4-6, showing the sheet materials to be only slightly sensitive to the saltwater environment. At low ΔK's, the data was consistent with other data (Ref. 4) for 1-in.-thick Ti-6Al-4V recrystallized annealed plate of a similar composition (beta-annealed plate). The "ΔK threshold" for both air and saltwater at R = 0.05 appears to occur near a K level of 10 ksi$\sqrt{\text{in.}}$ Texture effects on crack growth rate were not significant in that the texture varied greatly between the two sheets, yet only a slight difference in growth rate was noted.

4.2 PLATE

Three plates, meeting the requirements of AST-2 for composition and microstructure, were evaluated for mechanical and fracture characteristics. Plane strain fracture was determined using compact tension specimens. Stress corrosion resistance (K_{ISCC}) was determined with both notched bend specimens and double-cantilever beam specimens. Round tensile specimens were used to determine mechanical properties. Fracture specimens were fabricated from both the transverse (WR) and longitudinal (RW) grain directions. Specimen configurations and test procedures are described in Appendix A.

Two plates were produced by Timet (0.5- and 1.0-in.-thick by 36 by 48 in.) which represented a lean chemical composition material with respect to AST-2 specification limits, Table 4-4. A third plate, 0.57 in. thick, produced by RMI originally for the SST prototype program, was included in the evaluation since it represented a rich composition at the extreme limits of the AST-2 specification. The Timet plates were produced from the same 1800-lb ingot as were the sheets. Ingot breakdown to sheet bar was described earlier in the sheet section. The plates were cross-rolled from 3.25- by 24-in. sheet bar to gage and then beta-annealed at 1900°F for 15 min and air cooled. Final annealing was done at 1350°F for 4 hr followed by air cooling. Mechanical and fracture tests were conducted by Timet and the results are included in Table 4-5.

TABLE 4-3.—Ti-6Al-4V SHEET MECHANICAL PROPERTIES[a]

Thickness (in.)	Supplier and heat (b)	Test lab	Test direction (c)	Tensile properties				Fracture properties		
				TUS (ksi)	TYS (ksi)	Elong %	Min bend r/t	K_c (d) (ksi $\sqrt{in.}$)	K_{SL} (e) (ksi $\sqrt{in.}$)	K_{scc} (d) (ksi $\sqrt{in.}$)
0.050	Timct V4826	Timet	L	123	116	16	3.7	–	–	–
			T	123	119	16	3.7	–	75.9 NF 167.0 F	
		Boeing	L	124.5	120.1	15	–	202.2	–	173
			T	125.0	125.0	14	–	197.1	–	160
0.150	Timet G8080	Timet	L	131	107	14.5	5.0	–	–	–
			T	130	116	14.5	5.0	–	75.0 NF 142.0 F	–
		Boeing	L	132.8	116.2	14	–	182.0	–	147
			T	131.9	131.9	15	–	202.0	–	183

[a]Supplier tensile data are averaged from duplicate tests. All other data are single values.

[b]Timet—Titanium Metals Corporation of America

[c]L—Longitudinal
T—Transverse or WR for fracture specimens

[d]Fracture data determined using 12-in.-wide center-notched panels

[e]Fracture data determined using 3-in.-wide single edge, notched panels

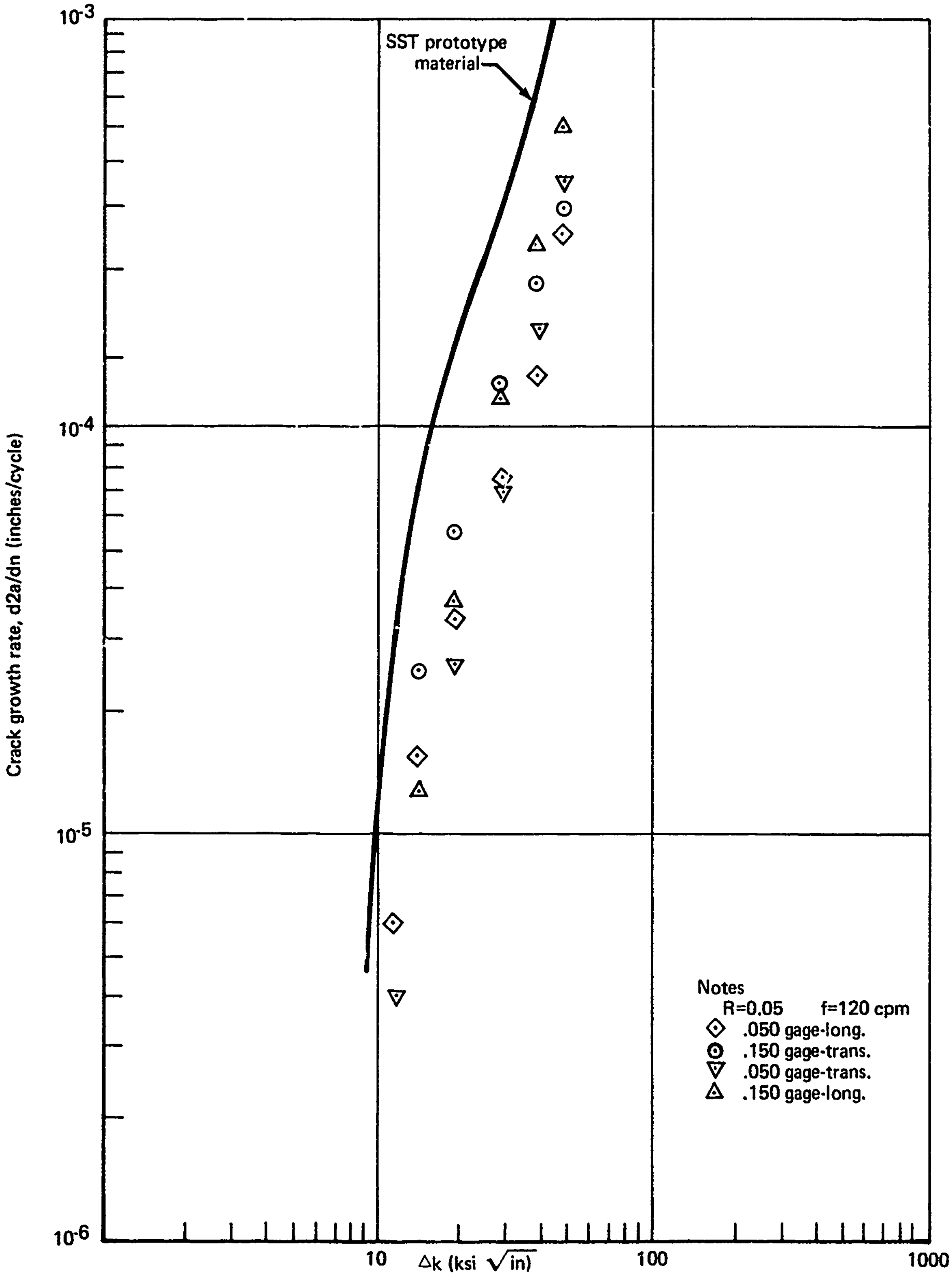


FIGURE 4-5.—FATIGUE CRACK GROWTH RATES IN 3.5% NaCl FOR Ti-6Al-4V SHEET—DUPLEX ANNEALED

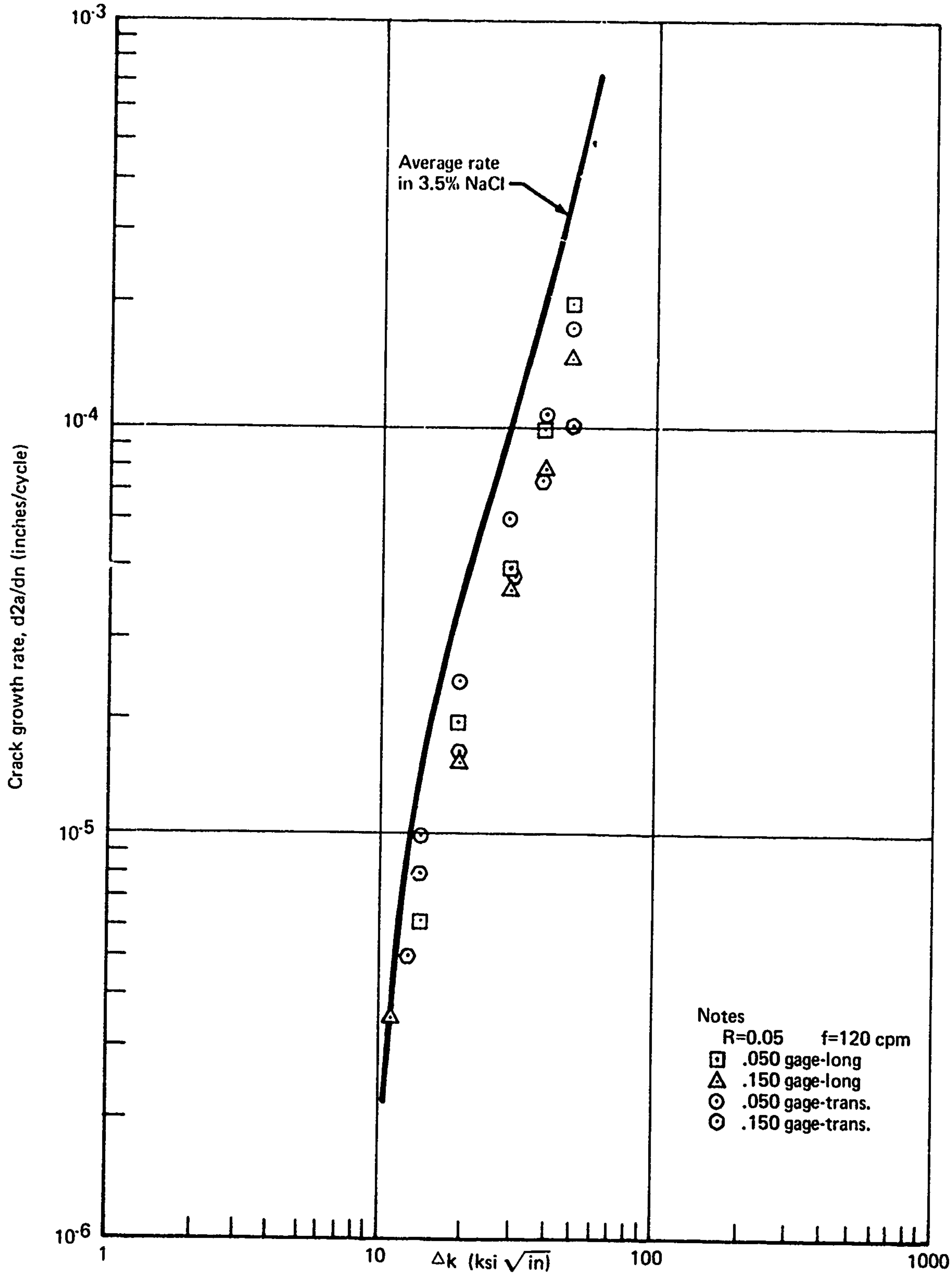


FIGURE 4-6.—FATIGUE CRACK GROWTH RATES IN AIR FOR Ti-6Al-4V SHEET DUPLEX ANNEALED

TABLE 4.4.—CHEMICAL COMPOSITIONS OF VERIFICATION TEST Ti-6Al-4V PLATE

Thickness (in.)	Heat	Test lab (a)	Alloying elements (weight %)						
			O_2	Al	V	Fe	N_2	C	H_2
0.570	295549 -08	RMI	0.106	5.9	3.9	0.19	0.010	0.02	
		Boeing	.082	5.99	3.88	.22	.011	.02	
.500	V4826	Timet	.084	5.6	4.0	.05	.007	.025	.0072
		Boeing	.085	5.98	4.15	.08	.0088	.020	
1.00	V4826	Timet	.087	5.6	4.0	.05	.007	.025	.0080
		Boeing	.080	5.64	4.13	.08	.0067	.030	
AST-2 requirements			.07 -.11	5.7 -6.2	3.6 -4.4	0.25 Max	0.03 Max	0.05 Max	.0125 Max

[a]RMI = Reactive Metals Incorporated

Timet = Titanium Metals Corporation of America

The RMI plate, 0.57 by 38 by 110 in., was produced in the conventional manner from a standard size ingot (~8,000 lb) and then beta annealed at 1900°F for 20 min and subsequently air cooled. Final annealing was done at 1350°F for 4 hr followed by air cooling. The oxygen content as determined by RMI was 0.106 wt. %.

Metallurgical characterization testing at Boeing included evaluations for chemical composition, microstructure and basal plane texture. Analytical procedures are described in Appendix A.

4.2.1 Composition

Boeing chemical analyses for the plates compared well with those conducted by the supplier, with several exceptions (Table 4-4). The Boeing analyses for oxygen content of 0.57-in. plate was particularly low and the aluminum content of the 0.5-in. plate was high. The higher vendor analysis for oxygen in the 0.57-in. plate appears more correct since the tensile properties were also relatively high. In addition to oxygen content, the RMI plate also had higher aluminum and iron contents.

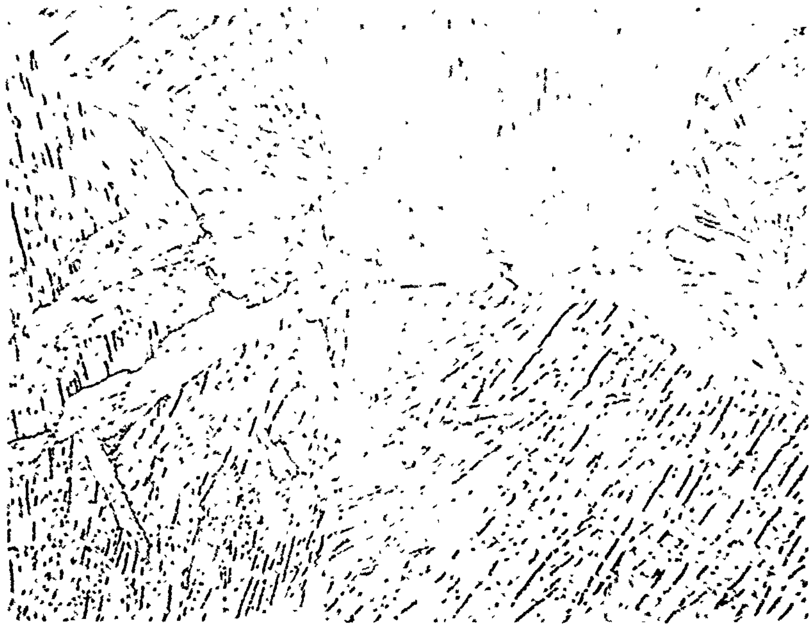
4.2.2 Microstructure

Plate microstructures were typical of beta annealed Ti-6Al-4V material followed by mill annealing, Figures 4-7 and 4-8. The microstructures consisted of transformed beta morphology (basketweave) with some discontinuous retained beta phase. Discontinuous beta phase in a Ti-6Al-4V basketweave structure is usually a result of the mill annealing step (1350°F, 4 hr air cool). The extent or incidence of discontinuous beta phase was less for the 0.57-in. plate than that of the Timet plates, Figures 4-7 and 4-9.

TABLE 4-5.—Ti-6Al-4V PLATE MECHANICAL PROPERTIES[a]

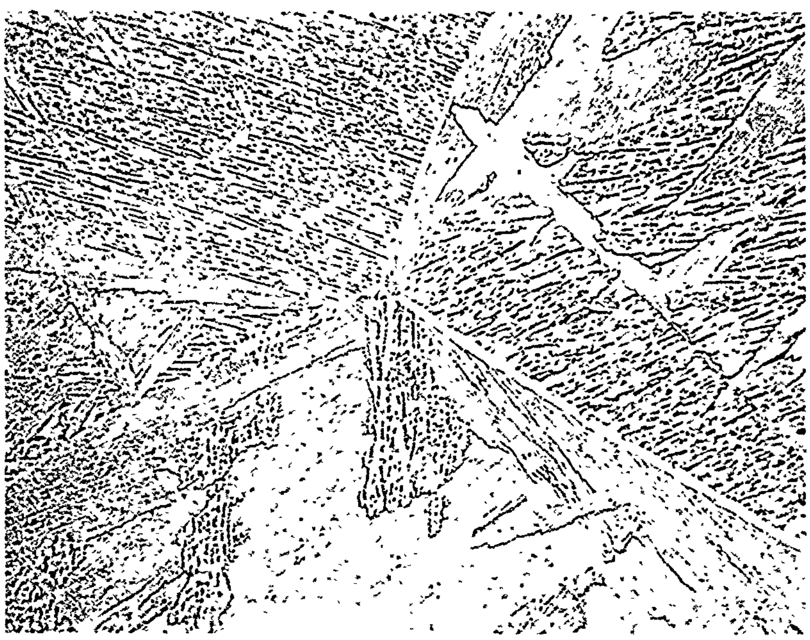
Thickness (inches)	Supplier and heat (b)	Test lab	Test direction (c)	Tensile properties				Fracture properties		
				TUS (ksi)	TYS (ksi)	Elong (%)	RA (%)	K_{Ic} (ksi $\sqrt{in.}$)	K_{SL} (ksi $\sqrt{in.}$)	K_{Iscc} (d) (ksi $\sqrt{in.}$)
0.5	Timet V4826	Timet	L	126	118	15	31	–	–	–
			T	124	112	18	27	–	55NF 107F	–
		Boeing	L	126.7	120.4	13.5	29	97.0	–	96
			T	122.4	110.4	12.0	26	94.8	–	62
0.57	RMI 295549-08	Boeing (e)	L	136.1	126.1	12.5	28	69.5	–	50 [49] 44
			T	135.4	125.3	14.0	27	74.5	–	49 [49] 49
1.0	Timet V4826	Timet	L	121	113	17	32	–	–	–
			T	121	112	16	32	–	55NF 108F	–
		Boeing	L	120.3	112.5	14	31	97.3	–	59
			T	121.4	112.8	13.5	30	92.1		66 61

[a]Supplier tensile data are averaged from duplicate tests.
All other data are single values
[b]Timet-Titanium Metals Corporation of America
RMI-Reactive Metals Incorporated.
[c]L-Longitudinal
[d]K_{Iscc} values in brackets denote notch bend test data.
All other K_{Iscc} data are from double cantilever beam specimens.
[e]RMI inspection data not available.



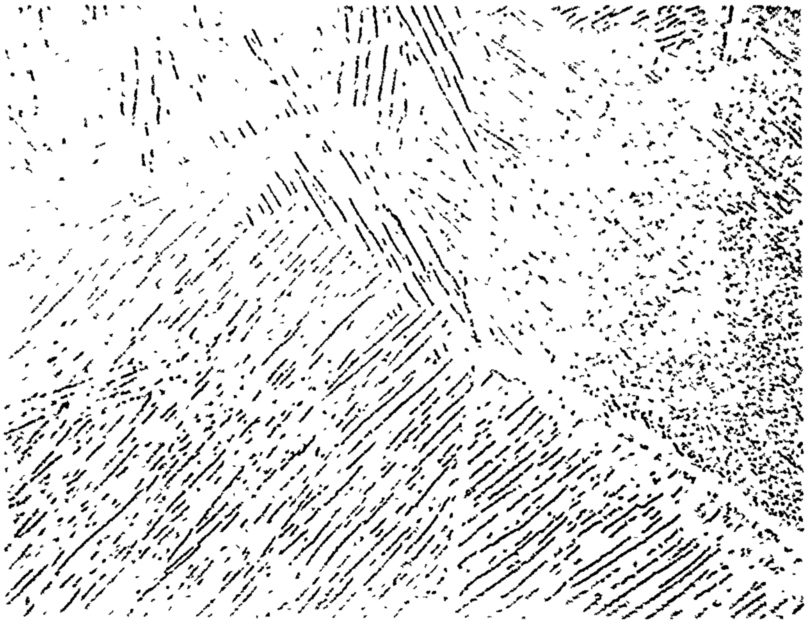
X500

FIGURE 4-7.—TRANSFORMED BETA (BASKETWEAVE) WITH DISCONTINUOUS RETAINED BETA IN BETA ANNEALED PLUS MILL ANNEALED 0.5 IN. Ti-6Al-4V TIMET PLATE—LONG TRANSVERSE ORIENTATION



X500

FIGURE 4-8.—TRANSFORMED BETA AND DISCONTINUOUS RETAINED BETA IN BETA ANNEALED PLUS MILL ANNEALED 0.57 IN. Ti-6Al-4V RMI PLATE—LONG TRANSVERSE ORIENTATION



X500

FIGURE 4-9.—TRANSFORMED BETA AND DISCONTINUOUS RETAINED BETA IN BETA ANNEALED PLUS MILL ANNEALED 1.0 IN. Ti-6Al-4V TIMET PLATE—LONG TRANSVERSE ORIENTATION

4.2.3 Texture

The basal texture of the RMI 0.57-in. plate was typical of textures observed previously for beta-annealed Ti-6Al-4V plate (Ref. 2). The basal planes were relatively random oriented, Figure 4-10, as shown by the basal plane pole figure. The highest intensity peaks shown by the pole figure are only 2 times random and are primarily a result of the relatively large prior beta grain size.

The textures of the Timet plates, 0.5 in. and 1.0 in., were more pronounced, Figures 4-11 and 4-12. The 0.5-in. plate basal plane texture was similar to textures observed for Ti-6Al-4V extrusions extruded above the beta transus. The majority of the basal plane poles are oriented parallel to the longitudinal grain direction. This type of texture is not typical of beta-annealed plate, but was observed previously in a lean composition Ti-6Al-4V plate after beta annealing (Ref. 2). Texture intensity factors are shown in Table 4-6.

TABLE 4-6.—TEXTURE INTENSITY FACTORS AND GRAIN DIRECTION FOR Ti-6Al-4V PLATE

Thickness (inches)	I_T	I_L	I_{ST}
0.50	45	29	26
0.57	34	33	33
1.0	34	35	31

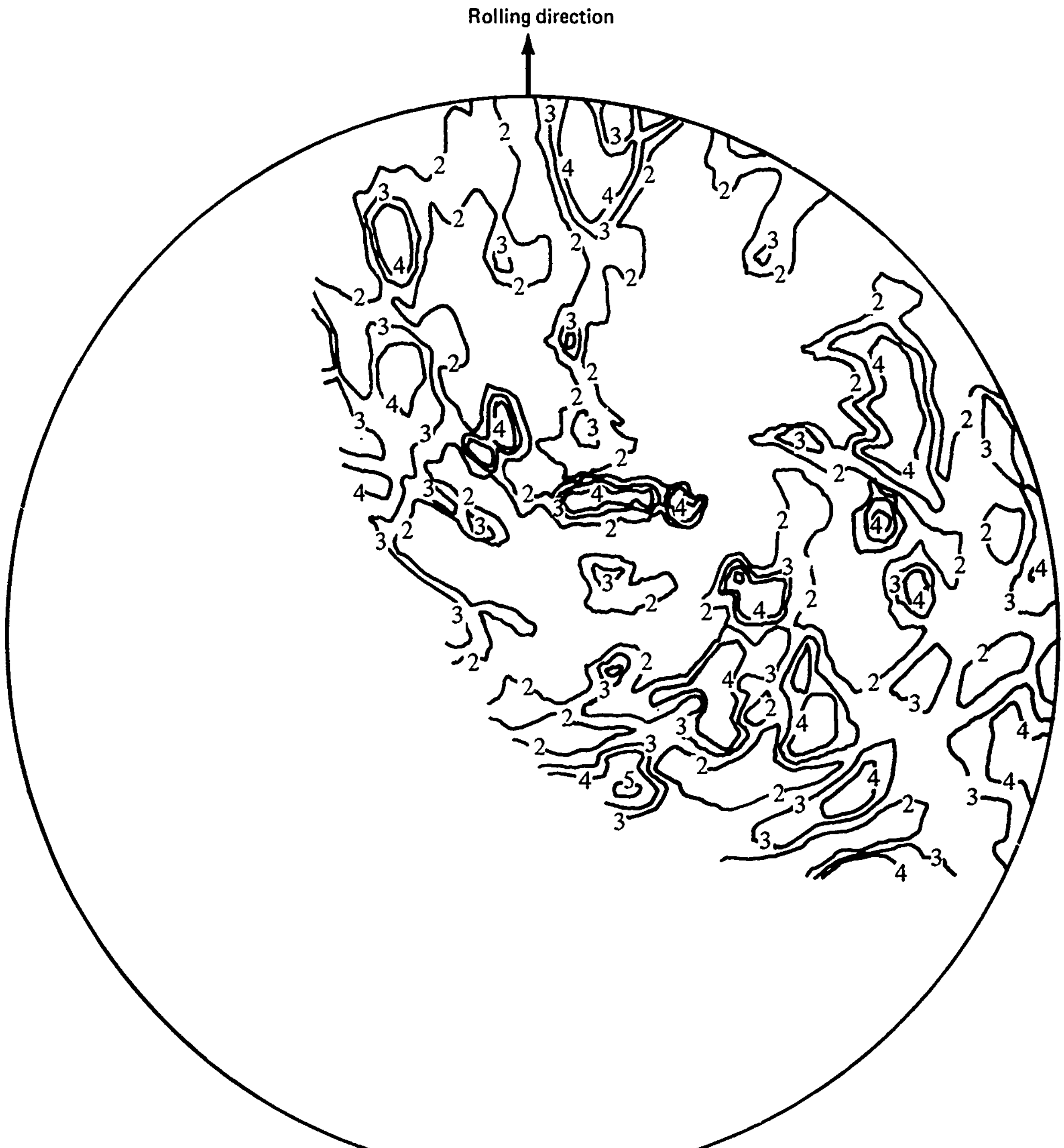
4.2.4 Mechanical Properties

The results of the tensile testing conducted by Boeing on the 3 plates are listed in Table 4-5. The supplier test values agree reasonably with the Boeing test results. The test results for TUS and TYS on the 0.5-in. plate averaged 5 ksi and 4 ksi respectively below the proposed AST-2 specification values of 130 ksi and 115 ksi. Texture as measured by ΔTUS (transverse minus longitudinal values) met the specification requirement of 4 ksi maximum difference. The ΔTYS requirement of 5 ksi, however, was not met. This result was anticipated since the basal plane texture of the 0.5-in. plate was more pronounced.

The tensile properties of the 1.0-in. plate were also below the proposed specification minimums of 127 ksi TUS and 115 ksi TYS. Texture as measured by both ΔTUS and ΔTYS was negligible, which is consistent with the texture demonstrated by the basal pole figure.

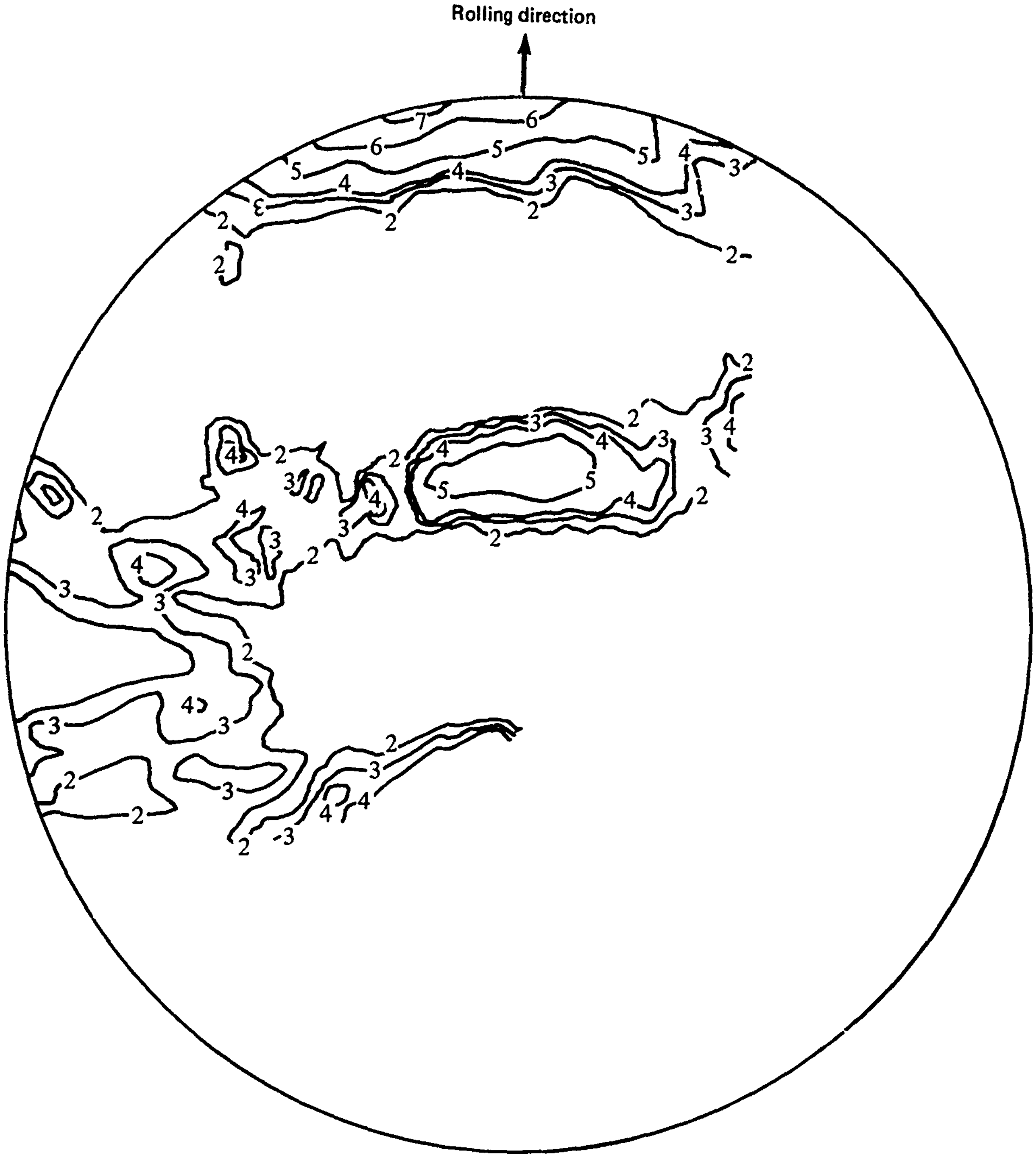
4.2.5 Fracture Properties

Both timet plates exhibited excellent fracture toughness with K_{Ic} values greater than 92 ksi $\sqrt{\text{in.}}$ for compact tension specimens. The combined factors of material thickness, low TYS and high K values render the calculated K_{Ic} values conservative (K_Q values). The stress corrosion resistance (K_{Iscc}) as determined using DCB specimens was also excellent, with



Contour line	1	2	3	4	5
Times random intensity	0.5	1	1.5	2	4

FIGURE 4-10.—TEXTURE POLE FIGURE FOR BETA ANNEALED PLUS MILL ANNEALED 0.57 IN. RMI Ti-6Al-4V PLATE SPECIMEN



Contour line	1	2	3	4	5	6	7
Times random intensity	0.5	1	1.5	2	4	8	14

FIGURE 4-11.—TEXTURE POLE FIGURE FOR BETA ANNEALED PLUS MILL ANNEALED 0.50 IN. TIMET Ti-6Al-4V PLATE SPECIMEN

Contour line	1	2	3	4	5
Times random intensity	0.5	1	1.5	2	4

FIGURE 4-12.—TEXTURE POLE FIGURE FOR BETA ANNEALED PLUS MILL ANNEALED 1.0 IN. TIMET Ti-6Al-4V PLATE SPECIMEN

values ranging from 59 to 96 ksi$\sqrt{in}$. The high value for the RW test direction (see Fig. A-5, Appendix A) of the 0.5-in. plate was not expected, since the basal plane texture for this direction was less than optimum.

The 0.57-in. plate exhibited only moderate fracture toughness as K_{Ic} values ranged from 70 to 76 ksi$\sqrt{in}$. Again, the values were conservative (K_Q values).

K_{Iscc} values were determined for both grain directions of the RMI plate using both DCB specimens and notched bend specimens. Both specimen types were included to determine the effect of specimen configuration on test values. Previous testing of thick plate (Ref. 5) used only notched bend specimens. Test values (Table 4-5) were very consistent with 4 of 6 values determined to be 49 ksi$\sqrt{in}$. The lack of directionality in test direction was expected, based on the random basal plane texture of the plate. The K_{Iscc} level at 49 ksi$\sqrt{in}$. did not meet the proposed specification (AST-2) requirement of 55 ksi$\sqrt{in}$. This low value is most likely related to the higher aluminum, oxygen, and iron content of the material. All 3 elements have been shown to reduce stress corrosion resistance.

4.3 FORGED BAR

Two forged Ti-6Al-4V bars were specially produced by Timet to the requirements of AST-3 for composition and microstructure. The small bar, 1.5 in. by 3 in. by length, was forged from the material heat used for the plate production, heat V-4826. The large bar, 6 in. by 8 in. by length, was from heat G-8080. Both heats represented ELI compositions and were the same ones used to fabricate the two sheet materials. The large bar was forged from a 15-in.-square billet at 2100°F to a rectangle 10 in. by 15 in. Subsequently, the rectangle was forged at 1850°F to the final size of 6 in. by 8 in. by length.

Forging of the small bar began from the 12- by 16-in. billet at 1850°F, 6 in. by 8 in. by length. This size was then forged to a 3.5-in. diameter round at 1800°F. Final forging to 1.5- by 3-in. bar was done by GFM forging at 1700°F. After final forging, both bars were beta-annealed at 1900°F for 15 min and air cooled. Final annealing was done at 1350°F for 4 hr followed by air cooling.

Metallurgical characterization, mechanical, and fracture testing was conducted in the same manner as for the plate and extrusion material. Metallurgical evaluation included chemical composition, microstructure, and basal plane crystallographic texture. Specimen configurations and detailed test procedures are described in Appendix A.

4.3.1 Composition

The bar compositions are generally characterized as very lean in alloy elements with respect to the AST-3 specification limits. Both heats had minimum or slightly below minimum contents of oxygen and aluminum as shown by the supplier analysis, Table 4-7. The Boeing analysis for oxygen resulted in slightly lower values (0.01 wt %). Iron contents were also on the low side of the composition range.

TABLE 4-7.—CHEMICAL COMPOSITIONS OF VERIFICATION TEST Ti-6Al-4V BAR

Size (inches)	Heat	Test lab	Alloying elements (weight %)						
			O_2	Al	V	Fe	N_2	C	H_2
1.5X3	V4826	Timet	0.070	5.6	4.0	0.05	0.007	0.025	0.0053
		Boeing	0.062	5.81	4.22	0.08	0.0063	0.030	0.0073
6X8	G8080	Timet	0.070	5.8	4.1	0.04	0.010	0.023	0.0038
		Boeing	0.064	6.07	4.26	0.09	0.0076	0.030	0.0054
AST-3 requirements	—	—	0.07	5.7	3.6	0.15	0.03	0.05	0.0125
			.11	6.2	4.4	.30	Max	Max	Max

4.3.2 Microstructure

The microstructure and macrostructure varied throughout the cross-sections of both bars. This is shown for the large bar in Figure 4-13 and in Figure 4-14 for the 1.5- by 3-in. bar. Variations in microstructure for the 6- by 8-in. bar are demonstrated by Figure 4-15 for the center of the bar and by Figure 4-16 for material near the bar surface (bar corner). The coarser alpha platelets observed in center of the bar are typical for Ti-6Al-4V slow-cooled from the beta transus temperature. The near-surface material microstructure was more typical of faster cooled material (e.g., plate). For the size of bar, the cooling has been shown to vary significantly for the center and surface materials.

The variations in microstructure exhibited by the small bar are more related to variations in forging rather than cooling rate, since size of bar limits large variations in cooling rate. The variation in forging throughout the cross-section of the bar was indicated by the observed differences in microstructure, Figure 4-17.

4.3.3 Texture

The texture of basal planes for both bars is shown by the pole figures in Figures 4-18 and 4-19. The large bar exhibited a relatively random crystallographic texture typical of beta-annealed Ti-6Al-4V plate. Maximum determined intensities were 4 times random. These intensity peaks are more a result of the large prior beta grain size than a particular texture development. Texture intensity factors are shown in Table 4-8.

The texture of the small bar was highly directional, with the majority basal plane poles oriented in the longitudinal grain direction. The texture exhibited the highest basal plane pole intensities observed for all of the verification test materials, with peak intensities reaching 14 times random. This type of texture, classified as a "negative" texture, has been observed previously for Ti-6Al-4V extrusions (Ref. 2).

TABLE 4-8.—TEXTURE INTENSITY FACTORS AND GRAIN DIRECTION FOR Ti-6Al-4V BAR

Size (inches)	I_T	I_L	I_{ST}
1.5X3	28	36	36
6X8	38	29	33

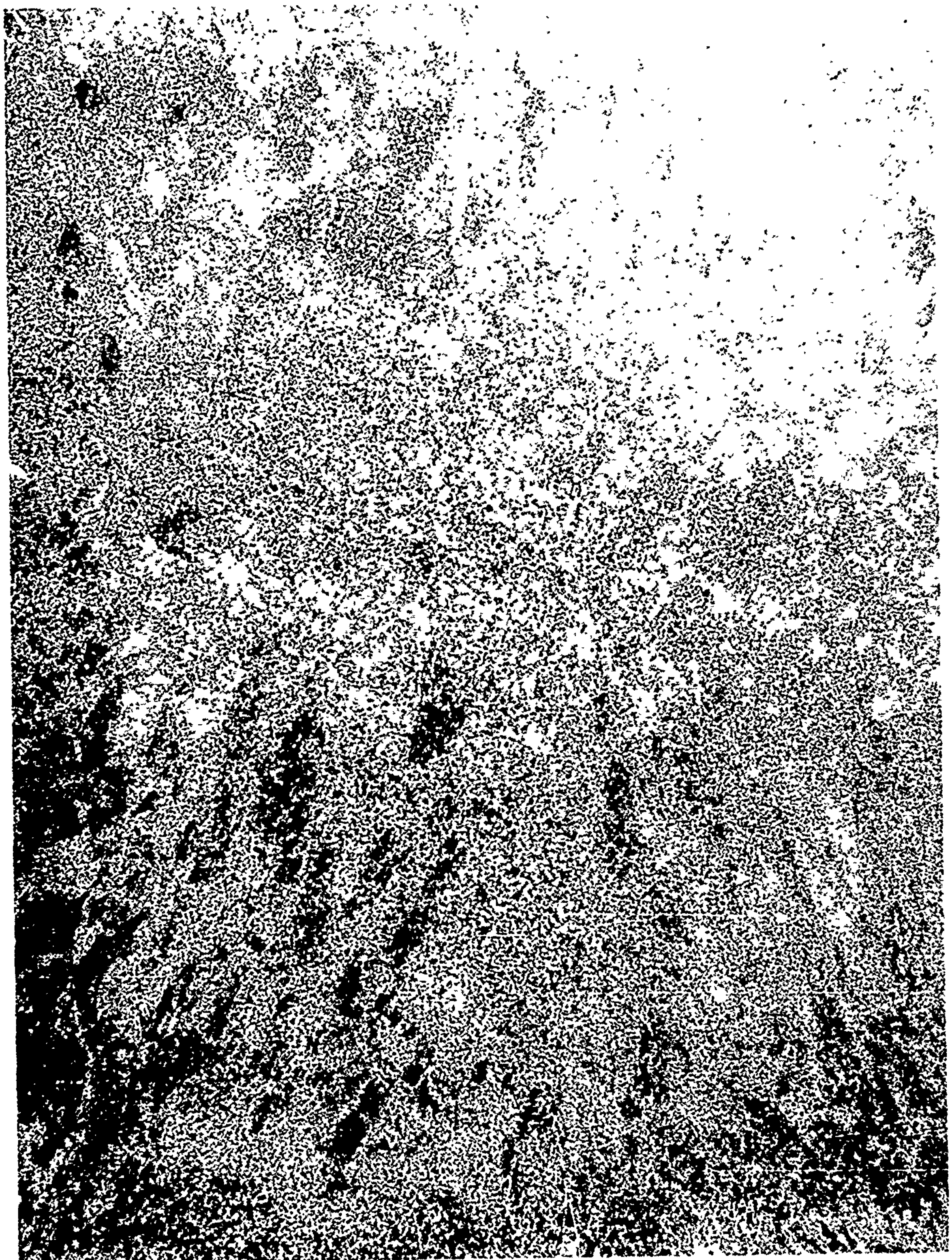
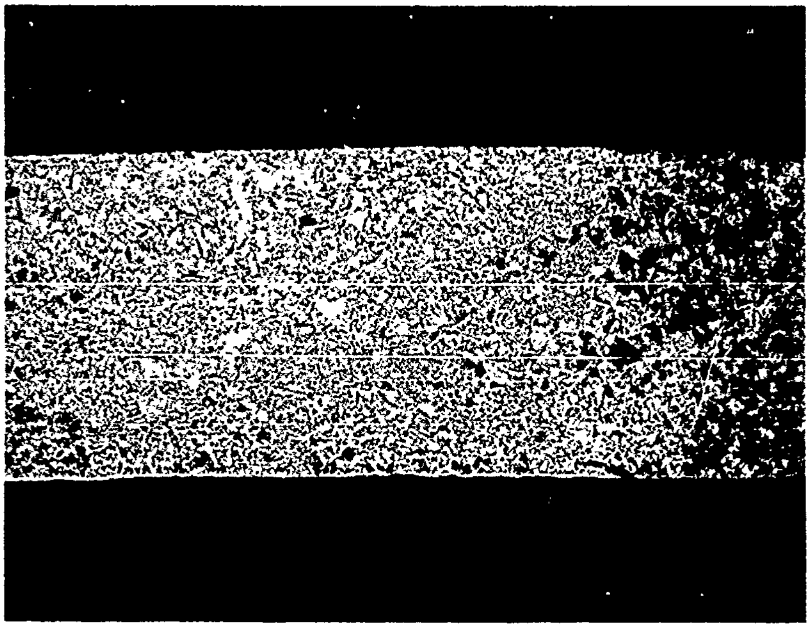
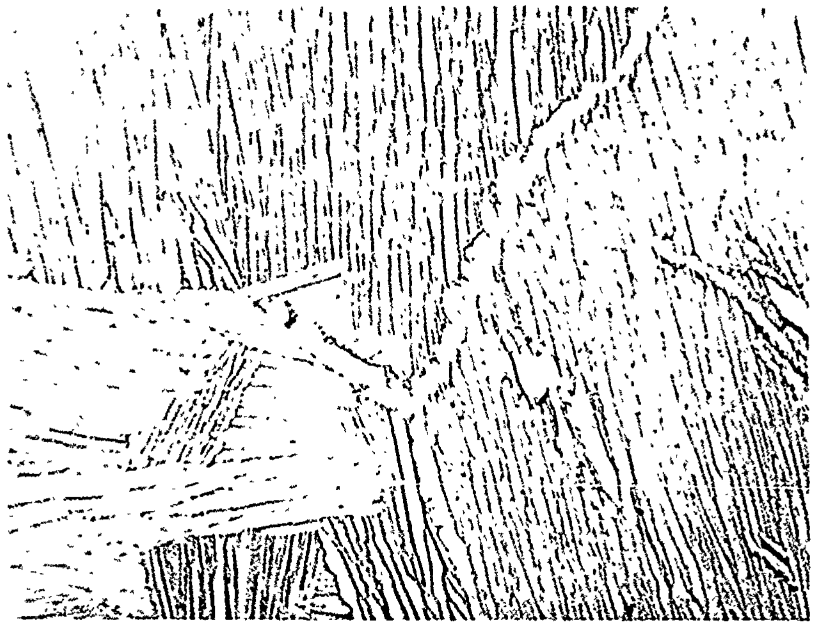


FIGURE 4-13.–MACROSTRUCTURE OF THE LARGE (6X8 IN.) Ti-6Al-4V BAR, BETA ANNEALED PLUS MILL ANNEALED



X1.1

FIGURE 4-14.—MACROSTRUCTURE OF THE SMALL (1.5X3 IN.) Ti-6Al-4V BAR, BETA ANNEALED PLUS MILL ANNEALED



X500

Note coarse alpha platelets

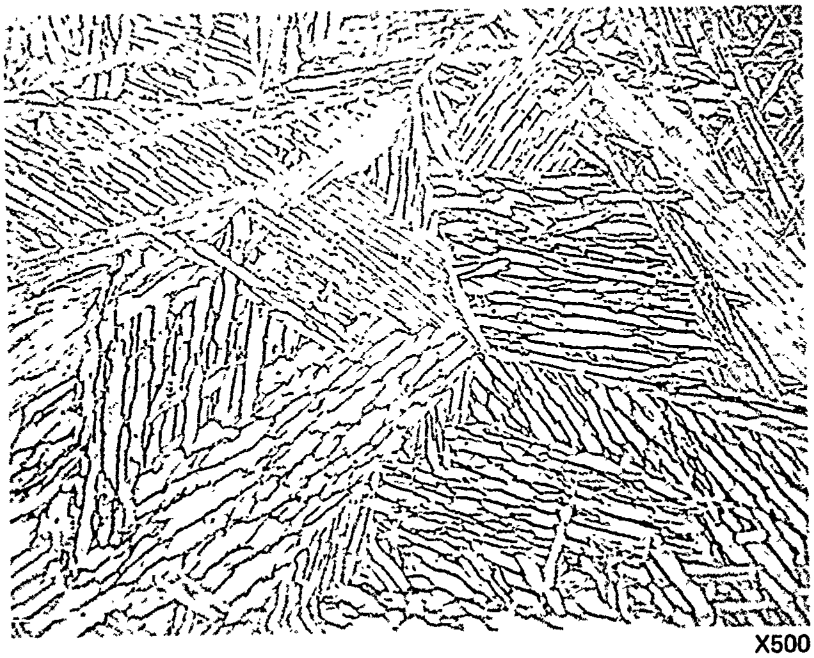
FIGURE 4-15.—MICROSTRUCTURE NEAR CENTER OF THE LARGE Ti-6Al-4V BAR, ANNEALED, LONG TRANSVERSE ORIENTATION

X500

FIGURE 4-16.—MICROSTRUCTURE NEAR CORNER OF THE LARGE Ti-6Al-4V BAR, ANNEALED, LONG TRANSVERSE ORIENTATION

X500

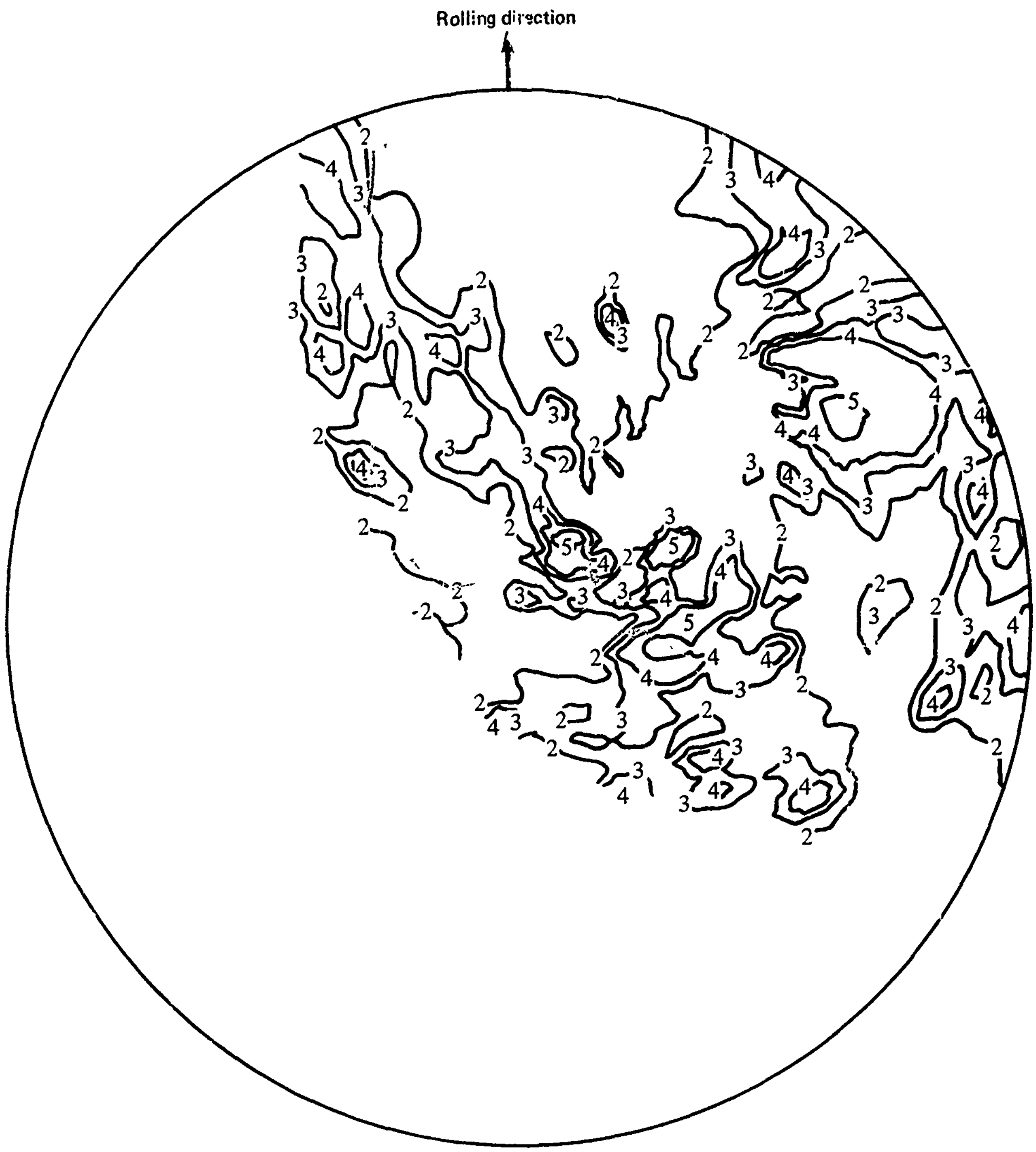
a. Longitudinal Orientation



X500

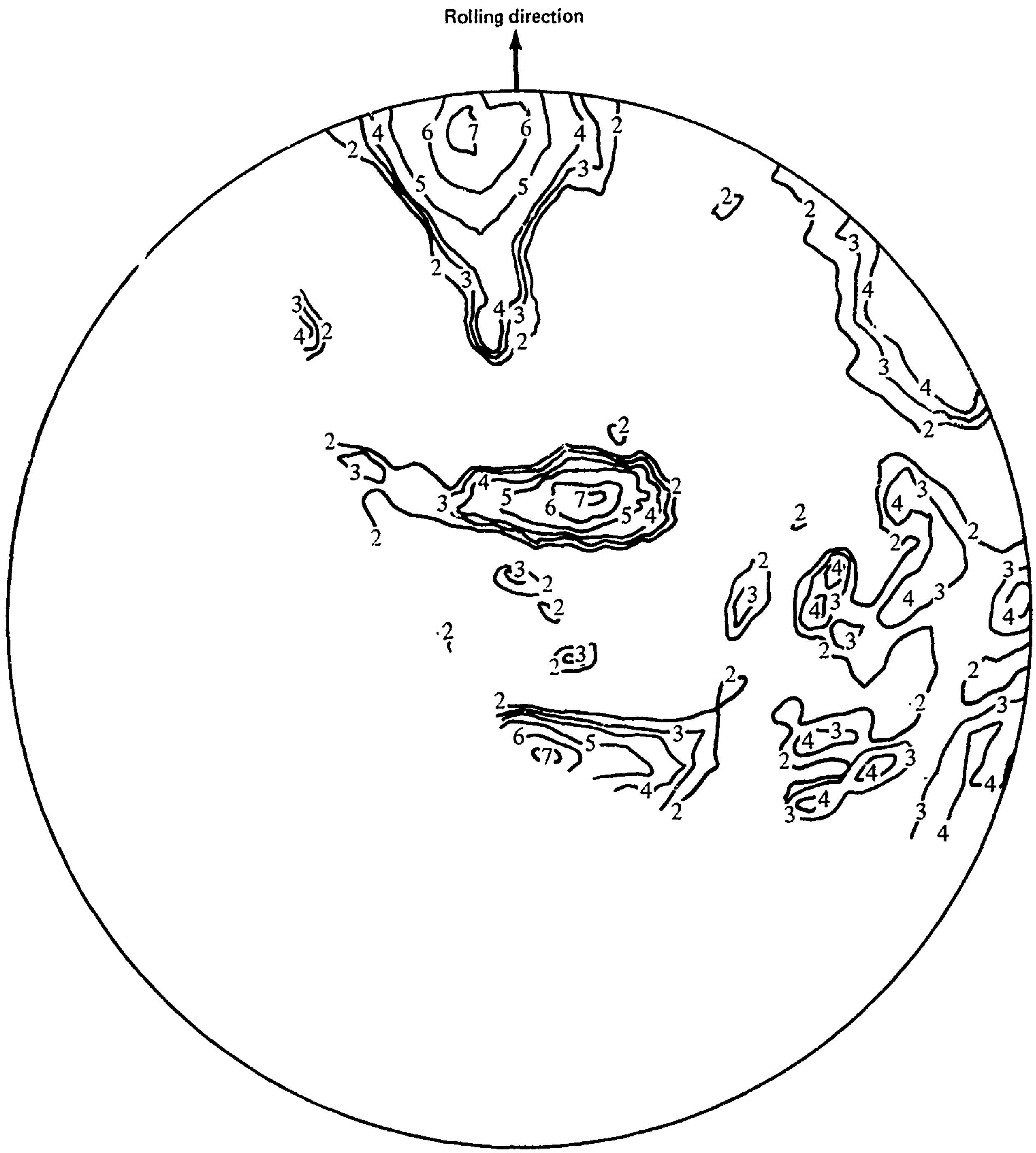
b. Long Transverse Orientation

FIGURE 4-17.—MICROSTRUCTURE OF THE SMALL Ti-6Al-4V BAR, ANNEALED



Contour line	1	2	3	4	5
Times random intensity	0.5	1	1.5	2	4

FIGURE 4-18.—TEXTURE POLE FIGURE FOR THE LARGE (6X8 IN.) Ti-6Al-4V BAR SPECIMEN, BETA ANNEALED PLUS MILL ANNEALED



Contour line	1	2	3	4	5	6	7
Times random intensity	0.5	1	1.5	2	4	8	14

FIGURE 4-19.—TEXTURE POLE FIGURE FOR THE SMALL (1.5X3 IN.) Ti-6Al-4V BAR SPECIMEN, BETA ANNEALED PLUS MILL ANNEALED

4.3.4 Mechanical Properties

The verification tensile test results for both bars are tabulated in Table 4-9. Supplier inspection test data are also tabulated in Table 4-9 for comparison. The 6- by 8-in. bar exhibited uniform properties with respect to grain direction and unusually high values of percent reduction in area. The non-directional properties were expected since both the texture and microstructure were relatively non-directional. The yield and ultimate strength test values were approximately 8 ksi below the proposed AST-3 specification minimums. This difference can be attributed to both the lean composition and optimistic specification limits. The unusually high tensile ductility is also a result of the lean composition.

The mechanical properties of the small bar also were below the proposed specification minimums, approximately 5 ksi for TUS and TYS. Again, the lean composition of bar and the relatively coarse prior beta grain size contribute to the lower properties. The effect of the highly directional texture was apparent on the tensile properties except for the slightly higher longitudinal yield strength. The lower ductility of the transverse grain direction was contradictory to other test results and appeared to result from particular coarse grain in the specimen test section.

4.3.5 Fracture Properties

Both bars demonstrated excellent fracture toughness (apparent K_{Ic}) with values ranging from 79 to 104 ksi$\sqrt{in.}$ The values were the highest achieved among the verification test materials. The stress corrosion resistance values (K_{Iscc}) were also the highest obtained, ranging from 83 to 99 ksi$\sqrt{in.}$ The high toughness and low yield strength of the material again combined to result in conservative or invalid test values with respect to ASTM standards. The high values of K_{Iscc} which were higher than the K_{Ic} values were further evidence of the conservative nature of the K_{Ic} test values. The effect of texture on fracture characteristics was not demonstrated by the test values.

4.4 EXTRUSIONS

Three extrusions, produced in AST-4 specification requirements for composition and microstructure, were evaluated to verify high fracture characteristics, mechanical properties, and metallurgical characteristics. The extrusions, consisting of a small tee (2.8 sq in.), a large tee (6.5 sq in.), Figure 4-20, and an extruded bar 1.5 in. by 3 in. cross-section were produced by MMT from an 1800-lb ingot specifically melted for the DOT program. The 3 pieces were extruded above the beta transus temperature to produce the desired basketweave microstructure. Billets of 8-in. diameter were used as starting stock for the extrusions.

Compact tension specimens were used to determine plane strain fracture toughness and DCB specimens and notched bend specimens were used to evaluate stress corrosion resistance. Where sufficient material was available, DCB specimens were fabricated, otherwise, notched bend specimens were made. Mechanical properties were determined using 0.25-in. diameter tensile specimens. Both transverse (WR) and longitudinal (RW) grain directions were evaluated. Specimen configurations and test procedures are described in Appendix A.

TABLE 4-9.—Ti-6Al-4V FORGED BAR MECHANICAL PROPERTIES[a]

Size (inches)	Supplier and heat (b)	Test lab	Test direction (c)	Tensile properties TUS (ksi)	TYS (ksi)	Elong (%)	RA (%)	Fracture properties K_{Ic} (ksi $\sqrt{in.}$)	K_{SR} (ksi $\sqrt{in.}$)	K_{Iscc} (ksi $\sqrt{in.}$)
1.5X3	Timet V4826	Timet	T	124	110	14	27	–	–	–
			T	125	110	12	26	–	55NF 100F	–
			T	125	110	11	25	–	–	–
		Boeing	L	125.4	110.1	13.5	34	84.1	–	88
			T	125.0	108.3	8.0	16	79.1	–	83
6X8	Timet G8080	Timet	L	121	105	13	33	–	–	--
			T	118	101	13	38	–	55.5NF 147.0F	–
		Boeing	L	123.6	108.5	15	38	104.1	–	99
			T	122.6	107.8	13	37	103.5	–	93
			ST	121.9	106.9	14	40	100.3	–	98

a Supplier tensile data are averaged from duplicate tests. All other data are single values

b Timet—Titanium Metals Corporation of America

c L—Longitudinal or RW for fracture specimens
T—Transverse or WR for fracture specimens
ST—Short transverse

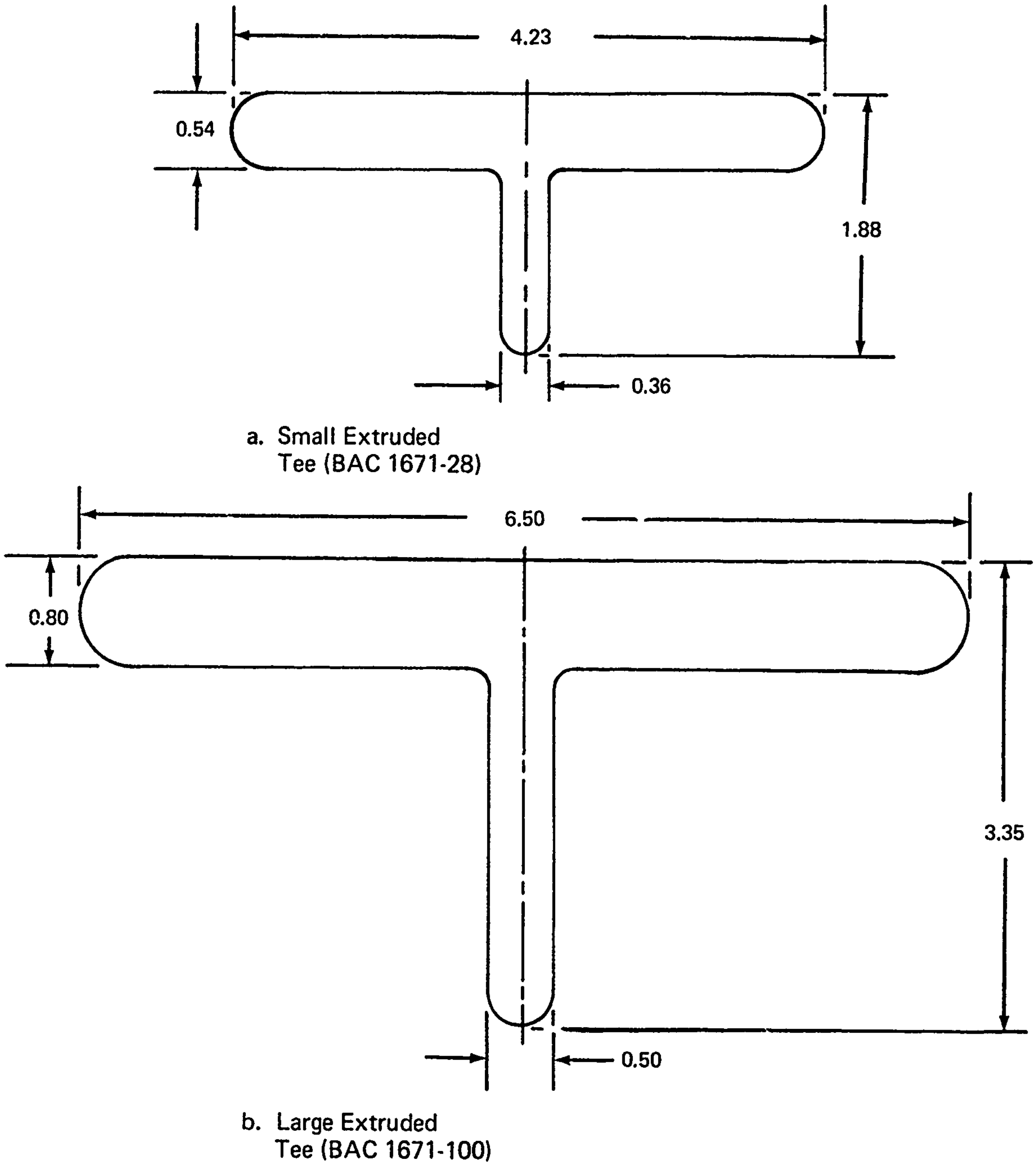


FIGURE 4-20.—EXTRUDED Ti-6Al-4V TEE CROSS SECTIONS

Metallurgical characterization testing at Boeing included evaluations for chemical composition, microstructure, and crystallographic texture. Analytical procedures are described in Appendix A.

4.4.1 Composition

Boeing and vendor chemical analyses for the extrusion agreed well, Table 4-10. The compositions represented mean or typical compositions with respect to AST-4 composition limits. The iron contents averaging 0.18 wt % were about 2 times higher than those of the plates produced by Timet.

4.4.2 Microstructure

Each extrusion microstructure consisted of a fully transformed beta morphology (basketweave) with average prior beta grain size of 0.016 in., Figures 4-21, 4-22, and 4-23. The prior beta grains were equiaxed similar to those of beta-annealed plate. This type of microstructure in titanium extrusions results from a complete recrystallization above the beta transus temperature after the extrusion process.

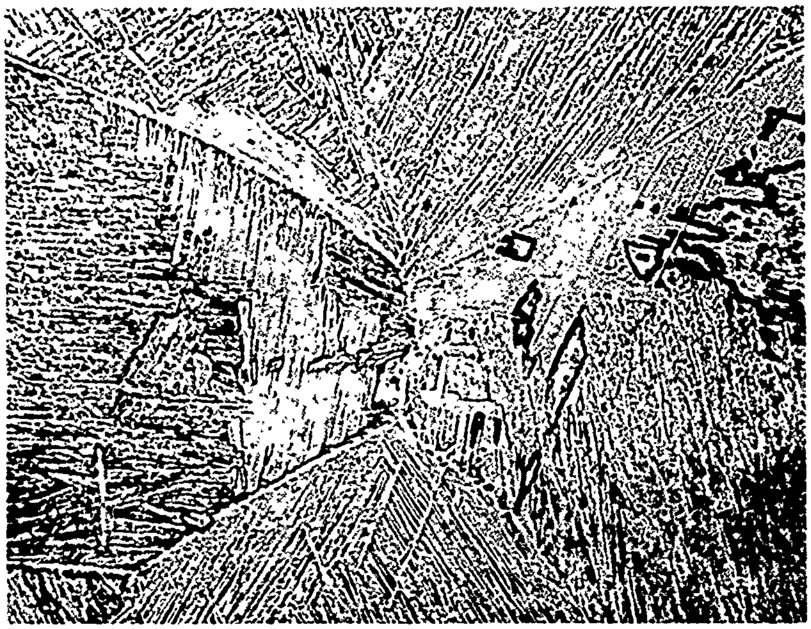
TABLE 4-10.—CHEMICAL COMPOSITIONS OF VERIFICATION TEST Ti-6Al-4V EXTRUSIONS

Mill product size	Heat	Test lab (a)	Alloying elements (weight %)						
			O_2	Al	V	Fe	N_2	C	H_2
Tee (large) BAC 1671-100	BZ 65	MMT	0.09	5.99	3.97	0.20	0.007	0.018	0.0065
		Boeing	0.10	6.15	–	0.15	0.010	0.010	0.005
Tee (small) BAC 1671-28	BZ 65	MMT	0.09	5.99	3.97	0.20	0.007	0.018	0.0077
		Boeing	0.088	5.95	3.8	0.17	0.010	0.010	0.0060
Bar 1.5X3		MMT	0.09	5.99	3.97	0.20	0.007	0.018	0.0068
		Boeing	0.097	5.86	3.8	0.15	0.007	0.010	0.0057
AST-4 requirements	–	–	0.07	5.7	3.6	0.15	0.03	0.05	0.0125
			-0.11	-6.2	-4.4	0.25	Max	Max	Max

[a]MMT—Martin Marietta Titanium

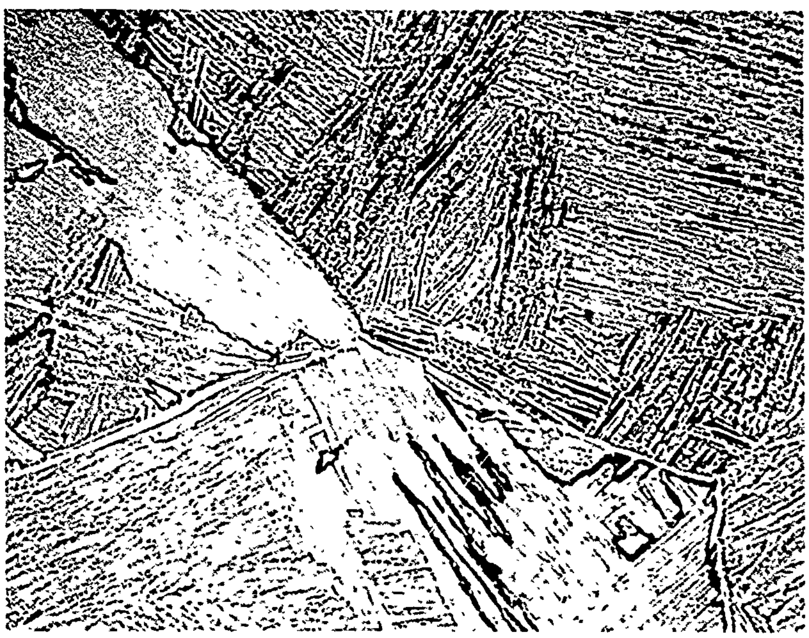
4.4.3 Texture

The basal plane crystallographic texture of each extrusion was determined using the Boeing computerized X-ray pole figure technique (Appendix A). The pole figures generated were oriented with respect to the extrusion direction such that the extrusion flange thickness was considered the short transverse direction and the extrusion flange width the



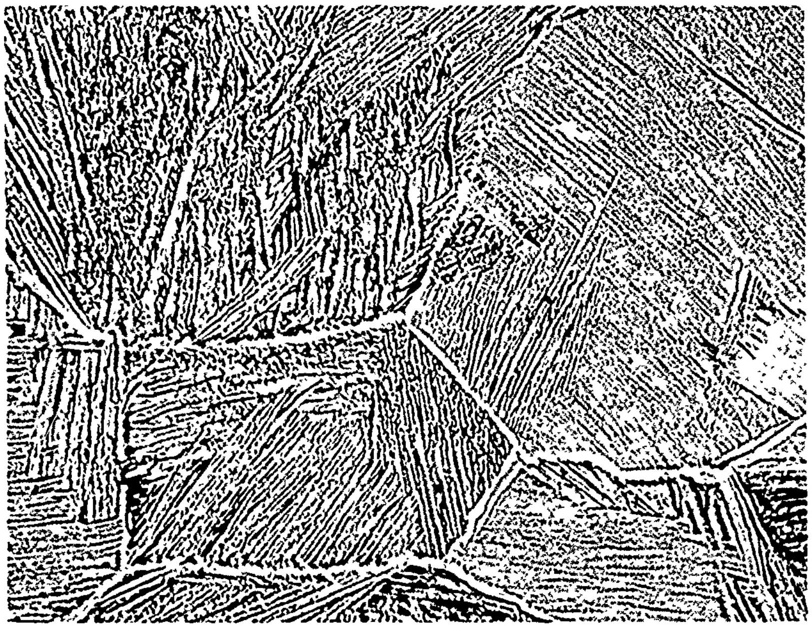
X500

FIGURE 4-21.–MICROSTRUCTURE OF THE SMALL TEE Ti-6Al-4V EXTRUSION, ANNEALED, END VIEW



X500

FIGURE 4-22.–MICROSTRUCTURE OF THE LARGE TEE Ti-6Al-4V EXTRUSION, ANNEALED, END VIEW



X500

FIGURE 4-23.–MICROSTRUCTURE OF Ti-6Al-4V EXTRUDED BAR, ANNEALED, END VIEW long transverse direction, Figure 4-24. The textures of the three extrusions were similar, Figures 4-25, 4-26, and 4-27, and typical of Ti-6Al-4V extruded near or above the beta transus. Earlier evaluations (Ref. 6) have shown similar textures for Ti-6Al-4V alloy extruded at temperatures near the beta transus. Texture intensity factors are shown in Table 4-11.

TABLE 4-11.—TEXTURE INTENSITY FACTORS AND GRAIN DIRECTION FOR Ti-6Al-4V EXTRUSIONS

Form and size (inches)	I_T	I_L	I_{ST}
Bar 1.5X3	34	34	32
Small tee	36	32	32
Large tee	34	32	34

4.4.4 Mechanical Properties

Tensile test results for the three extruded shapes are tabulated in Table 4-12. Directionality of tensile properties was low, with the maximum difference for Δ TYS less than 6 ksi. The Boeing test data agreed reasonably with the supplier (MMT) test data (Table 4-12), except that the TUS test values were slightly higher. The test values were below the proposed AST-4 specification minimums of 130 ksi for TUS and 120 ksi for TYS, indicating that the specification requirements were optimistic. The extruded bar properties, however, were superior to those of the forged bar of identical size.

4.4.5 Fracture Characteristics

The compact tension specimen test results for evaluating plane strain fracture toughness varied from 67.5 to 82.7 ksi$\sqrt{\text{in.}}$ Although these values are only moderately high, the values are conservative since the small size of the test specimens resulted in excessive yielding. Larger specimens were not possible because of the extrusion sizes.

Stress corrosion resistance (K_{Iscc}) of the extrusions was excellent, ranging from 70 to 86 ksi$\sqrt{\text{in.}}$ All 3 extrusions met the proposed specification minimum of 55 ksi$\sqrt{\text{in.}}$ For the majority of cases, the K_{Iscc} values were higher than their respective K_{Ic} values. Although this might be expected since the toughness values are considered conservative, it does provide an indication of the immunity of the extrusion material to stress corrosion cracking in saltwater.

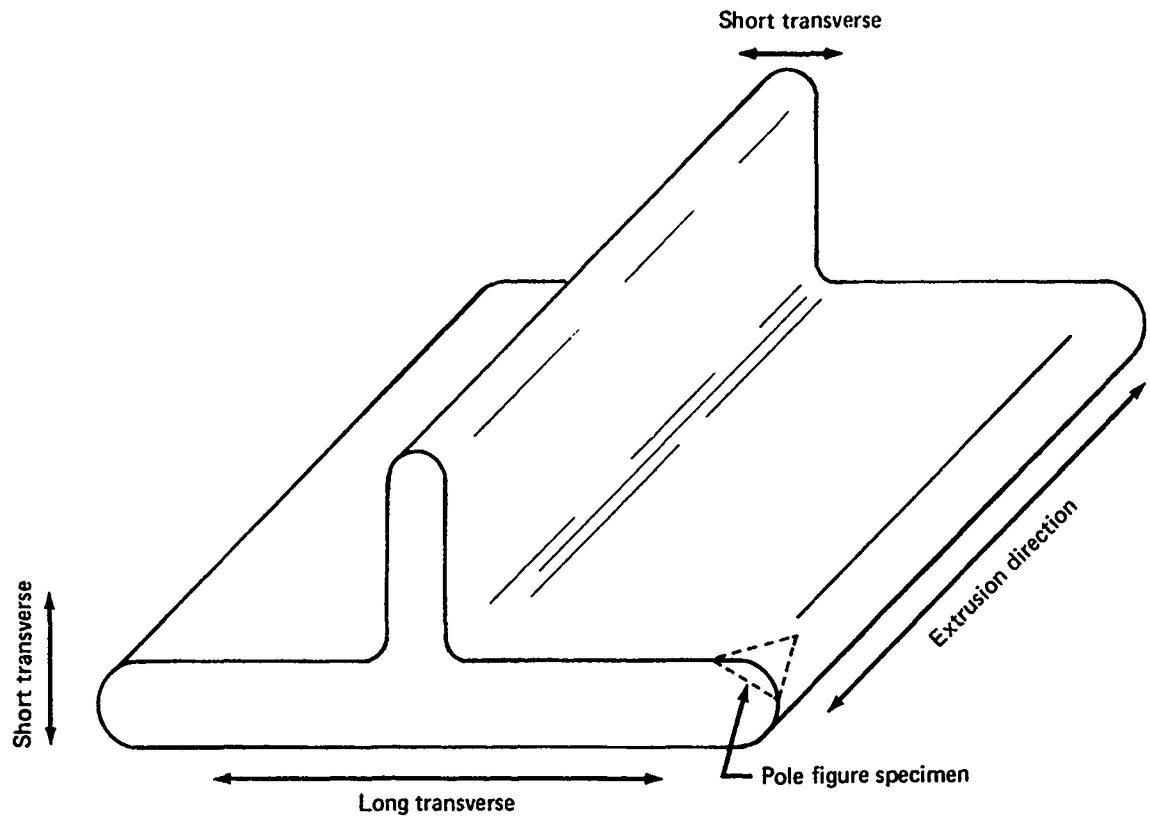
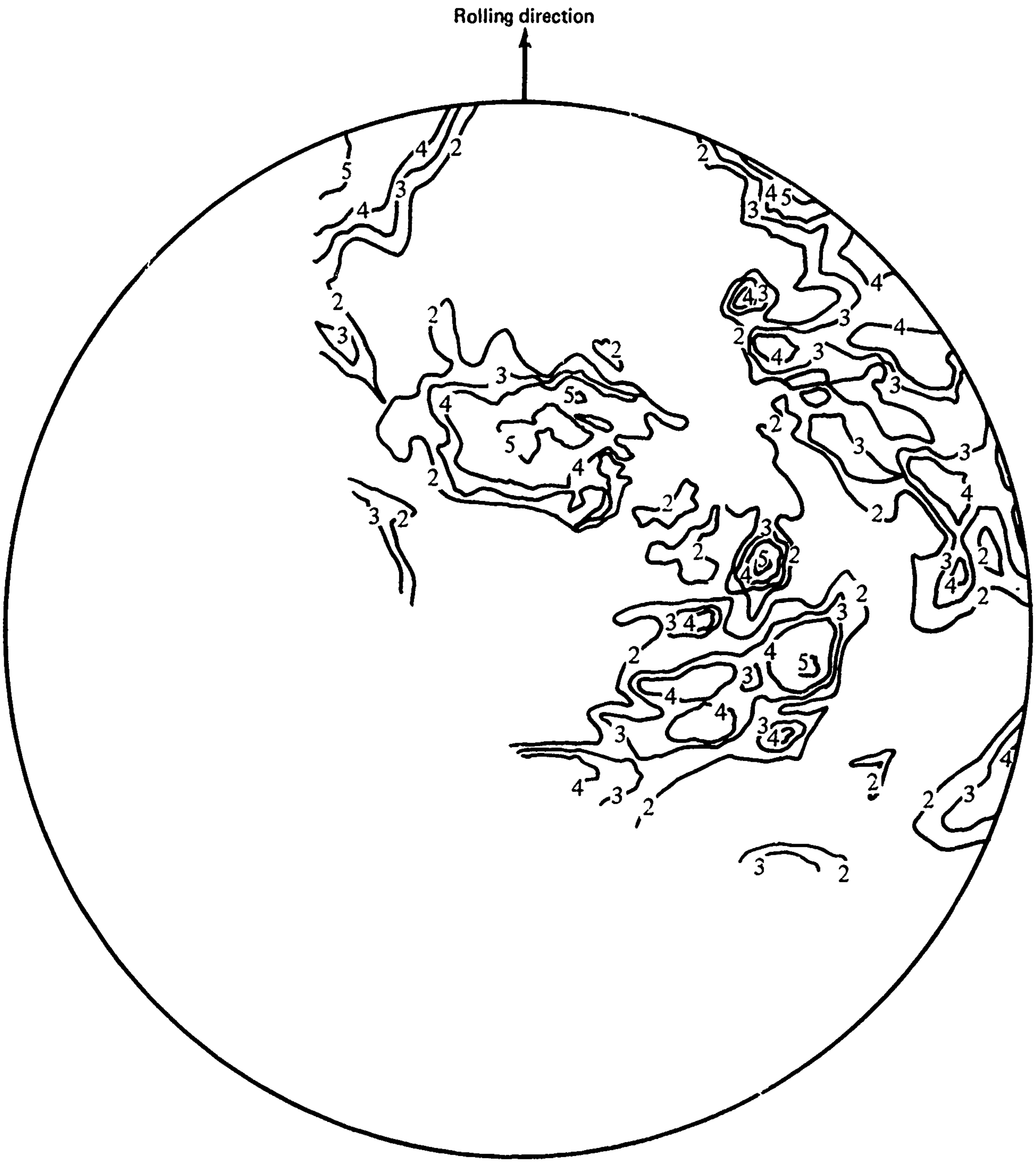
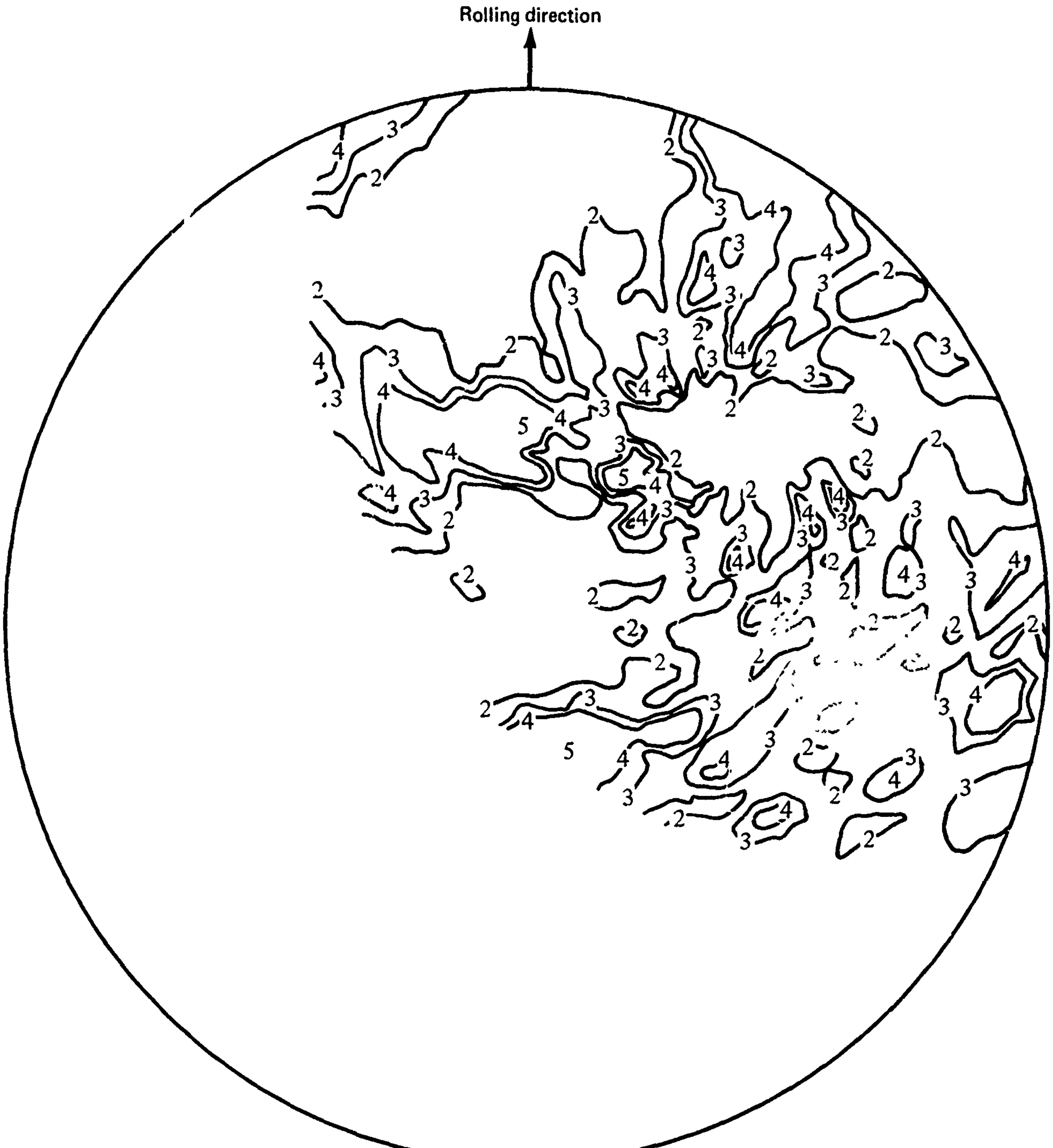


FIGURE 4-24.—ORIENTATION OF POLE FIGURE SPECIMENS FOR Ti-6Al-4V EXTRUSIONS



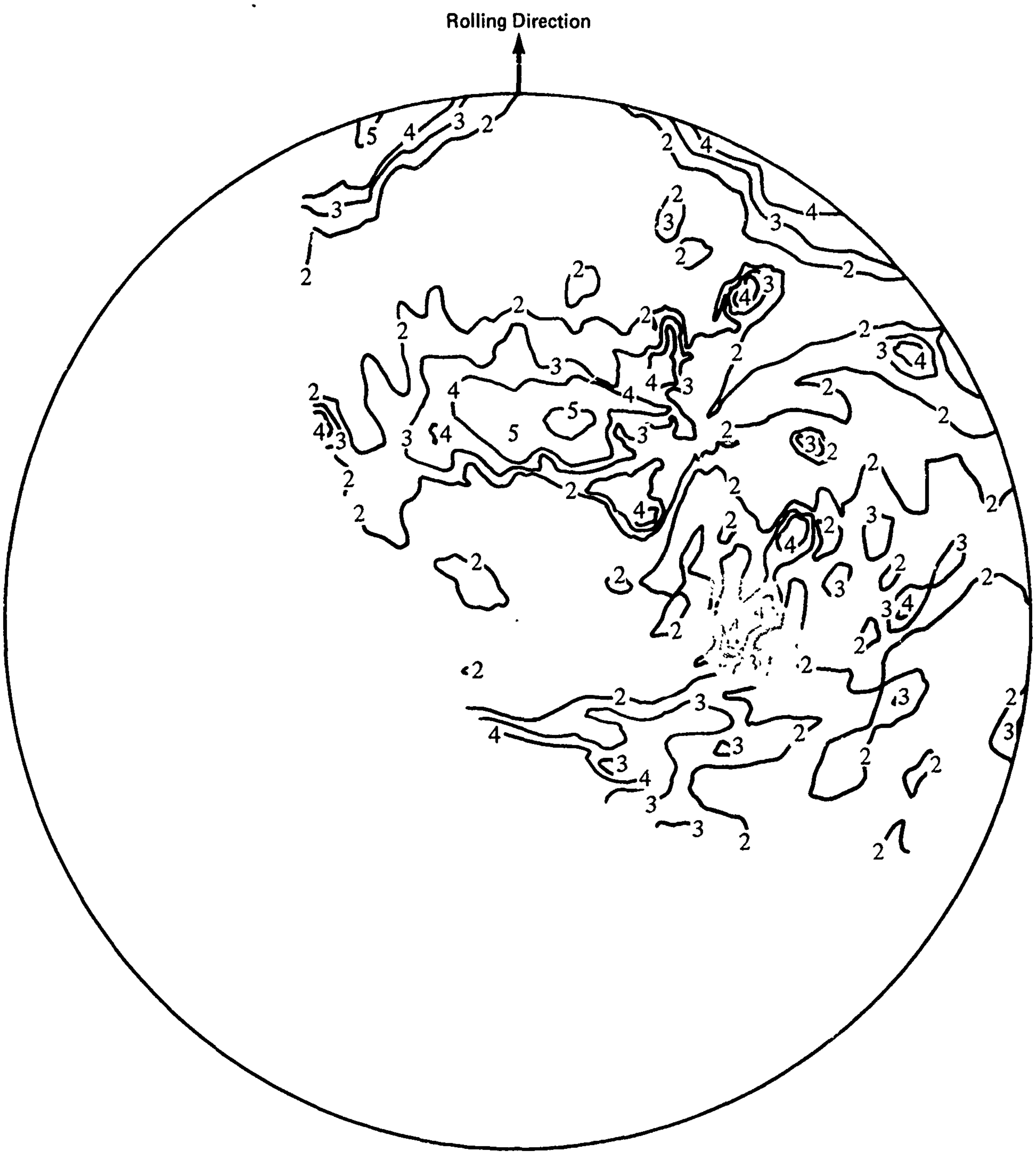
Contour line	1	2	3	4	5
Times random intensity	0.5	1	1.5	2	4

FIGURE 4-25.—TEXTURE POLE FIGURE FOR THE SMALL TEE Ti-6Al-4V EXTRUSION



Contour line	1	2	3	4	5
Times random intensity	0.5	1	1.5	2	4

FIGURE 4-26.—TEXTURE POLE FIGURE FOR THE LARGE TEE Ti-6Al-4V EXTRUSION



Contour line	1	2	3	4	5
Times random intensity	0.5	1	1.5	2	4

FIGURE 4-27.—TEXTURE POLE FIGURE FOR Ti-6Al-4V EXTRUDED BAR (1.5X3.0 IN.)

TABLE 4-12.—Ti-6Al-4V EXTRUSION MECHANICAL PROPERTIES[a]

Mill form and size (inches)	Supplier and heat (b)	Test lab	Test direction (c)	Tensile properties				Fracture properties	
				TUS (ksi)	TYS (ksi)	Elong (%)	RA (%)	K_{Ic} (ksi$\sqrt{in.}$)	K_{Iscc} (ksi$\sqrt{in.}$)
Small tee	MMT	MMT	L	122	113	14	34	–	–
			T	121	113	12	33	–	–
		Boeing	L	126.3	114.7	14	35	67.5	77
			T	126.0	113.9	13	31	70.9	70
Large tee	MMT BZ65	MMT	L	122	113	12	32	–	–
			T	123	113	12	29	–	–
		Boeing	L	128.8	120.0	13.5	29	78.6	76
			T	126.5	114.2	13.5	33	82.7	80
Bar 1.5X3.0	MMT	MMT	L	122	114	13	27	–	–
			T	121	113	15	30.3	–	–
		Boeing	L	123.8	112.0	15	32	80.7	86
			T	123.5	112.2	12	32	78.7	83

a Supplier tensile data are averaged from duplicate tests
All other data are single values
b MMT—*Martin Marietta Titanium*
c L—Longitudinal or RW for fracture specimens
T—Transverse or WR for fracture specimens

5.0 GENERAL DISCUSSION

Generally, all the mill products evaluated in the verification test program possessed excellent fracture characteristics, but slightly lower strength properties. One exception was the RMI 0.57-in. plate. The mill products met the proposed AST specification limits for stress corrosion resistance in saltwater, but did not meet the proposed minimums for tensile properties. The resulting fracture properties were the highest recorded to date at Boeing for Ti-6Al-4V mill products, Figure 5-1. These materials were characterized by lean compositions, varying degrees of basal plane texture and minor variations in microstructure.

The effects of the various textures on fracture properties were not dramatic or consistent, indicating that the importance of texture is less for lean compositions than for rich compositions (i.e., oxygen contents of 0.13 to 0.20 wt %). The previous study, involving mostly rich compositions (Ref. 2), found texture to be the major factor influencing fracture properties. The causes of texture variations associated with the beta-annealing of these lean compositions are not well understood.

The RMI plate met mechanical property requirements, but did not meet the requirement for stress corrosion resistance. The RMI plate was characterized by a rich composition, a random texture and a uniform equiaxed transformed beta microstructure. The resulting properties, therefore, were a result of the richer composition.

These results demonstrate the need for composition control and adequate thermomechanical processing. Tighter limits on variations of composition, specifically oxygen and aluminum, can result in the achievement of both high fracture properties and moderate strength if thermomechanical processing is controlled. The proposed lower limits on oxygen (0.07 wt %) and aluminum (5.5 wt %) were too low to provide TUS values consistently above 130 ksi. Figures 5-2 and 5-3 show the trends of oxygen and aluminum as related to TYS for the verification test data. Thermomechanical processing effects on TYS contribute to the scatter shown by the data plots. (Note: Metallurgical effects are better depicted by TYS rather than TUS; the latter however, is more generally used in design.)

The effects of variations in thermomechanical processing on mechanical properties are illustrated by the difference in TYS between highly worked material (e.g., 0.5-in. plate) and moderately worked material (e.g., large 6- by 8-in. bar) where the strength difference varied as high as 13 ksi. Property variations for a constant Ti-6Al-4V composition are a result of variations in crystallographic texture and microstructure. The type of texture and microstructure are in turn a result of thermomechanical processing.

To obtain the optimum balance of fracture properties and mechanical properties in Ti-6Al-4V, composition, microstructure, and texture must be controlled. To control composition, tight limits must be placed on variations in significant alloying elements. To control texture and microstructure, thermomechanical processing must be controlled. This approach, however, must be tempered by practicality and the limitations inherent in the titanium industry. For example, the same thermomechanical processing used for sheet obviously cannot be specified for large bar. Processing in general is usually impractical to control by a material specification. Complex process variations are required to produce the

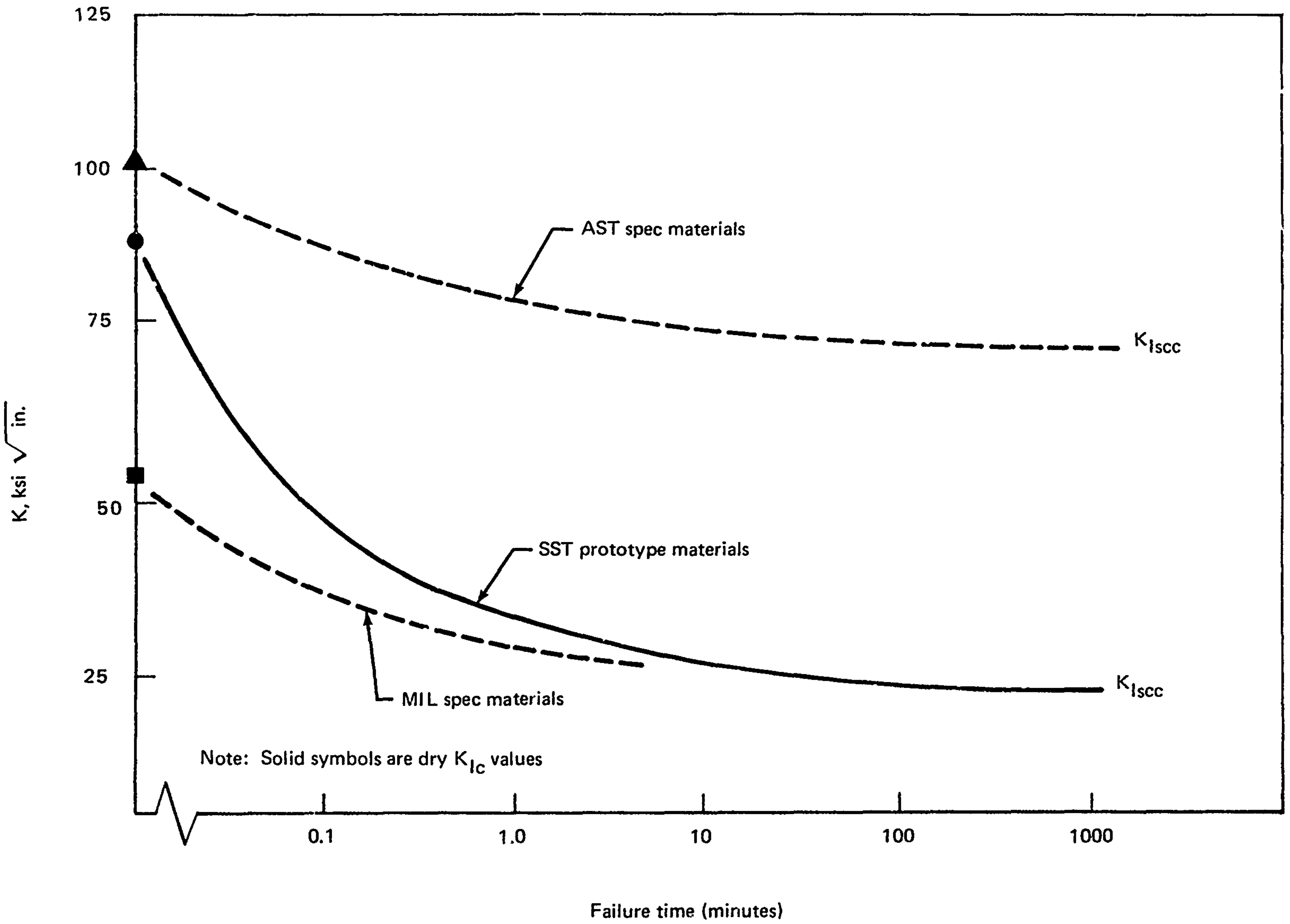


FIGURE 5-1.—Ti-6Al-4V STRESS CORROSION CHARACTERISTICS

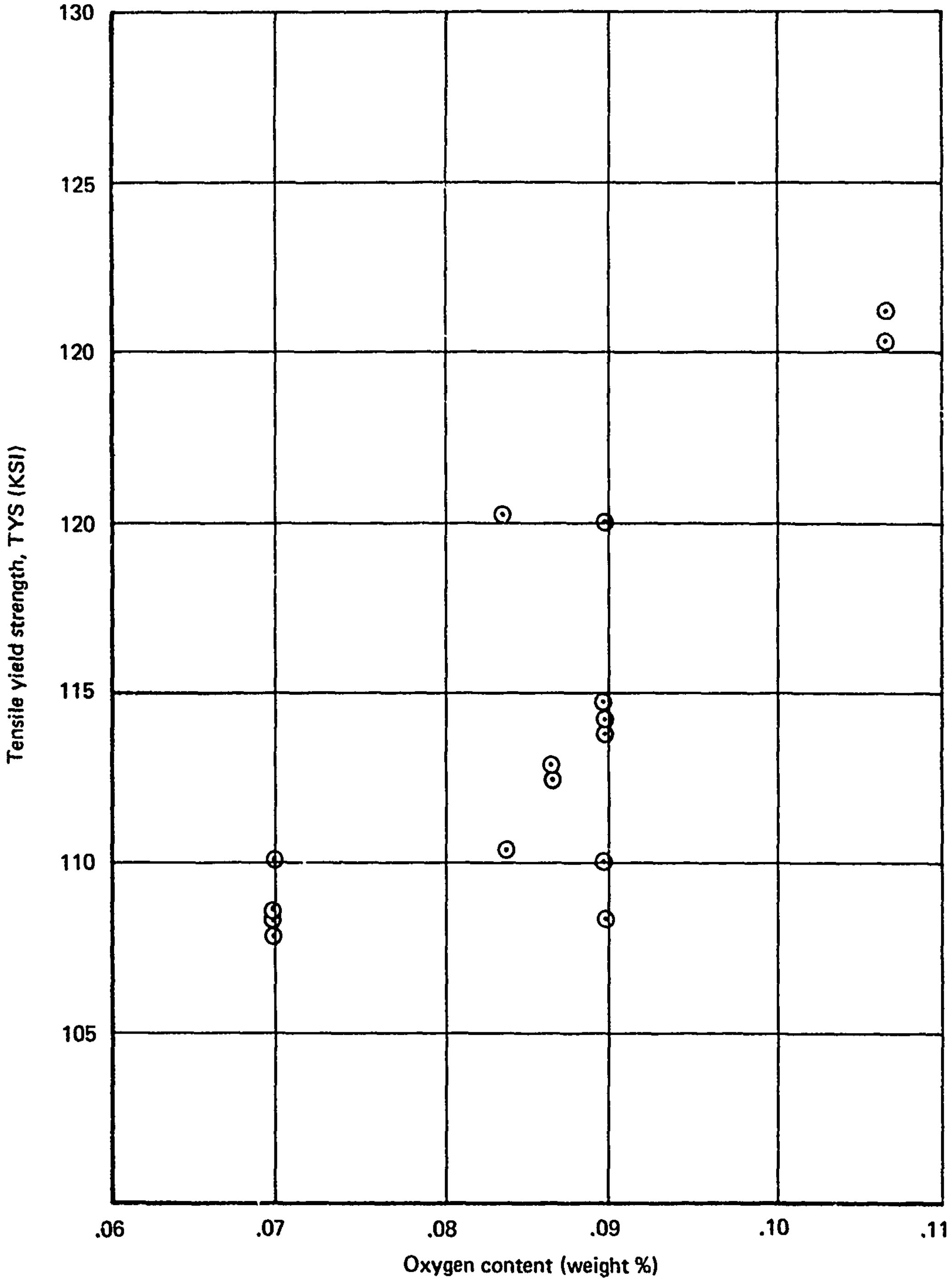


FIGURE 5-2.—EFFECT OF OXYGEN CONTENT ON TYS FOR BETA ANNEALED Ti-6Al-4V ALLOY

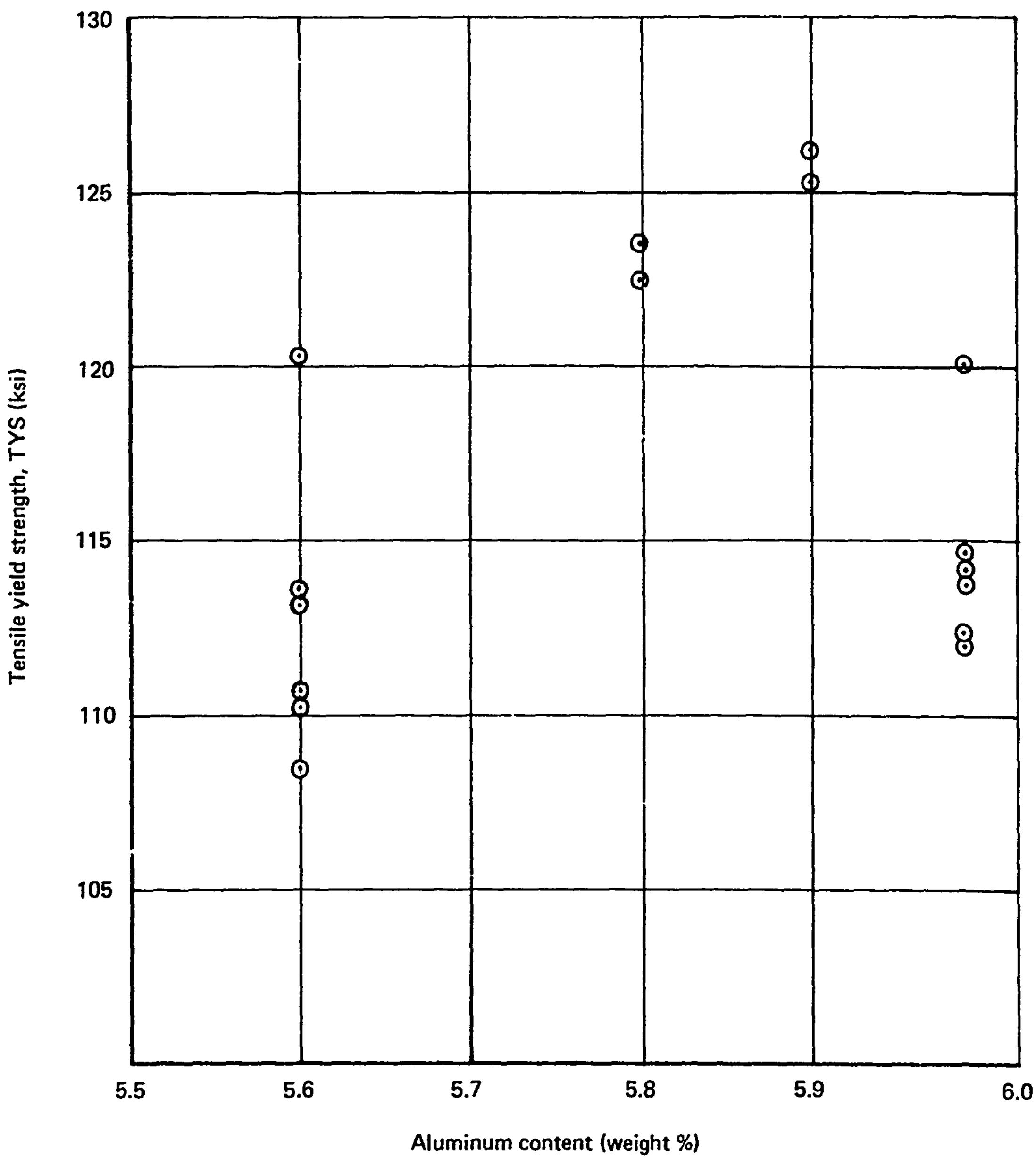


FIGURE 5-3.—EFFECT OF ALUMINUM ON TYS FOR BETA ANNEALED Ti-6Al-4V ALLOY

various product sizes. To assure product quality, these unduly cumbersome process variations would be required in the specifications, which would increase product costs. In addition, by specifying a particular process, the producer is inhibited from making process improvements that could improve the product or lower costs. To control thermomechanical processing in the AST specifications, end-product properties were specified, including texture, microstructure, strength, and saltwater-fracture toughness.

The results of the verification testing revealed the need to make minor modifications in the proposed AST specifications to achieve consistently an optimum balance of properties. The vendors have indicated that composition ranges set too narrow in comparison with producer melting accuracy increase ingot rejection rates and result in higher costs. The modifications were based on the verification test results, vendor comments on practicality and a review of the titanium technology generated under the Phase I program (Ref. 2). The final proposed versions of each AST specification are included in Appendices B through E. The modifications to the specification requirements are as follows:

a) Composition
The lower limit on oxygen was raised from 0.07 to 0.08 wt % and on aluminum from 5.5 to 5.7 wt % to promote an increase in mechanical properties.

b) Mechanical Properties
The minimums for tensile properties were reduced to better reflect those properties obtained from the verification test materials. Because tensile properties reflect thermomechanical processing as well as alloy composition, they were maintained sufficiently high to assure adequate thermomechanical processing.

c) Saltwater Fracture Test
The minimum requirement for K_{SL}, saltwater fracture toughness, in Ti-6Al-4V sheet was increased from 75 to 85 ksi$\sqrt{\text{in}}$. The time of sustained loading was maintained at 20 minutes.

Cost estimates made by the vendors for mill products made to the initial AST specifications ranged from 9 to 12% higher than costs for the SST prototype material. The modifications added to the specifications should not increase costs by more than an additional 5%.

6.0 CONCLUSIONS

Development and evaluation of the proposed AST material specifications and characterization of verification test materials has led to the following conclusions:

1) Material specifications for high toughness Ti-6Al-4V mill products were developed and verified by the evaluation of materials procured to the new specification requirements.

2) Excellent fracture toughness, stress corrosion resistance, and environmental fatigue crack growth characteristics in Ti-6Al-4V mill products are achieved by utilizing compositions lean in oxygen and aluminum. K_{scc} values for sheet of over over 180 ksi $\sqrt{in.}$ and K_{Iscc} values for thick section products approaching 90 ksi $\sqrt{in.}$ were attained.

3) The initial specification requirements for minimal mechanical properties were too high for the proposed limits on alloy composition and modifications were necessary.

4) Tensile properties of the high toughness Ti-6Al-4V are 4 to 9% lower than Ti-6Al-4V mill products procured to conventional industry specifications.

5) The effect of variations in basal plane texture on properties in lean compositions of Ti-6Al-4V are not as dramatic as in richer compositions of Ti-6Al-4V (e.g., 0.13 wt % oxygen and higher).

6) Fatigue crack growth rates in high toughness Ti-6Al-4V sheet are slightly accelerated by a saltwater environment.

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7.0 RECOMMENDATIONS

The development of specifications for high toughness Ti-6Al-4V mill products and the verification of improved mechanical and fracture properties provide a major step towards the utilization of a new material. However, to fully establish the material as an industry standard, additional work is recommended.

1) Military or AMS specifications should be prepared for high toughness Ti-6Al-4V sheet, plate, extrusions, bar, and forgings, based on the proposed AST specifications.

2) An allowables determination program including both mechanical and fracture properties should be conducted on materials procured to the requirements of proposed AST specifications and the data should be included in design handbooks.

3) The smooth and notched fatigue characteristics of the improved Ti-6Al-4V mill products should be investigated.

4) The effects of various thermomechanical processing prior to beta annealing on resultant basal plane crystallographic texture and mechanical properties should be investigated for lean and rich compositions within the proposed composition limits.

APPENDIX A

TEST SPECIMEN CONFIGURATIONS, TESTING PROCEDURES, AND METALLURGICAL CHARACTERIZATION TESTING

MECHANICAL PROPERTIES TESTING

Tensile Test

Material receipt inspection tests were performed per Boeing Material Specification requirements in accordance with ASTM E8 testing procedures. Figure A-1 shows specimen configurations used. The strain rate was held within 0.003 to 0.007 in./in./min using class B extensometers.

FRACTURE TOUGHNESS TESTING

Compact Tension Specimens

Compact tension fracture toughness specimens in accordance with Figure A-2 and ASTM E-399 recommended procedures were used to obtain static fracture toughness values, except that specimen thickness was limited to 1.0 in. and less based on the available thickness of the material tested. For this reason some of the data do not represent valid K_{Ic} values by the accepted thickness relationship of $t \geq 2.5\ (K_{Ic}/TYS)^2$.

Center-Notched Panels

Center-notched panels (CNP) were used for sheet materials (< 0.188-in. thick). Figure A-3 shows a 12- by 36-in. CNP. The total crack length (2a) was kept at one-third the panel width. For these conditions, the panel width W must obey the following:

$$W \geq 5.91(K_c/TYS)^2$$

The term K_c mixed-mode or plane stress fracture toughness is used here, as thicknesses were normally much less than those required for K_{Ic}. In this regard, a 12-in.-wide panel would be valid for K_c determinations up to 185 ksi$\sqrt{\text{in.}}$ for a yield strength of 130 ksi.

The center-notched panels are tension-tension fatigue cycled to grow the fatigue crack from either 0.5 in. or 2.0 in. to 4.2 in. After fatigue cycling, the panels are fracture tested in room temperature air at a stress rate of 1000 psi/sec. K_c is calculated from the following equation:

$$K_c = \sigma_g \sqrt{\pi a} \left[\frac{W}{\pi a} \tan \frac{\pi a}{W} \right]^{1/2}$$

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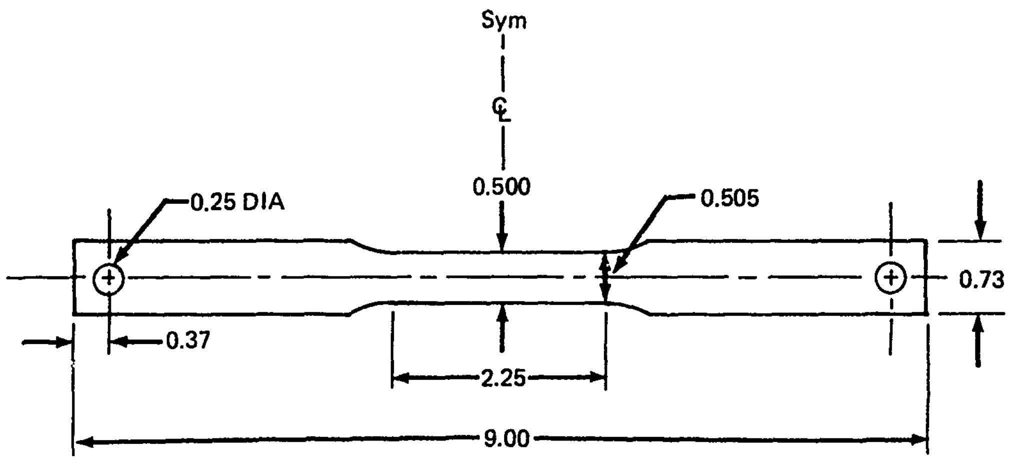
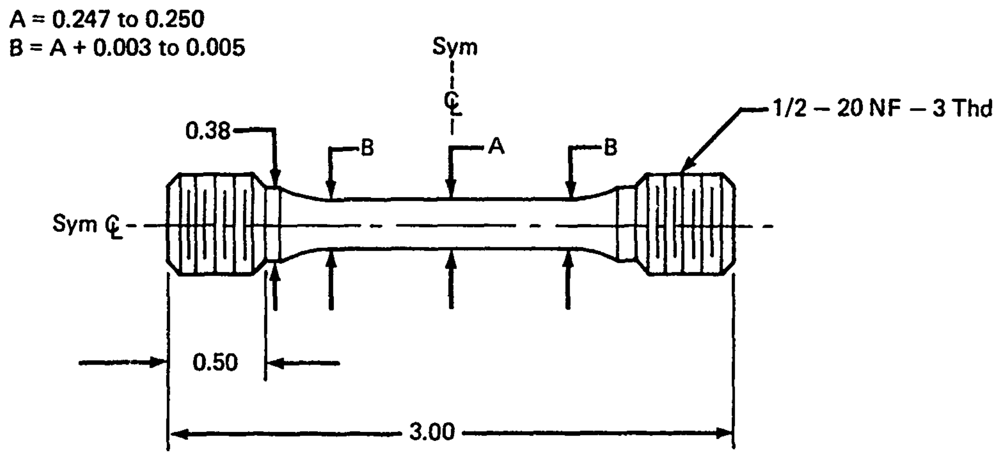


Flat Tensile Specimen



Round Tensile Specimen—Thick Material

FIGURE A-1.—TYPICAL TENSILE SPECIMENS

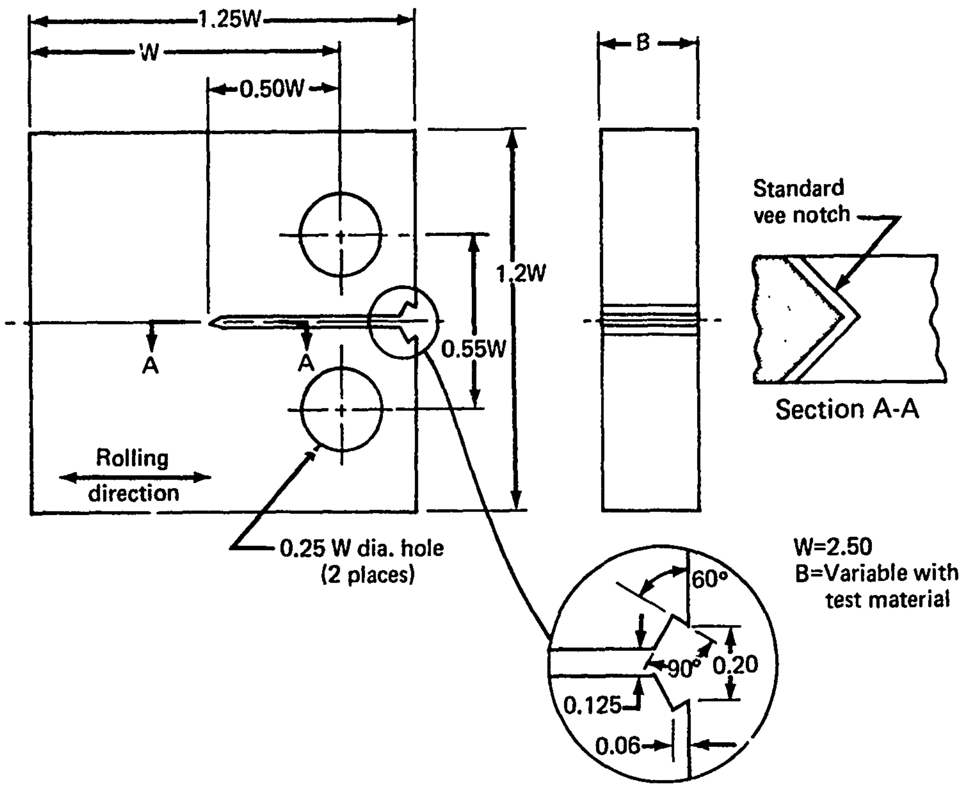
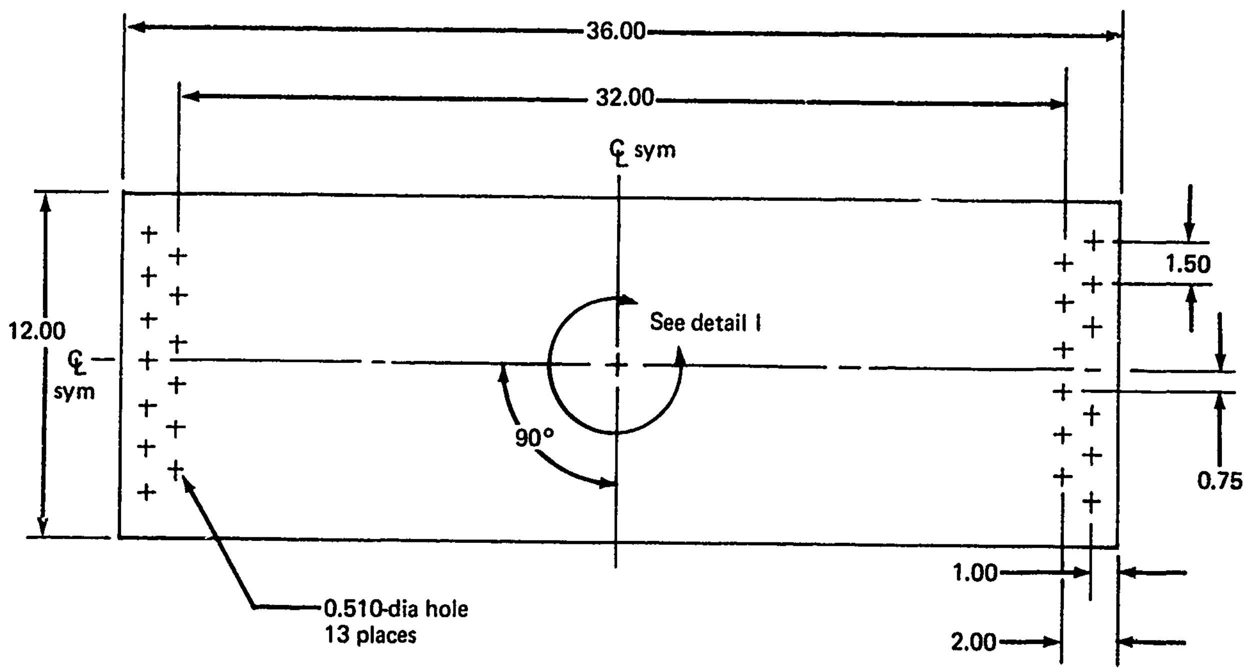
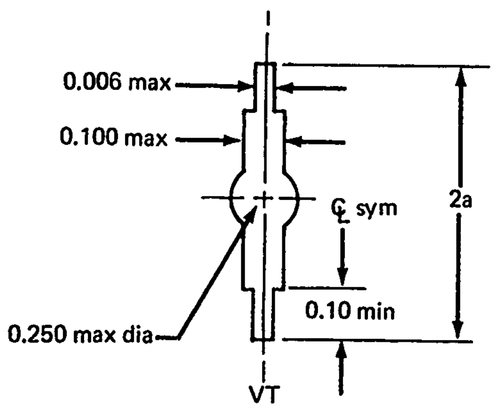


FIGURE A-2.—COMPACT TENSION SPECIMEN CONFIGURATION USED FOR STATIC FRACTURE TESTING Ti-6Al-4V





Detail I

Dimensions in inches

$$K=\sigma_g\sqrt{\pi a}\left[\frac{W}{\pi a}\tan\frac{\pi a}{W}\right]^{1/2}$$

FIGURE A-3.—CENTER-NOTCHED PANEL

The last term (in brackets) is the finite panel size correction factor and is 1.06 for a 12-in.-wide panel with 2a/W = 0.35. The calculation of K_c was based on maximum failure load and the initial fatigue crack length (a) prior to dynamic loading at 1000 psi/sec.

The fatigue crack growth procedures are discussed below under "Crack Growth Rates."

STRESS-CORROSION RESISTANCE

Notched Bend and Center-Notched Panel Specimens

Stress-corrosion tests were conducted using notched bend and center-notched panel specimens (Figs. A-3 and A-4) and a sustained loading technique in the environment of 3.5% NaCl aqueous solution. Figure A-5 shows the notch orientation code. The stress intensity level is plotted versus time to failure and a curve is drawn to determine the threshold value at which no failure occurs. This value is defined as K_{scc} for thin sections and K_{Iscc} for thicker sections. No attempt is made to separate the two or to determine the cutoff gage for transition from K_{scc} to K_{Iscc}. The main interest is to determine the threshold stress intensity level that a material will sustain in 3.5% NaCl. Figure A-6 shows a plot of sustained load K versus time and the resulting threshold value.

It is realized that this approach is slightly nonconservative, but it was felt that it was more desirable to obtain the best possible estimate of the actual threshold in order to study the interrelationship of such material parameters as composition, heat treatment, texture, etc., rather than a conservatively biased approach using, say, the highest no-failure K level.

Notched Bend Specimen

Figure A-4 shows the standard four-point-loaded notched bend specimen and related formulas. Again, specimen size was limited by the natural or available thickness of the test material.

Double Cantilever Beam (DCB) Specimens

Smooth, uniform height DCB stress corrosion test specimens, Figure A-7, have been used in previous investigations of the stress corrosion cracking susceptibility of Ti-6Al-4V in 3-1/2% aqueous NaCl solutions (Ref. 4). A considerable amount of experience was obtained in the Reference 4 investigation applying the DCB specimen testing procedures, and the data resulting from the DCB specimen tests were very consistent and repeatable. These same procedures were applied in the present work. DCB specimens were loaded hydraulically and wedges inserted to maintain the preselected load during testing. A close-up of the test setup is shown in Figure A-8.

Stress corrosion cracking results were evaluated by plotting increase in crack length versus test duration using intermittent readings of crack length versus time. The slopes of the resultant curves were taken as the SCC velocities. Corresponding stress intensity factors were determined using the measured crack opening displacements at the end of the

Formulas

K_{Ic} — $P_5 \alpha$ stress intensity factor (critical)

$$\alpha \quad \frac{L}{BW^{3/2}} \left[\left(\frac{1}{1 - \mu^2} \right) \left(34.7 \frac{a}{W} - 55.2 \left(\frac{a}{W} \right)^2 + 196 \left(\frac{a}{W} \right)^3 \right] ^{1/2}$$

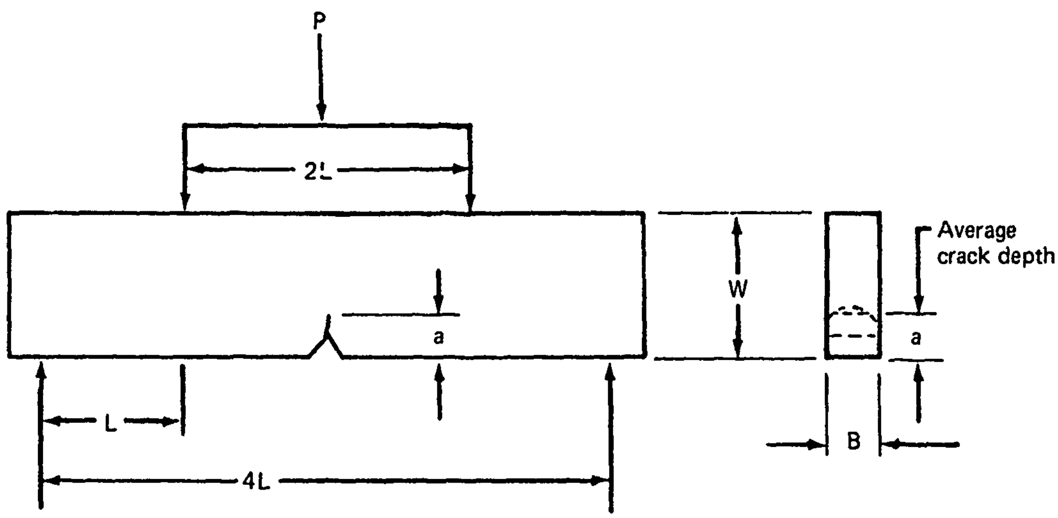
$$G_{Ic} \quad K_{IE}^2 \left(\frac{1 - \mu^2}{E} \right)$$

P_5 = intersection of load deflection curve and line drawn from origin with slope offset 5% from linear portion of load-deflection curve

E = modulus of elasticity (assumed=16.0×10^3 ksi)

μ = Poisson's ratio (assumed - 0.33)

σ_N = net area stress = $\frac{Mc}{I}$ where $M = \frac{LP_5}{2}$ and $I = \frac{B(W-a)^3}{12}$



L=1.50
B=0.480 or (t)
W=1.50

FIGURE A-4.—FOUR-POINT-LOADED NOTCHED BEND SPECIMEN

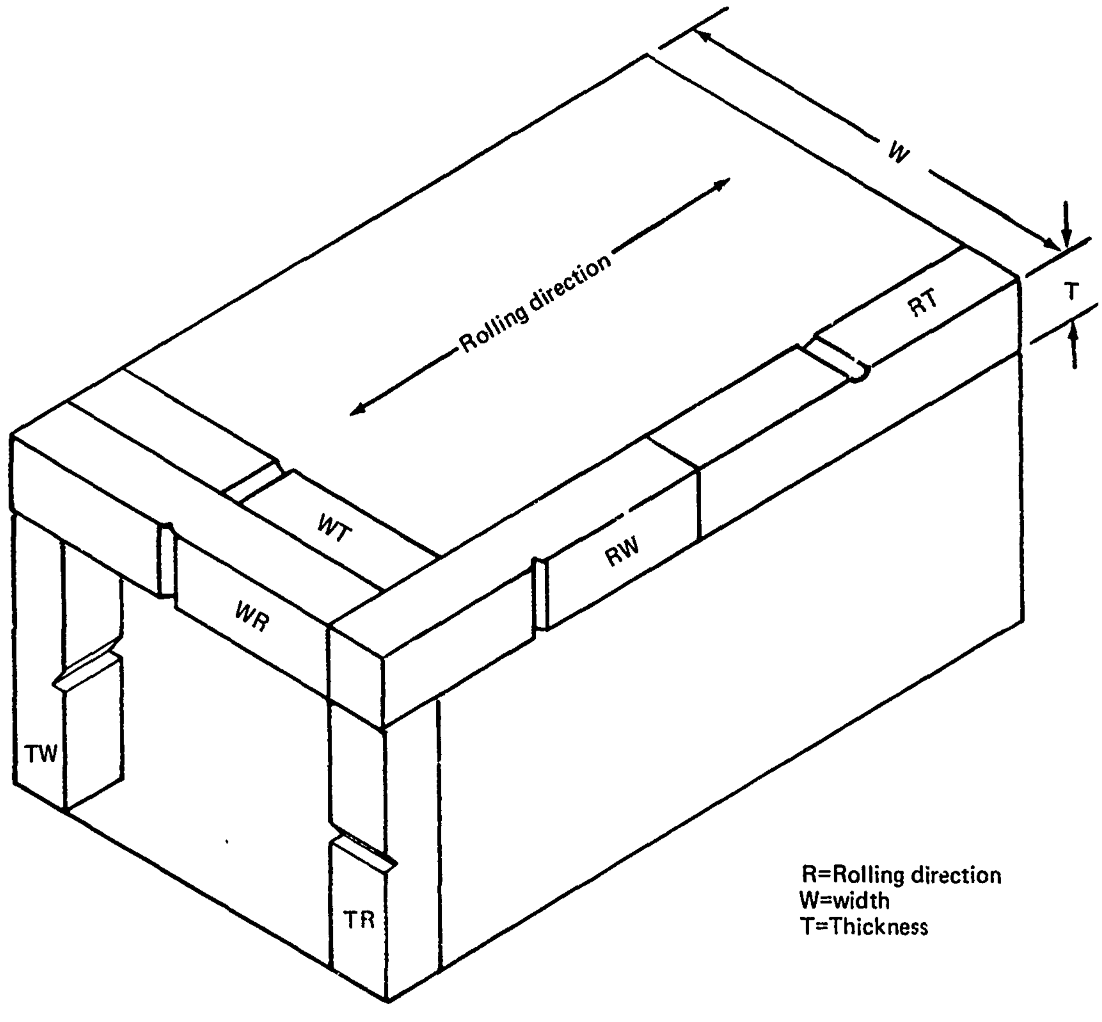


FIGURE A-5.—NOTCH ORIENTATION CODE FOR NOTCHED BEND SPECIMENS

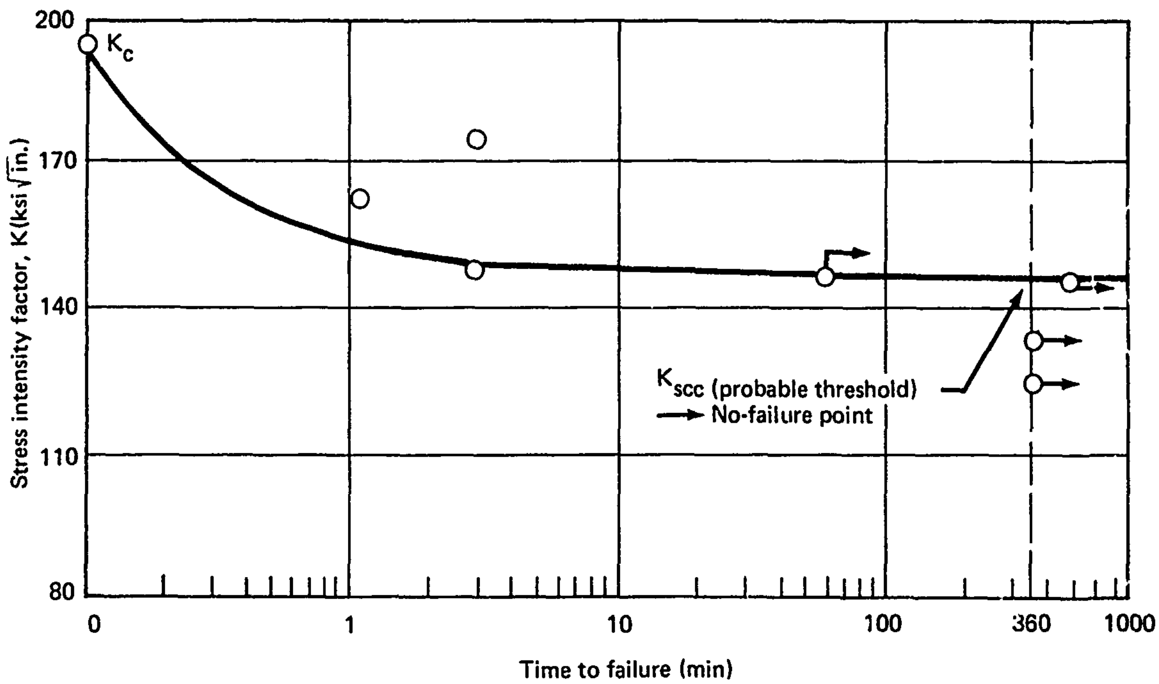


FIGURE A-6.—TYPICAL SUSTAINED-LOADING CHARACTERISTICS OF TITANIUM SHEET IN SALTWATER

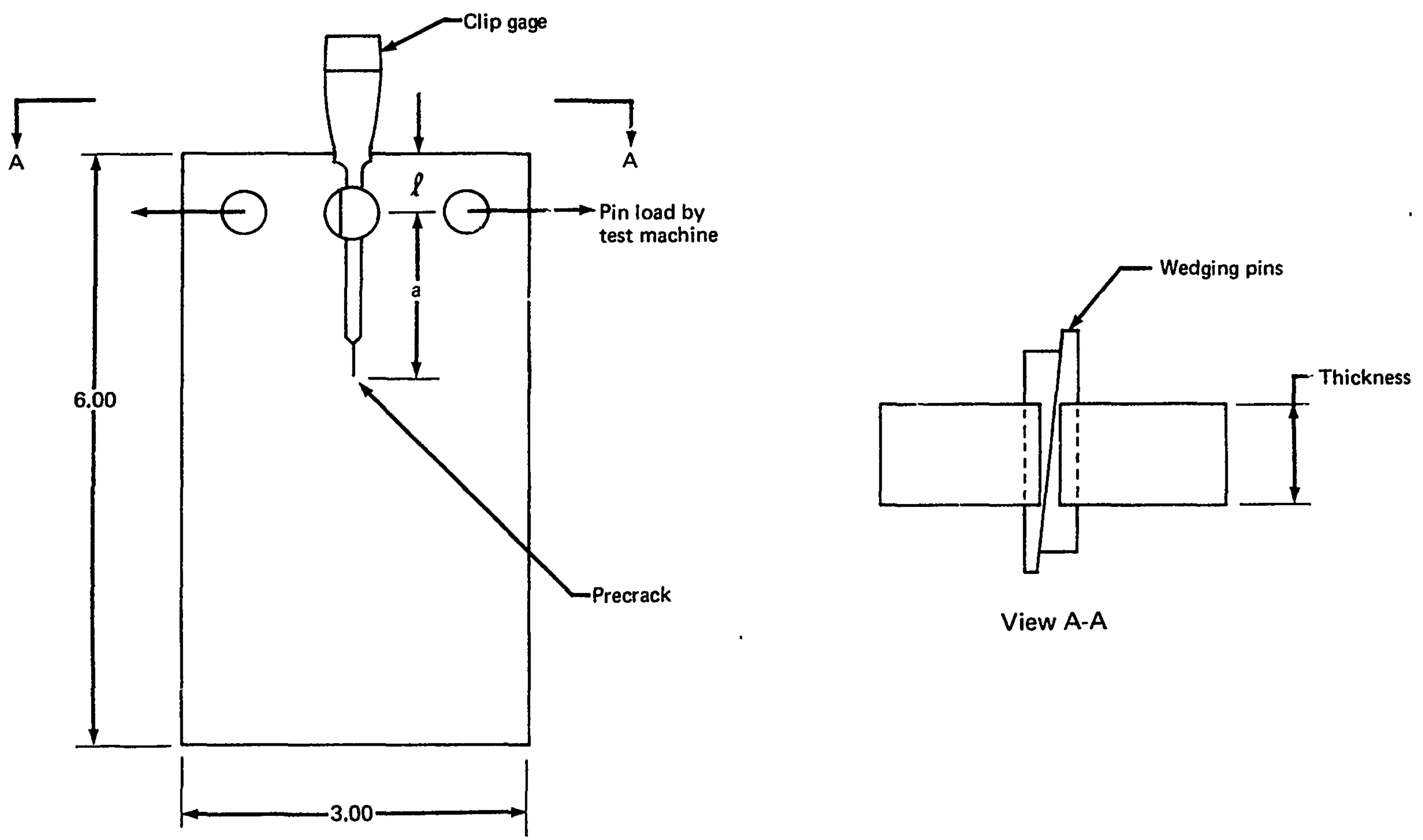


FIGURE A-7.—SCC TEST SPECIMEN AND LOADING METHOD FOR 6Al-4V TITANIUM ALLOY

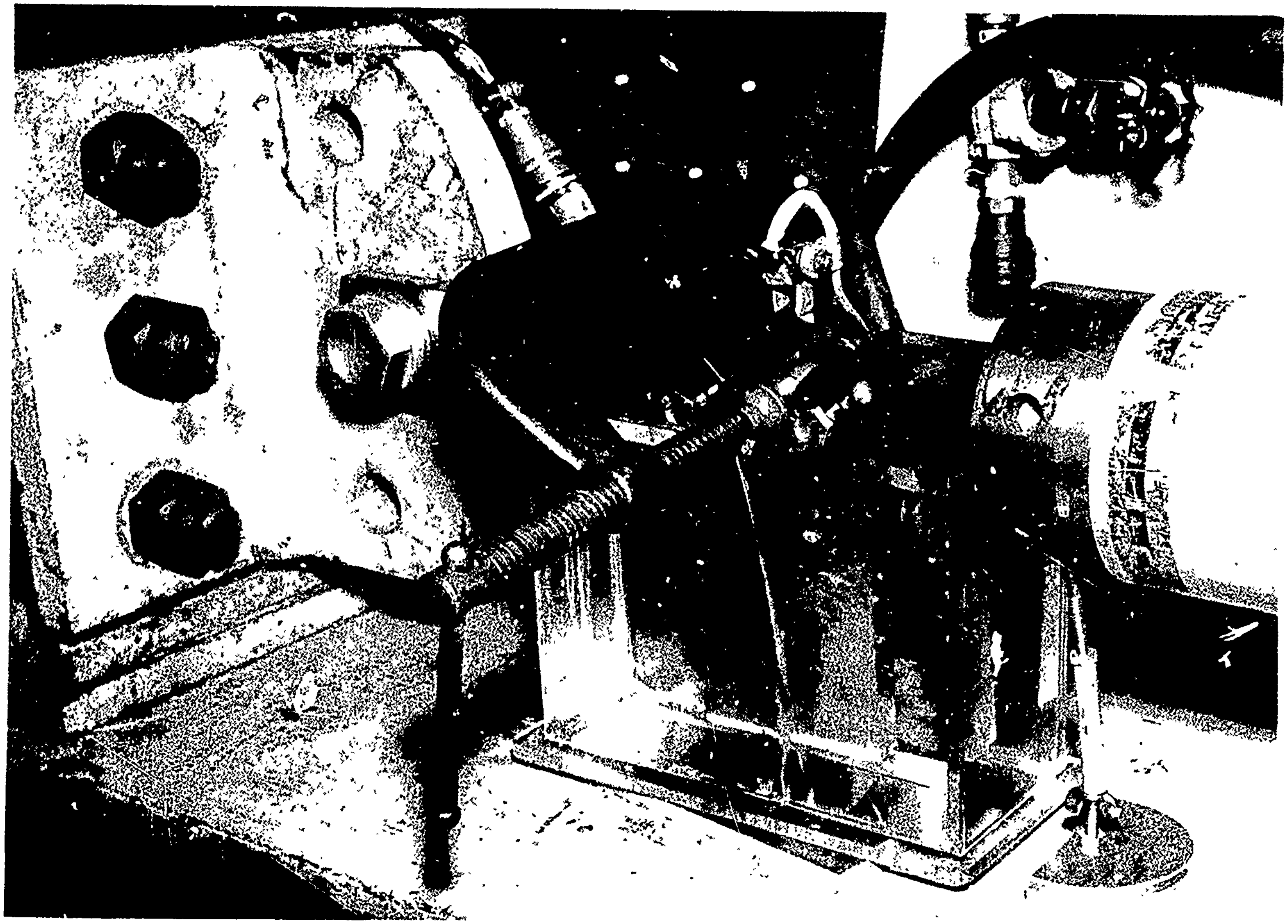


FIGURE A-8.—DCB TEST SETUP

specimen. For specimens loaded as shown in Figure A-7, deflections measured with the clip gage were multiplied by the ratio of a/(a + 1) to determine the displacement at the load line. Stress intensity factors were calculated by substituting measured displacements (Δ) into the equation.

$$K_I = \frac{\delta Eh[3h(a + 0.6h)^2 + h^3]^{1/2}}{\sqrt{1 - \mu^2}\; 4[(a + 0.6h)^3\, h^2 a]}$$

where:

h is one-half the specimen height

E is Young's modulus

a is crack length

μ is Poisson's ratio

Crack Growth Rates

Fatigue crack growth rates were determined from analysis of the growth of the fatigue crack for a measured number of cycles. Plexiglass buckling restraints were used during fatigue cracking to prevent the material in the region close to the center crack from cycling in and out of the plane of the panel. Since the maximum gross area stress is known the K level is calculated and the data replotted as ΔK level (K_{max}-K_{min}) during fatigue versus crack extension per cycle. This rate (d2a/dN) varies with the environment and the minimum/maximum stress ratio, R. The environments investigated were air (with the relative humidity noted), and 3.5% aqueous saltwater. The R ratio used was 0.05.

Metallurgical Analysis

Several analytical techniques were developed in support of the SST titanium programs with heavy emphasis on fundamental characterization of Ti-6Al-4V produced in various forms (sheet, plate, extrusions, bar, etc.) from various suppliers. Attempts were made to quantify the metallurgical variables based on relationships with actual mechanical property test data.

Chemical Composition

The bulk or average composition for each of the various Ti-6Al-4V mill products was determined using techniques per ASTM E-120. Aluminum contents were determined by atomic absorption. Vanadium and iron contents were determined by spectrographic analysis. Hot extraction technique was used to determine hydrogen contents. Oxygen was evaluated by neutron activation analysis. Carbon and nitrogen contents were analyzed using the Leco carbon analyzer and the Microkjedahl method respectively.

Optical Microscopy

Conventional light microscopy was used to assess basic metallurgical characteristics of the Ti-6Al-4V plate. Krolls 2% HF etch was used as the etchant. Photomicrographs were taken at 500X for detailed microstructure analysis and at much lower magnifications (5X-11X) to evaluate the size and shape of the prior beta grains. Optical photomicrographs were taken of the microstructure as viewed from the longitudinal, transverse, and short transverse directions. Percentage transformed beta structure was determined by lineal analysis.

Preferred Orientations

A quantitative computerized pole figure analysis for determining the preferred orientation in titanium alloys has been developed and modified over the past 4 years by Olsen (Ref. 7), and the following provides a brief description of the procedure. X-ray diffraction data are obtained using a modified Siemens texture goniometer that is precisely aligned. Approximately 700 data points are taken as shown in Figure A-9. A computer program analyzes the data, subtracting for background and correcting for defocusing, and then plots a pole figure, as shown in Figure A-10. This pole figure gives the iso-intensity lines of poles* for a given crystallographic plane in terms of "times random intensity." This random intensity can be likened to taking all the data from a preferred titanium sample and spreading the data evenly over the entire pole figure. This results in an average or a "random" intensity. The pole figure, then, is a contour map showing the alignment of given planes.

Texture Intensity Factors

In order to quantify by a number, a particular texture depicted in a pole figure such as in Figure A-10, X-ray diffraction intensities resulting from basal plane pole vector components were integrated to give the values i_T, i_L, and i_{ST} for the transverse, longitudinal, and short transverse directions, respectively. A total value, i_{total}, was then obtained, i.e., $i_{total} = i_T + i_L + i_{ST}$. The texture intensity percentage factors I_T, I_L, and I_{ST} were then calculated as follows:

$$I_T = \frac{i_T}{i_{total}} \times 100$$

$$I_L = \frac{i_L}{i_{total}} \times 100$$

$$I_{ST} = \frac{i_{ST}}{i_{total}} \times 100$$

*Poles are normal to the crystallographic plane.

In this manner the textures can be readily compared, e.g., an $I_T \geq 50\%$ shows a decided transverse texture, whereas $I_T \approx I_L \approx I_{ST} \approx 33\%$ would show a random orientation or isotropic texture.

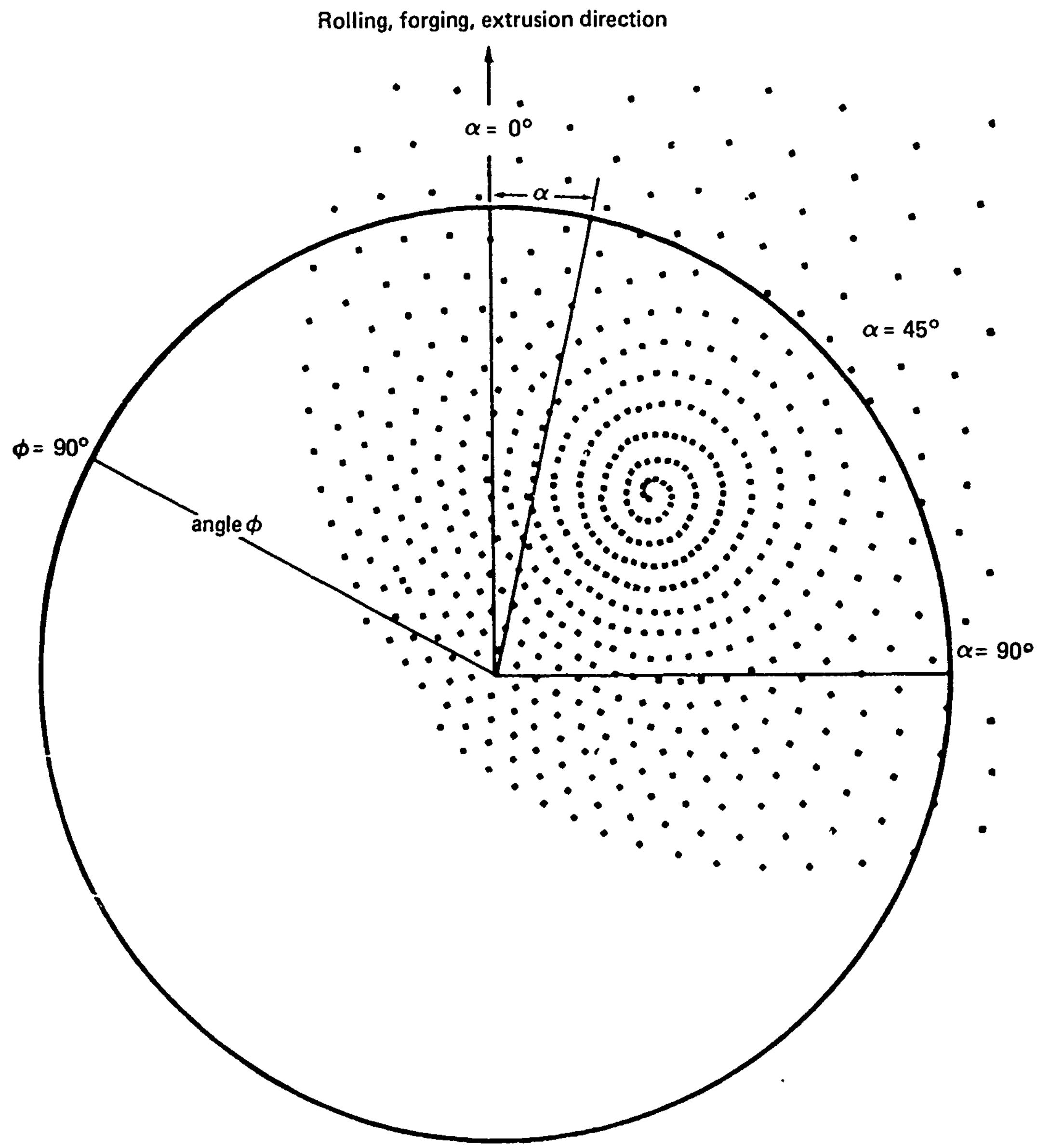
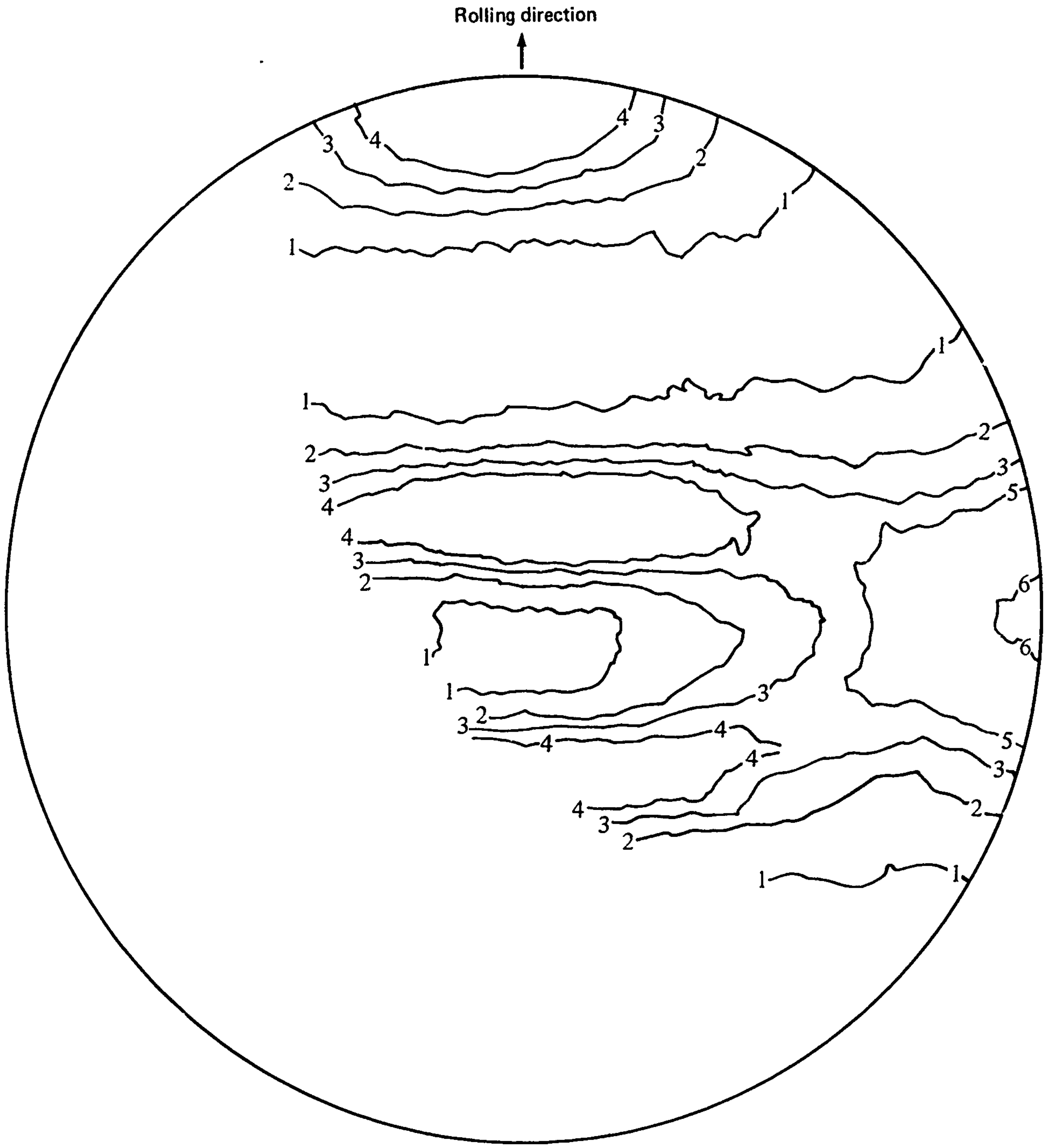


FIGURE A-9.—METHOD OF COLLECTING POLE FIGURE DATA



Contour lines	1	2	3	4	5	6
Times random intensity	0.5	1.0	1.5	2.0	4.0	8.0

FIGURE A-10.—POLE FIGURE SHOWING BASAL (0002)α PLANES AT TIMES RANDOM INTENSITY

APPENDIX B

PROPOSED ADVANCED SUPERSONIC TRANSPORT MATERIAL SPECIFICATION

(Prepared for the Federal Aviation Administration)

TITANIUM ALLOY 6Al-4V SHEET

1. SCOPE

1.1 Scope - This specification covers Ti-6Al-4V titanium alloy sheet for high toughness applications.

1.2 Classification

1.2.1 Conditions - Material shall be furnished in one of the following conditions, as specified on the purchase order:

Condition I - Duplex Annealed
Condition II - Solution Treated
Condition III - Solution Treated and Aged at 1000F

1.2.2 Types

Type AA - Extra close thickness tolerance
Type A - Close thickness tolerance
Type B - Nominal thickness tolerance

2. APPLICABLE DOCUMENTS

Except where a specific issue is indicated, the issue of the following documents in effect on the date of invitation for bid shall form a part of this specification, to the extent indicated herein.

a. AMS 2242 - Tolerances, Corrosion Resistant Steel Sheet, Plate, and Strip.

b. AMS 2249 - Chemical Check Analysis Limits, Titanium and Titanium Alloys.

c. ASTM E-146 - Hot Extraction of Hydrogen

d. Federal Test Method Standard No. 151 - Metals, Test Methods

e. Federal Standard No. 184 - Identification Markings for Aluminum, Titanium and Magnesium

f. MIL-H-81200 - Heat Treatment of Titanium and Titanium Alloys.

3. REQUIREMENTS

3.1 Material

3.1.1 Melting and Fabrication Practice - Material shall be produced by multiple melting under vacuum or inert gas with at least one of the melt stages under vacuum. Melting processes shall include either singly, or in combination, electroconsumable arc, electron beam or other vacuum processes suitable for melting to meet the requirements of this specification. The material shall be hot rolled in the alpha-beta field, annealed or heat treated, and finished by mechanical or chemical descaling and chemical milling or pickling.

3.1.2 Heat Treatment Conditions - Material shall be heat treated as specified in Table B-1

TABLE B-1- HEAT TREATMENT

Condition	Heat Treatment	Description (1), (2), (3), (5)
I (4)	Duplex Anneal	1675°F for nominally 10 minutes and air cool, hold at 1350°F and 4 hours, cooling rate optional.
II (6)	Solution Treated	1650°F to 1700°F for nominally 10 minutes and water quench
III	Solution Treatment and Age at 1000F	1650°F and 1700°F for nominally 10 minutes and water quench, age at 1000°F for 4 hours, cooling rate optional.

(1) Where nominal holding times are specified they are intended only as guides. Material in all cases shall be held for sufficient time to assure that complete solution has occurred.

(2) Maximum quench delay shall be 6 seconds. Quench delay shall not be cause for rejection if the tensile requirements are met.

(3) Quench delay time begins when the furnace door starts to open and ends when the material is completely immersed. In facilities in which it has been established that heat losses due to convection are slight while the furnace door is being opened and the actual material temperature is not lowered below the specified heat treat temperature range, the increment of time required for the furnace door to open need not be considered as a part of the maximum quench delay time.

(4) Condition I shall be capable of being heat treated per Table B-1 to Condition III tensile properties.

TABLE B-1(Continued)

(5) Furnace tolerances at the specified temperatures shall be ±25°F with temperature control and calibration per MIL-H-81200.

(6) Condition II material shall be proven capable of being aged per Table B-2 to Condition III. A tensile sample from each sheet shall be aged per Table B-1 and tested per Section 4.4.3.

3.1.3 Finish - Material shall have a surface appearance equivalent to a 2D finish for commercial corrosion resistant steel and shall have a 32 RHR or better surface roughness. All material shall have been sanded and subsequently pickled with a minimum of 0.0015 inch removed by pickling per surface.

3.2 Chemical Composition - The chemical composition shall comply with Table B-2 when sampled and analyzed as specified in Section 4.4.1.

TABLE B-2 - CHEMICAL COMPOSITION

Element	Composition (Weight Percent) (1)
Titanium (2)	Remainder
Aluminum	5.7 - 6.2
Vanadium	3.6 - 4.4
Iron	0.25 max.
Carbon	0.C5 max.
Hydrogen	0.0125 max.
Oxygen	0.080 - 0.110
Nitrogen	0.03 max.
Other Impurities (3)	0.40 max.

(1) Check analysis shall be per AMS 2249. Check analysis tolerances do not broaden the specified analysis requirements but cover variations between laboratories in the measurement of chemical content. The producer shall not ship material which is outside the weight percent limits specified in the above table. The purchaser shall not reject for chemical analysis, material within the check analysis tolerance.

(2) Need not be reported

(3) Need not be reported. Any individual element shall not exceed 0.10 percent.

3.3 Mechanical Properties

3.3.1 Minimum Tensile Properties - The tensile properties of the material shall conform to the requirements specified in Tables B-3, 4, and 5 when tested in accordance with Section 4.4.3. The average results of the tensile tests for each lot shall not exceed a maximum difference between the transverse and longitudinal directions of 7.0 for the ultimate strength and 9.0 for the yield strength.

TABLE B-3 - CONDITION I MINIMUM TENSILE PROPERTIES

Thickness (in)	Ultimate Strength (ksi)	Yield Strength (0.2% offset)ksi	Elong. % in 2 in Long. & Trans.
Under 0.017	125	115	6.0
0.017-0.032	125	115	8.0
0.033-0.187	125	115	10.0

TABLE B-4 - CONDITION II TENSILE PROPERTIES

Thickness (in)	Ultimate Strength (ksi)	Yield Strength (0.2% offset) ksi (Maximum)	Elong. % in 2 in.
Under 0.32	(1)	140	6.0
0.32-0.187	(1)	140	8.0

(1) Minimum of 15 ksi above yield strength

TABLE B-5 CONDITION III MINIMUM TENSILE PROPERTIES

Thickness (in)	Ultimate Strength (ksi)	Yield Strength (0.2% Offset) (ksi)	Elong. % in 2 in.
Under 0.032	150	135	4.0
0.032-0.049	150	135	5.0
0.050-0.187	150	135	6.0

3.3.2 Bend Properties - Condition I and II material shall meet the bend requirements in Table B-6 at room temperature without showing a separation of the outer fibers as observed at 20X magnification when tested in accordance with Section 4.4.4.

TABLE B-6 - BEND PROPERTIES

Nominal Thickness (in)	Ratio of Bend Radius to Thickness
Under 0.070	4.5
0.070-0.187	5.0

3.4 Dimensional Tolerances

3.4.1 Thickness Tolerances -

a. Type AA sheet shall not exceed the following thickness tolerances:

Thickness (in)	Tolerance (in)
0.060 - 0.089	$\pm$ 0.0015
0.090 - 0.124	$\pm$ 0.002
0.125 - 0.187	$\pm$ 0.003

b. Type A and B sheet shall not exceed the following tolerances:

Thickness (in)	Tolerance (% of nominal gage) Type A	Type B
Under 0.016	$\pm$ 10	$\pm$ 20
0.016-0.030	$\pm$ 7	$\pm$ 14
0.031-0.187	$\pm$ 5 (1)	$\pm$ 10 (2)

(1) Except $\pm$ 0.007 in. maximum

(2) Except $\pm$ 0.014 in. maximum

3.4.2 Length, Width, and Straightness Tolerances - Length, width, and straightness tolerances shall conform to AMS 2242. Length tolerance for sheet over 20 feet long shall be plus 3/4 inch minus 0.

3.4.3 Flatness Tolerances - All material shall be flat as specified in Table B-7 when measured as specified in Section 4.4.5.

TABLE B-7 - FLATNESS

Heat Treatment	Gage (in)	Width (in)	Flatness (%)
Cond. I, III	Under .025	36 & Under	3
Cond. I, III	Under .025	Over 36	5
Cond. I, III	.025 - .187	All	3
Cond. II	Under .070	All	5
	.070 - .187	All	4

3.5 Microstructure - Microstructure shall be determined per Section 4.4.6. The microstructure shall show no surface oxygen contamination as evidenced by a different microstructure morphology (stabilized alpha) at the surface.

The microstructure shall consist of equiaxed primary alpha grains and regions of transformed beta. The regions of transformed beta shall constitute a minimum of 10 percent and a maximum of 40 percent of the microstructure by area. Example of unacceptable microstructure are shown in Figure B-1(non-equiaxed primary alpha). Figure 2 shows an example of acceptable Condition I microstructure.

3.6 Saltwater Fracture Test - Material shall meet a K_{SL} of 85 ksi $\sqrt{in.}$ when tested per 4.4.7. One test shall be conducted in the longitudinal direction per lot. One test shall be conducted in the transverse direction per sheet until such time as a statistical test plan is agreed upon between purchaser and the supplier.

3.7 Identification of Product - Each sheet and strip shall be marked in accordance with FED-STD-184. In addition, each sheet and strip shall be marked with heat number, the number of this specification, type, composition, and heat treatment condition.

3.8 Workmanship - The material shall be uniform in microstructure, quality, strength, and condition. It shall be clean, sound, free from oil cans and ripples of depth in excess of the flatness tolerance, harmful alloy segregation, foreign materials, internal and external imperfections and characteristics detrimental to the fabrication and/or performance of parts. Evidence of contamination and surface imperfections such as folds, laminations, inclusions, scotchbrite finish, rolled-in scale, pits, cracks, cuts, seams, blisters, dents, and grind marks shall be cause for rejection. All material shall be free of interstitial surface contamination. The material shall be capable of showing no more than 0.22 weight percent oxygen in the outer 0.005 inches of surface when analyzed per Section 4.4.1.

4. QUALITY ASSURANCE PROVISIONS

4.1 Responsibility for Inspection - Unless otherwise specified in the contract or purchase order, the supplier is responsible for the performance of all inspection requirements as specified herein. Except as otherwise specified, the supplier may utilize his own facilities or any commercial laboratory acceptable to the procuring activity. The purchaser reserves the right to perform any of the inspections, set forth in the specification where such inspections are deemed necessary to insure supplies and services conform to prescribed requirements. The supplier shall furnish three copies of a report of the individual results on each test including photomicrographs for each lot shipped.

4.2 Lot - Unless otherwise specified in the contract or order (see 6.2), any sheet or group of sheets which were processed together through all rolling, thermal, and chemical processing operations.

4.3 Sampling - Except as otherwise specified sampling plans and procedures in the determination of the acceptability of products submitted by a supplier shall be in accordance with the provisions set forth in MIL-STD-105.

4.3.1 Examination of Product

4.3.1.1 Sheet and Strip - Samples for visual examination and dimensional tolerances shall be selected from each lot of sheet or strip of titanium and titanium alloy in accordance with the provisions of MIL-STD-105. Acceptance criteria shall be in accordance with MIL-STD-105, Inspection Level II, Acceptable Quality Level 1.5 percent.

4.3.1.2 Samples shall be visually examined for conformance with requirements for condition, identification, workmanship, and dimensions.

4.4 Quality Conformance Tests

4.4.1 Chemical Analysis

4.4.1.1 Sampling - After all processing has been completed, at least one sample from each lot shall be taken for oxygen and hydrogen analysis as described in Method 111 or Method 112 of Federal Test Method Standard No. 151.

4.4.1.2 Analysis - Chemical composition for all elements except hydrogen shall be determined using ASTM-E-120. Analysis for hydrogen shall be performed using the hot extraction method described in ASTM-E-146. Check analysis shall be according to AMS 2249. Any other analysis methods having equivalent or better accuracy and precision than the above methods, may be used provided they are approved by the purchaser. Analysis for oxygen content shall be performed by a technique having an accuracy standard deviation of 50 ppm.

4.4.1.3 The supplier shall furnish adjacent chemical analysis blanks (approximately two square inches) to the purchaser.

4.4.3 Mechanical Properties -

a. Tensile testing shall be done in accordance with Method 211 of Federal Test Method Standard No. 151. The strain rate shall be 0.003 - 0.007 inches per inch per minute through 0.2% offset plastic strain and then increased to 0.075 - 0.125 inches per inch per minute to failure. If a dispute occurs between the purchaser and supplier a referee test shall be performed on a machine having a strain rate pacer, using a rate of 0.005 inches per inch per minute through the yield strength.

b. One longitudinal and one transverse tensile test shall be conducted on specimens cut from each sheet until such time as a statistical sampling plan is approved by the purchaser.

c. The supplier shall furnish adjacent tensile blanks to the purchaser.

4.4.4 Bending Properties -

a. At least three transverse and three longitudinal specimens shall be tested from each sheet until such time as a statistical sampling plan is approved by the purchaser. Specimens shall be selected and bent so that test results are obtained for each side of the material when stressed in tension in the longitudinal and transverse directions. Specimens from material up to 0.075 inch thickness shall not be less than 0.750 inch wide. Specimens from material 0.075 inch thickness and over shall have width equal to at least ten times the thickness. Specimen length shall be at least 2 inches and shall be parallel to the grain direction. The specimens shall be bent to a final unrestrained included angle of 75 degrees maximum at room temperature using an open lower die. A V-block lower die is not acceptable. The nominal thickness of the sheet shall be used for calculation of R/t and tool clearance values. The radius of the punch shall be used for calculation of R/t and tool clearance values. The radius of the punch shall be equal to the bend radius.

b. The supplier shall furnish an adjacent bend specimen blank (approximately nine inches x width per 4.4.4) to the purchaser.

4.4.5 Determination of Flatness Variation - Flatness shall be measured as the percentage of the distance between contact points of a straight edge laid in any direction upon the material. The amount of variation from flat shall be determined by measuring the distance from the straight edge to the material at the point of greatest deviation. Both sides of each sheet shall be inspected for flatness.

4.4.6 Determination of Microstructure - One microstructural determination shall be made from each lot. The specimen shall be taken with the specimen surface parallel to the rolling direction and perpendicular to the surface (transverse view). Examination shall be made by traversing the whole thickness at a magnification of 500X. Etching shall be accomplished by immersion in Kroll's etch (2% HF, 10% HNO_3, 88% H_2O) for approximately 15 seconds with a water rinse followed by immersion in 0.5% HF solution for 5-10 seconds. A photograph of the typical microstructure at the center and edge of the sheet shall be taken at 500 magnification.

4.4.7 Test for Environmental Fracture Toughness (K_{SALT}) - This testing procedure covers the determination of fracture toughness for Ti-6Al-4V sheet in a salt water environment.

4.4.7.1 List of Terms -

K_{SALT}	A measure of fracture toughness in an environment of salt water
K	A stress intensity factor derived from fracture mechanics
K_{SL}	A stress intensity factor sustained at a specified level for 20 minutes in aqueous 3-1/2% NaCl
B	Specimen thickness
W	Specimen width
a	Total crack length (sum of notch and fatigue crack length)

4.4.7.2 Apparatus - The K_{SALT} A test shall be conducted on any tensile machine capable of developing 30,000 pounds load, and conforming in other respects to ASTM E4, Verification of Testing Machines. The machine shall also be capable of sustaining load at a specified level within ± 2 percent for a period of twenty minutes. Test fixtures shall be capable of maintaining alignment in the transfer of load from the machine to the specimen. It is required that the precracked area of the specimen be completely immersed throughout the test in aqueous 3.5% sodium chloride solution.

4.4.7.3 Test Specimen - Single-edge-crack tension specimens (3-inches wide) shall be prepared per Figure B-3 . The specimen thickness shall be that of the product.

The notch may be prepared by mill cutting. It is mandatory that the root radius be no larger than 0.015 inches or fatigue precracking is extremely difficult to control. Any procedures which reduce the size of the root radius are permissible.

The specimens shall be precracked by fatigue loading until the crack extends a minimum of .050" and a maximum of .200" on each side of the specimen. The crack may be started at higher K values, but during the final 0.050 inches of extension, the maximum K should not exceed 2/3 of K_{SL}.

4.4.7.4 Test Procedure -

a. Measure the specimen's thickness at two points, one on each side of the notch. Average the measurements.

b. Measure the specimen's width from edge to edge on each side surface along the crack plane. Average the measurements.

c. Measure the crack length from the edge to the crack tip on each surface of the specimen. Average the measurements.

d. Calculate the load required to develop K_{SL} using the equation of step h.

e. Assemble a saltwater reservoir enclosing the precracked area.

f. Fill the reservoir with saltwater making sure that the crack tip is completely immersed.

g. Load the specimen to K_{SL} = 85 ksi $\sqrt{in.}$ at a crosshead separation rate of approximately .05 inches per minute. Hold the load at K_{SL} for 20 minutes. If the specimen has not failed after 20 minutes at K_{SL}, raise the load so that K increases 15 ksi $\sqrt{in.}$ and hold at this new level for 7 minutes. If the specimen does not fail at this level (K_{SL} + 15). Continue this procedure with increases of 15 ksi $\sqrt{in.}$ for 7 minute periods until failure.

h. Calculate K_{SL} and all other K-values using the following:

$$K_{SL} \text{ or } K = \frac{P\sqrt{a}}{BW}\left[1.99 - 0.41\,(a/W) + 18.70(a/w)^2 - 38.48(a/w)^3 + 53.85\,(a/w)^4\right]$$

where - P is the load required to develop a desired K-level
a is the crack length
B is specimen thickness
W is specimen width

i. Record the following results:

(1) If the specimen passes K_{SL} but fails the next 7 minute K level, report the value of K_{SL}.

(2) If the specimen passes K_{SL} and subsequent 7 minute K levels, report the highest 7 minute level passed.

(3) The test values obtained shall be reported on the material certification as K_{SALT} values in ksi $\sqrt{in.}$

5. PREPARATION FOR DELIVERY

5.1 Identification - Each sheet shall be marked in accordance with Federal Standard No. 184. In addition, each sheet shall be marked with heat number, lot, condition, type and the number of this specification, including the applicable revision letter.

5.2 Packaging and Marking -

a. Packaging shall be such as to assure safe delivery.

b. Each container shall be durably and legibly marked with the following information:

Material specification number including the applicable revision letter, the appropriate condition and type, the supplier's name, product designation, lot number, purchase order number and quantity.

6. NOTES

6.1 Intended Use - The materials procurable under this specification are intended for structural applications in airborne vehicles and equipment where high fracture toughness is required. The materials are weldable by electron beam, plasma arc, friction, and diffusion welding processes.

6.2 Ordering Data - Procurement document should state the following:

a. Title, number, and date of this specification.

b. Composition or commercial alloy designation.

c. Heat treatment condition (see 3.1.2).

d. Finish (see 3.1.3).

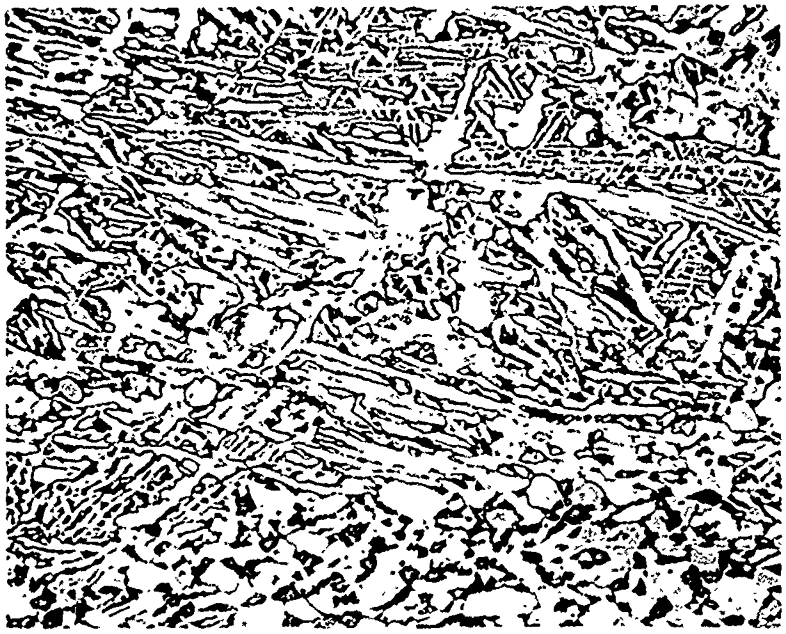
e. Size and thickness.

f. Marking requirements (see 3.6).

6.3 Definitions -

6.3.1 Sheet - A flat rolled product up to and including 0.1875 inch in thickness and 24 inches and over in width.

6.3.2 Strip - A flat product up to and including 0.1875 inch in thickness and generally furnished with slit, sheared, or slit and edge rolled in widths up to 24 inches inclusive; or with finished drawn or rolled edges in widths over 1¼ inches to 12 inches inclusive.



Nonequiaxed primary alpha

FIGURE B-1.—UNACCEPTABLE MICROSTRUCTURE (COND I)

X500

Equiaxed primary alpha

Greater than 40% transformed beta

FIGURE B-2.—ACCEPTABLE MICROSTRUCTURE (COND I)

X500

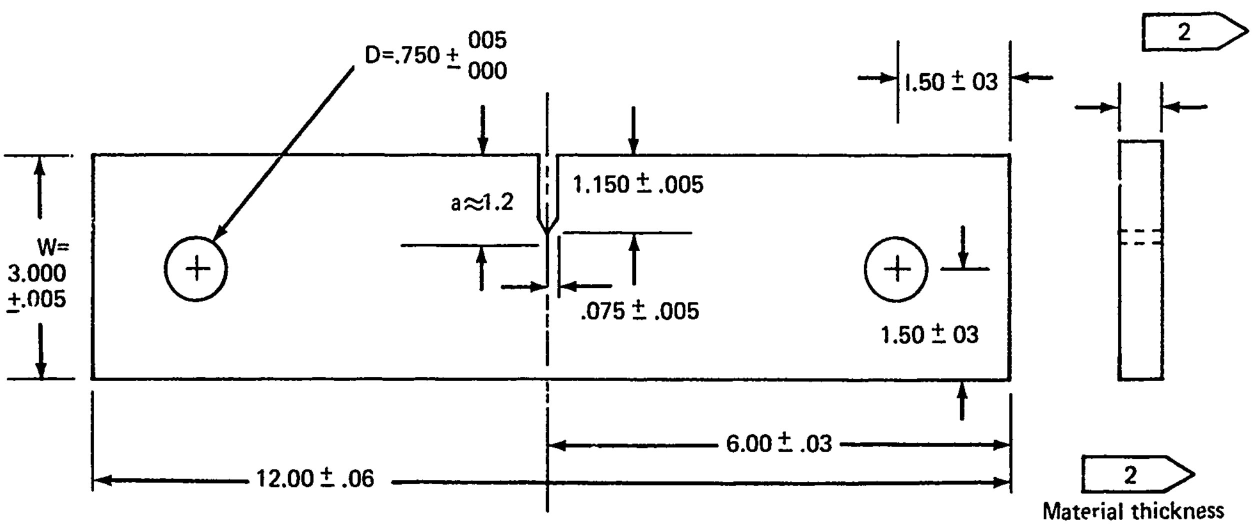


FIGURE B-3.—K_{SALT} TEST SPECIMEN

APPENDIX C

PROPOSED
ADVANCED SUPERSONIC TRANSPORT
MATERIAL SPECIFICATION

(Prepared for the Federal Aviation Administration)

TITANIUM ALLOY 6Al-4V BETA PROCESSED PLATE

1.0 SCOPE

1.1 Scope - This specification covers Ti-6Al-4V titanium alloy plate for high toughness applications.

1.2 Classification

1.2.1 Conditions - Material shall be furnished in one of the following conditions, as specified on the purchase order.

Condition I - Annealed

Condition II - Solution Treated

Condition III - Solution Treated and Aged at 1000F.

1.2.2 Types

Type A - Nominal flatness, grit blasted and pickled surface.

Type B - Premium flatness, grit blasted and pickled surface.

2.0 APPLICABLE DOCUMENTS

Except where a specific issue is indicated, the issue of the following documents in effect on the date of invitation for bid shall form a part of this specification, to the extent indicated herein.

a. AMS 2242 - Tolerance, Corrosion Resistant Steel Sheet, Plate, and Strip.

b. AMS 2249 - Chemical Check Analysis Limits, Titanium, and Titanium Alloys

c. ASTM E-120 - Methods of Chemical Analysis for Titanium and Titanium Alloys

d. ASTM E-146 - Hot Extraction of Hydrogen

e. MIL-I-8950 - Inspection, Ultrasonic, Wrought Metals, Process

f. Federal Standard No. 48 - Tolerances for Steel and Iron Wrought Products

g. Federal Test Method Standard No. 151 - Metals, Test Methods

h. Federal Standard No. 184 - Identification Markings for Aluminum, Titanium and Magnesium

i. MIL-H-81200 - Heat Treatment of Titanium and Titanium Alloys

3. REQUIREMENTS

3.1 Material

3.1.1 Melting and Fabrication Practice - The material shall be produced by multiple melting under vacuum or inert gas atmosphere. Melting processes shall include either singly or in combination, electro-consumable arc, electron beam, or other vacuum melting processes suitable for the production of materials meeting the requirements of this specification.

The material shall be hot rolled at least 50 percent below the beta transus prior to beta processing. Plate must be beta processed by heating the plate above the beta transus (beta annealing) after finish rolling. Beta annealing shall be conducted above the beta transus at 1850°-1900°F for nominally 5 minutes with a minimum cooling rate of 50°F per minute to a maximum temperature of 1100°F.

3.1.2 Heat Treatment Conditions - Material shall be heat treated as specified in Table I.

Table C-1 - Heat Treatment

Condition	Heat Treatment	Description (1), (2), (3), (5)
I (4)	Anneal	1350F for 4 hours, cooling rate optional
II (6)	Solution Treatment	1675°F for nominally 10 minutes and water quench
III	Solution Treatment and Age at 1000F	1675°F for nominally 10 minutes and water quench, age at 1000F for 4 hours, cooling rate optional.

(1) Where nominal holding times are specified they are intended only as guides. Material in all cases shall be held for sufficient time to assure that complete solution has occurred.

(2) Maximum quench delay for material that has a thickness of 0.250 inch or less shall be 6 seconds. For material thicker than 0.250 inch, maximum quench delay shall be 8 seconds. Quench delay shall not be cause for rejection if the tensile requirements are met.

(3) Quench delay time begins when the furnace door starts to open and ends when the material is completely immersed. In facilities in which it has been established that heat losses due to convection are slight while the furnace door is being opened and the actual material temperature is not lowered below the specified heat treat temperature range, the increment of time required for the furnace door to open need not be considered as a part of the maximum quench delay time.

(4) Condition I sheet shall be capable of being heat treated per Table C-1 to Condition III tensile properties.

(5) Furnace tolerances at the specified temperatures shall be $\pm$ 25F, with temperature control and calibration per MIL-H-81200.

(6) Condition II material shall be proven capable of being aged per Table C-1 to Condition III. A tensile sample from each plate shall be aged per Table C-1 and tested per 4.4.2.

3.1.3 Finish - Types A and B plate shall be grit blasted and pickled.

3.2 Chemical Composition - The chemical composition shall comply with Table C-2 when sampled and analyzed as specified in Section 4.4.1.

Table C-2- Chemical Composition

Element	Composition (Weight Percent) (1)
Titanium (2)	Remainder
Aluminum	5.7 - 6.2
Vanadium	3.6 - 4.4
Iron	0.25 max.
Carbon	0.05 max.
Hydrogen	0.0125 max.
Oxygen	0.080 - 0.110
Nitrogen	0.03 max.
Other Impurities (3)	0.40 max.

(1) Check analysis shall be per AMS 2249. Check analysis tolerances do not broaden the specified analysis requirements but cover variations between laboratories in the measurement of chemical content. The producer shall not ship material which is outside the weight percent limits specified in the above table. The purchaser shall not reject for chemical analysis, material within the check analysis tolerance.

(2) Need not be reported.

(3) Need not be reported. Any individual element shall not exceed 0.10 percent.

3.3 Mechanical Properties

3.3.1 Minimum Tensile Properties - The tensile properties of the material shall conform to the requirements specified in Tables C-3, 4, and 5, when tested in accordance with 4.4.2. The average results of the tensile tests for each lot shall show a maximum difference between the transverse and longitudinal directions of 5.0 for the ultimate strength and 7.0 for the yield strength.

Table C-3 - Condition I Minimum Tensile Properties

Thickness (in.)	Ultimate Strength (ksi)	Yield Strength (0.2% Offset) (ksi)	Elong. % in 2 in. or 4D Long. & Trans.
0.188 - 0.500	125	112	10.0
0.501 - 2.000	122	110	10.0
2.001 - 4.000	120	108	8.0

Table C-4- Condition II Tensile Properties

Thickness (in.)	Ultimate Strength (ksi)	Yield Strength (0.2% Offset)ksi	Elong. % in 2 in. Long. & Trans.
0.188 - 4.00	(1)	140 max.	8.0

(1) Minimum of 15,000 psi above yield strength

Table C-5- Condition III Minimum Tensile Properties

Thickness (in.)	Ultimate Strength (ksi)	Yield Strength (0.2% Offset) (ksi)	Elong. % in 2 in.
0.188 - 0.500	150	135	6.0
0.501 - 0.750	145	130	6.0
0.751 - 1.000	140	125	6.0
1.001 - 1.500	135	120	6.0
1.501 - 2.000	130	115	6.0
2.001 - 2.500	125	110	6.0

3.4 Dimensional Tolerances

3.4.1 Thickness Tolerances - Plate shall have the following thickness tolerances.

Thickness (in.)	Tolerances (in.) Plus	Minus
0.188 to 0.374	0.046	0.010
0.375 to 0.749	0.054	0.010
0.750 to 0.999	0.060	0.010
1.000 to 2.000	0.070	0.010
2.001 and over	0.080	0.010

3.4.2 Length, Width and Straightness Tolerances - Length, width, and straightness tolerances shall conform to AMS 2242. Width tolerance for plate 260 inches and longer shall be plus 3/4 inch minus 1/4 inch. Length tolerance for plate over 360 inches long and 1 inch and over in thickness shall be plus 1-1/2 inch minus 1/4 inch.

3.4.3 Flatness Tolerances - Type A plate shall be flat as specified in Table C-6 when measured as specified in seciton 4.4.4. Type B plate shall have a maximum deviation of 0.060 when measured as specified in section 4.4.4. Cold flattening of Condition I material may be performed if the material is subsequently stress relieved by holding for 30 minutes at 1250 ± 25F. Condition II material may be cold straightened but shall not be stress relieved.

TABLE C-6 - FLATNESS

Cond. II, III	All	Fed. Std. 48 Table 4D5
Cond. I,	All	1/2 flatness tolerance of Fed. Std. 48, Table 4D5

3.5 Ultrasonic Inspection - Plate 3/8-4 inches in thickness shall be completely scanned ultrasonically in conformance with MIL-I-8950 and Secion 4.4.6. The minimum quality level shall conform to Table VII.

TABLE C-7 - ULTRASONIC QUALITY LEVELS

Thickness (Inch)	Ultrasonic Classification (1)
3/8 to 1.0 incl.	AA
Over 1.0 to 4.0	A

(1) Exception: Discontinuity indications equal to or exceeding 50 percent of the response from 3/64 flat bottomed hole for class AA and 5/65 flat bottomed hole for Class A shall not be located closer than one inch between centers or have lengths greater than 1/8 inch.

3.6 Microstructure - Microstructure shall be determined per Section 4.3.6. The microstructure shall show no surface oxygen contamination as evidenced by a different microstructure morphology (stabilized alpha phase) at the surface.

Plate microstructure shall be determined per Section 4.4.6. The microstructure shall consist of basketweave or Widmanstatten morphology (Figure C-1) and shall not contain primary or equiaxed alpha phase. The microstructure shall be uniform and shall be fine grain. Prior beta grains exceeding .050" in width or .100" in length shall constitute no more than 10% of the microstructure when examined at 10-50 magnification. A prior beta grain is a region of basketweave morphology which has transformed from a single beta grain.

3.7 Saltwater Fracture Test - Material annealed to condition I shall meet a K_{SL} of 55 ksi $\sqrt{in}$. when tested per 4.4.4. One test shall be conducted in the transverse direction per lot until such time as a statistical test plan is agreed upon between purchaser and the supplier.

3.8 Identification of Product - Each plate shall be marked in accordance with FED-STD-184. In addition each plate shall be marked with the heat number, the number of this specification, type, composition and heat treatment condition.

3.9 Workmanship - The material shall be uniform in microstructure, quality, strength, and condition. It shall be clean, sound, free from oil cans and ripples of depth in excess of the flatness tolerance, harmful alloy segregation, foreign materials, internal and external imperfections and characteristics detrimental to the fabrication and/or performance of parts. Evidence of contamination and surface imperfections such as folds, laminations, inclusions, scotchbrite finish, rolled-in scale, pits, cracks, cuts, seams, blisters, dents, and grind marks shall be cause for rejection except that local grind out marks are acceptable provided that the minimum measured material thickness minus the sum of the deepest single grindout from each side of the material is equal to or greater than the nominal thickness minus 0.010 inch. All material shall be free of interstitial surface contamination. The material shall be capable of showing no more than 0.22 weight percent oxygen in the outer 0.005 inches of surface when analyzed per Section 4.4.1.2.

4. QUALITY ASSURANCE PROVISIONS

4.1 Responsibility for Inspection - Unless otherwise specified in the contract or purchase order, the supplier is responsible for the performance of all inspection requirements as specified herein. Except as otherwise specified, the supplier may utilize his own facilities or any commercial laboratory acceptable to the procuring activity. The purchaser reserves the right to perform any of the inspections, set forth in the specification where such inspections are deemed necessary to insure material conforms to prescribed requirements. The supplier shall furnish three copies of a report of the individual test results including photomicrographs for each lot shipped.

4.2 Lot - Any plate, or group of plates which were processed together through all rolling, thermal, and chemical processing operations. Only plates which are eigher cut from a large plate after the final rolling operation or are folled as a stack are considered rolled together.

4.3 Sampling - Except as otherwise specified sampling plans and procedures in the determination of the acceptability of products submitted by a supplier shall be in accordance with the provisions set forth in MIL-STD-105.

4.3.1 Examination of Product - Plates shall be individually inspected. Acceptance criteria shall be in accordance with MIL-STD-105, Inspection Level II, Acceptable Quality Level 1.5 percent.

4.3.1.2 Samples shall be visually examined for conformance with requirements for condition, identification, workmanship, and dimensions.

4.4 Quality Conformance Tests

4.4.1 Chemical Analysis

4.4.1.1 Sampling - After all processing has been completed at least one sample from each lot shall be taken for oxygen and hydrogen analysis as described in Method 111 or Method 112 of Federal Test Method Standard No. 151.

4.4.1.2 Analysis - Chemical composition for all elements except hydrogen shall be determined using ASTM-E-120. Analysis for hydrogen shall be performed using the hot extration method described in ASTM-E-146. Check analysis shall be be according to AMS 2249. Any other analysis methods having equivalent or better accuracy and precision than the above methods, may be used provided they are approved by the purchaser. Analysis for oxygen content shall be performed by a technique having an accuracy standard deviation of 50 ppm.

4.4.1.3 The supplier shall furnish adjacent chemical analysis blanks (approximately two square inches) to the purchaser.

4.4.2 Mechanical Properties

a. Tensile testing shall be done in accordance with Method 211 of Federal Test Method Standard No. 151. The strain rate shall be 0.003 - 0.007 inches per inch per minute through 0.2% offset plastic strain and then increased to 0.075 - 0.125 inches per inch per minute to failure. If a dispute occurs between the purchaser and supplier a referee test shall be performed on a machine having a strain rate pacer, using a rate of 0.005 inches per inch per minute through the yield strength.

b. One longitudinal, one transverse, and for plate over 2.500 inches, one short transverse tensile test shall be conducted on specimens cut from each plate until such time as a statistical sampling plan is approved by the purchaser.

c. The supplier shall furnish adjacent tensile blanks to the purchaser.

4.4.3 Test for Environmental Fracture Toughness (K_{SALT}) - This testing procedure covers the determination of fracture toughness for Ti-6Al-4V beta processed plate in environment of salt water.

4.4.3.1 List of Terms

K_{SALT}	A measure of fracture toughness in an environment of salt water.
K	A stress intensity factor derived from fracture mechanics
K_{SL}	A stress intensity factor sustained at a specified level for 20 minutes in aqueous 3-1/2% NaCl
t	Specimen thickness
W	Specimen width
a	Total crack length (sum of notch and fatigue crack length)

4.4.3.2 Apparatus - The K_{SALT} test shall be conducted on any tensile machine capable of developing 30,000 pounds load, and conforming in other respects to ASTM E4, Verification of Testing Machines. The machine shall also be capable of sustaining load at a specified level within ± 2 percent for a period of twenty minutes.

Test fixtures shall be capable of maintaining alignment in the transfer of load from the machine to the specimen. Apply load at points indicated in Figure C-2 for Notched Bend test specimens. For Short Notched Bend specimens using specimen grips apply load per Figure C-3 and C-4.

It is required that the precracked area of the specimen be completely immersed throughout the test in aqueous 3.5% sodium chloride.

4.4.3.3 Test Specimen - Notch Bend specimens shall be prepared per Figure C-5 or C-6. The thickness of the specimen shall be that of the product for thicknesses to 1/2 inch. Specimens 1/2 inch thick shall be prepared from products whose thickness exceeds 1/2 inch.

The notch may be prepared by mill cutting. It is mandatory that the root radius be no larger than 0.015 inches or fatigue precracking is extremely difficult to control. Any procedures which reduce the size of the root radius are permissible.

The specimens shall be precracked by fatigue loading until the crack extends a minimum of .050" and a maximum of .200" on each side of the specimen. The crack may be started at higher K values, but during the final 0.050 inches of extension, the maximum K should not exceed 2/3 of K_{SL}.

4.4.3.4 Test Procedures

a. Measure the specimen's thickness at two points, one on each side of the notch. Average the measurements.

b. Measure the specimen's width from edge to edge on each side surface along the crack plane. Average the measurements.

c. Measure the crack length from the edge to the crack tip on each surface of the specimen. Average the measurements.

d. Calculate the load required to develop K_{SL} using the equation of step h.

e. Assemble a saltwater rerervoir enclosing the pre-cracked area.

f. Fill the reservoir with saltwater making sure that the crack tip is completely immersed.

g. Load the specimen to $K_{SL} = 55$ ksi $\sqrt{in}$ at a crosshead separation rate of approximately .05 inches per minute. Hold the load at K_{SL} for 20 minutes. If the specimen has not failed after 20 minutes at K_{SL}, raise the load so that K increases 15 ksi $\sqrt{in}$. and hold at this new level for 7 minutes. If the specimen does not fail at this level (K_{SL} + 15) continue this procedure with increases of 15 ksi $\sqrt{in}$ for 7 minute periods until failure.

h. Calculate K_{SL} and all other K-values using the following:

$$K_{SL} \text{ or } K = \frac{1.5P(S-s)\ a}{BW^2}\left[1.99-2.47\ (a/w) + 12.97\ (a/w)^2 - 23.17\ (a/w)^3 + 24.8\ (a/w)^4\right]$$

where

P is the load required to develop a desired K-level

S is the distance between the upper load points

s is the distance between the lower load points

a is the crack length

w is the specimen width

i. Record the following results:

(1) If the specimen passes K_{SL} but fails the next 7 minute K level, report the value of K_{SL}.

(2) If the specimen passes K_{SL} and subsequent 7 minute K levels, report the highest 7 minute level passed.

(3) The test values obtained shall be reported on the material certification as K_{SALT} values in ksi $\sqrt{in.}$

4.4.4 Determination of Flatness Variation - The amount of variation from flat shall be determined by measuring the distance from a straight edge laid in any direction upon the material, to the material surface at the point of greatest deviation. Both sides of each sheet, strip, and plate shall be inspected for flatness.

4.4.5 Determination of Microstructure - One microstructural determination shall be made for each lot. The specimen shall be taken with the specimen surface parallel to the rolling direction and perpendicular to the plate surface (Transverse view). Examination shall be made by traversing the whole thickness of the plate at a magnification of 500X. Etching shall be accomplished by immersion in Kroll's etch (2% HF, 10% HNO_3, 38% H_2O) for approximately 15 seconds with a water rinse followed by immersion in 0.5% HF solution for 5-10 seconds. A photograph of the typical microstructure at the center and both edges of the plate shall be taken at 500 magnification and one photograph at 10-50 magnification showing representative microstructure.

4.4.6 Ultrasonic Test - Ultrasonic inspection shall be performed in accordance with MIL-I-8950. Surface roughness shall not exceed 125 roughness height rating (RHR) at 5 megahertzen. The surface roughness of the reference standards shall not vary more than ± 25 RHR from the surface roughness of the material being tested. Instruments shall be adjusted to produce a difference in the height of indications from 2/64 and 3/64 inch diameter holes in reference standards. Hash or sonic noise indications shall not exceed 40 percent of the response height from a 3/64 flat-bottomed hole at the estimated depth of discontinuity.

5.0 PREPARATION FOR DELIVERY

5.1 Identification - Each plate shall be marked in accordance with Federal Standard No. 184. In addition, each sheet shall be marked with heat number, lot, condition, type and the number of this specification, including the applicable revision letter.

5.2 Packaging and Marking

a. Packaging shall be such as to assure safe delivery.

b. Each container shall be durably and legibly marked with the following information:

Material specification number including the applicable revision letter, the appropriate condition and type, the supplier's name, product designation, lot number, purchase order number and quantity.

6. NOTES

6.1 Intended Use - The materials procurable under this specification are intended for structural applications in airborne vehicles and equipment where high fracture toughness is required. Thematerials are weldable by electron beam, plasma arc, friction, and diffusion welding processes.

6.2 Ordering Data - Procurement document should state the following:

a. Title, number, and date of this specification.

b. Composition or commercial alloy designation.

c. Heat treatment condition (see 3.1.2).

d. Finish (see 3.1.3).

e. Size and thickness

f. Marking requirements (see 3.6).

6.3 Definitions -

Plate - A flat rolled product of 3/16 (0.1875) inch and over in thickness and over 12 inches in width with the width at least 10 times the thickness.

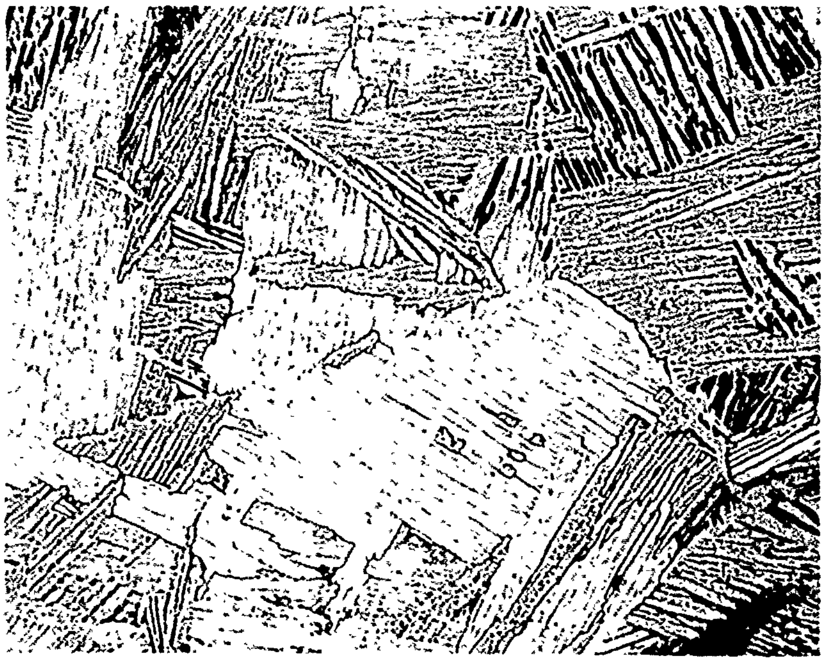


FIGURE C-1.–ACCEPTABLE TI-6A1-4V MICROSTRUCTURE WITH BASKETWEAVE MORPHOLOGY

(MAG. 500X)

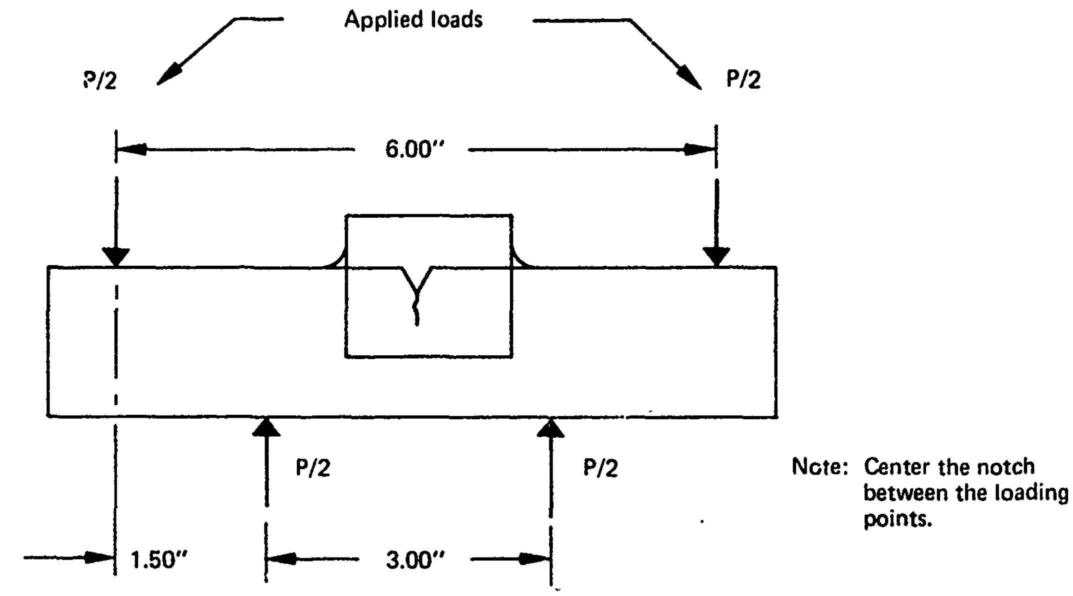


FIGURE C-2.—LOAD APPLICATION TO NOTCH BEND SPECIMEN

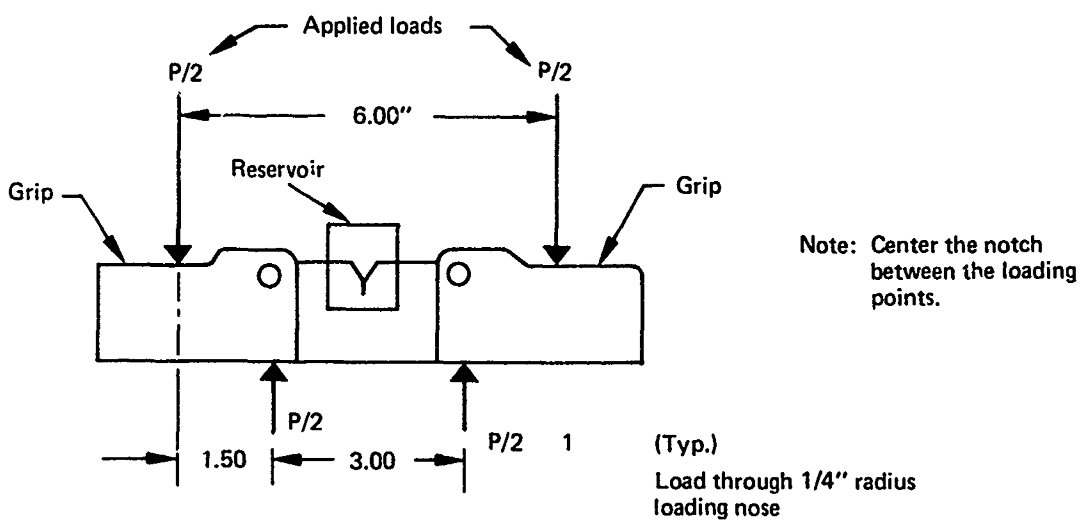
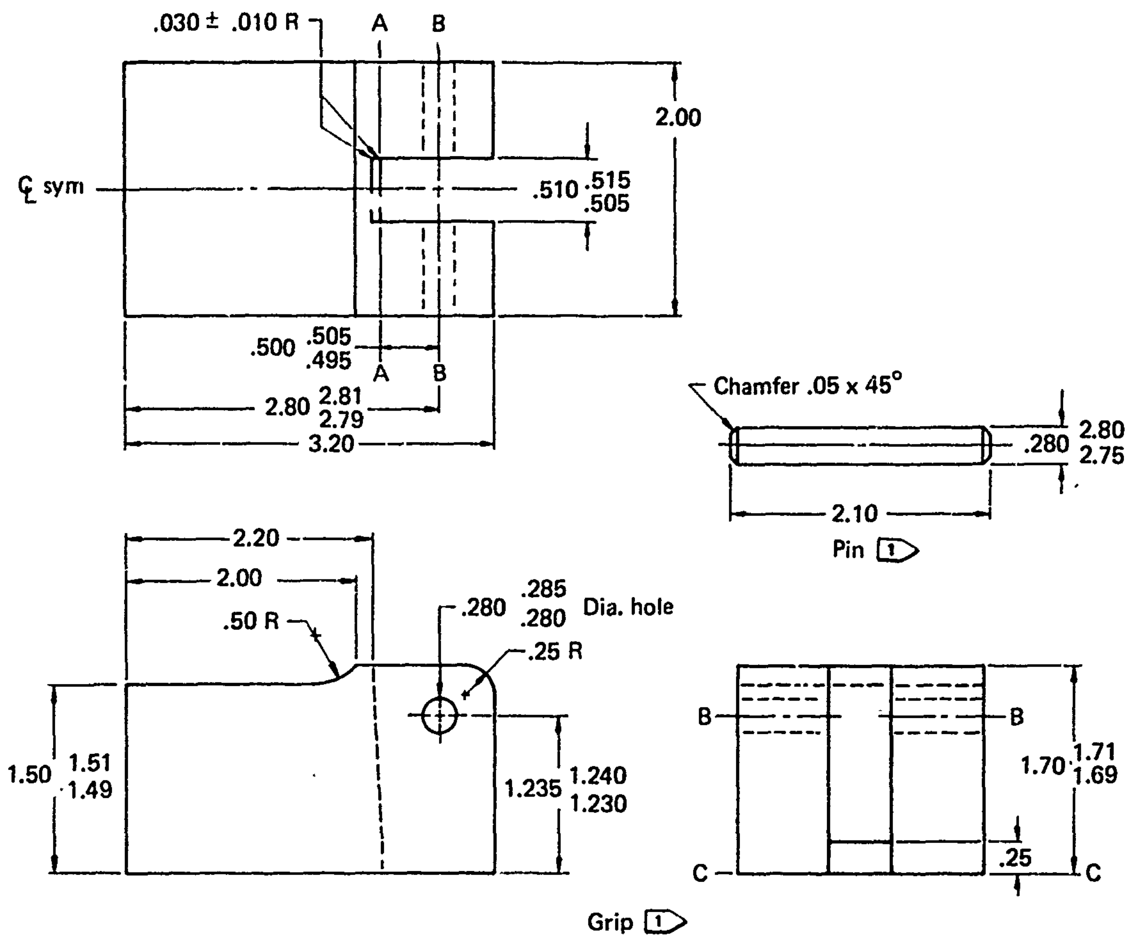


FIGURE C-3.—LOAD APPLICATION TO SHORT NOTCH BEND SPECIMEN



Line A-A to be parallel to line B-b within 0.001 inch.
Line B-B to be parallel to line C-C within 0.001 inch.

Notes: Remove all burrs.

125√finish all over.

Spray all of Grip (except inside of hole) with teflon spray

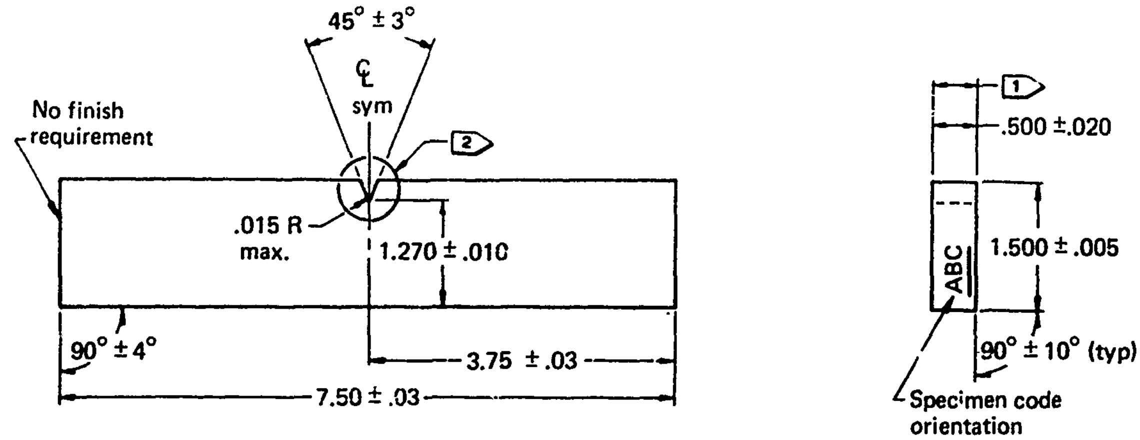
Tolerances ± .03 inch except as noted.

All linear dimensions in inches.

For use with short notch bend K_{salt} specimen shown in figure C-6

1 Pin and Grip should be fabricated from a high strength steel, ultimate tensile strength of 200 ksi minimum (e.g , AISI 4340).

FIGURE C-4.—SHORT NOTCH BEND SPECIMEN GRIP



Notes:

125 Finish all over except as noted.

Remove burrs but do not break off chamfer edges.

1 Remove an equal amount of material from each surface. The specimen shall be free from interstitial contamination.

2 Optional notch configuration as shown below (drawing not to scale)

All linear dimensions in inches.

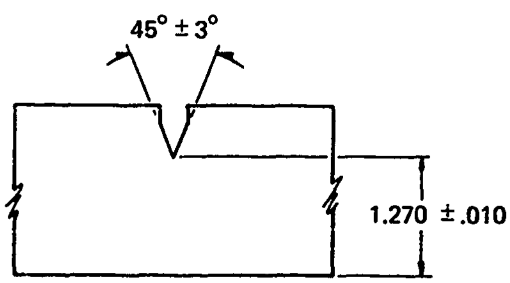
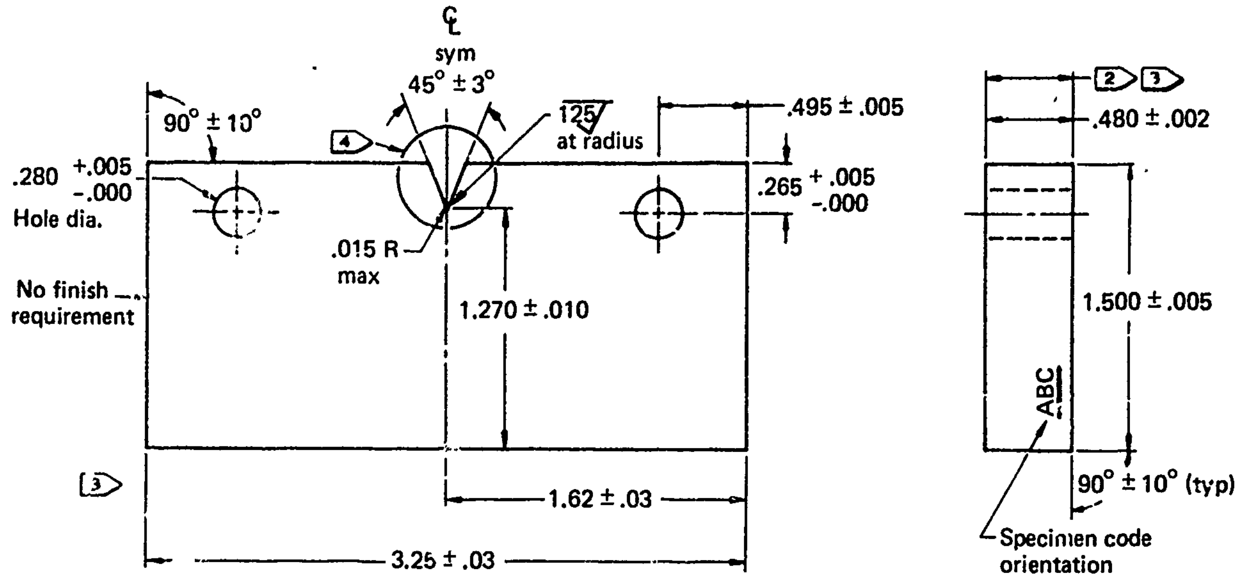


FIGURE C-5.–NOTCHED BEND SPECIMEN



1. 125 finish all over except as noted
2. Remove burrs but do not break or chamfer edges.
3. All linear dimensions in inches.
4. This specimen shall be used with the grip shown in figure C-4.

[1] Steel stamp or vibro-scribe (both ends).

[2] Remove an equal amount of material from each surface. The specimen shall be free from interstitial contamination.

[3] Perpendicular to surface within .003.

[4] Optional notch configuration as shown below (drawing not to scale):

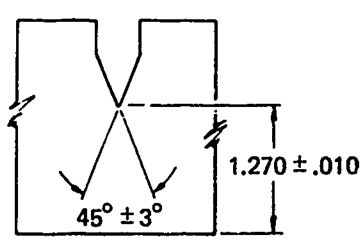


FIGURE C-6.—SHORT NOTCHED BEND SPECIMEN

APPENDIX D
PROPOSED
ADVANCED SUPERSONIC TRANSPORT
MATERIAL SPECIFICATION

(Prepared for the Federal Aviation Administration)

TITANIUM ALLOY 6Al-4V BETA PROCESSED BAR AND FORGINGS

1.0 SCOPE

1.1 Scope - This specification covers Titanium - 6 Aluminum - 4 Vanadium alloy forged and rolled bar; die forgings, hand forgings, and ring rolled shapes for high toughness applications.

1.2 Classification -

1.2.1 Conditions - Bar and forgings shall be furnished in one of the following conditions, as specified on the purchase order.

Condition I - Mill Annealed
Condition III - Solution Treated and Aged at 1000F
Condition IV - Solution Treated and Overaged at 1350F.

1.2.2 Forms- Forged bars, rolled bars, die forgings, hand forgings, and ring rolled shapes.

2.0 APPLICABLE DOCUMENTS

Except where a specific issue is indicated, the issue of the following documents in effect on the date of invitation for bid shall form a part of this specification to the extent indicated herein.

a. AMS 2241 - Tolerances, Corrosion and Heat Resistant Steel Bars and Forging Stock

b. AMS 2249 - Chemical Check Analysis Limits

c. ASTM E-8 - Tension Testing of Metallic Materials

d. ASTM E-120 - Methods of Chemical Analysis for Titanium and Titanium Alloys

e. ASTM E-146 - Hot Extraction of Hydrogen

f. MIL-I-8950 - Ultrasonic Inspection, Wrought Metals

g. Federal Test Method Standard No. 151 - Metals, Test Methods

h. MIL-H-81200 - Heat Treatment of Titanium and Titanium Alloys

i. MIL-I-6866 - Penetrant Methods of Inspection

j. Federal Standard No. 184 - Identification Markings for Aluminum, Titanium, and Magnesium

3.0 REQUIREMENTS

3.1 Material

3.1.1 Raw Material - The material shall be produced by multiple melting under vacuum or inert gas atmosphere. Melting processes shall include either singly or in combination, electro-consumable arc, electron beam, or other vacuum melting processes suitable for the production of materials meeting the requirements of this specification.

The material shall be rolled or forged 50 percent below the beta transus prior to beta processing. The material must be beta processed by beta annealing at 1850° to 1900°F for nominally 5 minutes and then cooling a minimum rate of 50°F per minute to a maximum temperature of 1100°F.

3.1.2 Heat Treatment Conditions

a. Material shall be furnished in the conditions described in Table D-1 as specified on the purchase order.

TABLE D-1 - MATERIAL CONDITIONS

Condition	Heat Treatment	Description
Condition I*	Mill Anneal	1350° ± 25°F for two (2) hours nominally and air cool
Condition III	Solution Treat and age at 1000F	1650° - 1700°F for fifteen (15) minutes nominally and water quench; age at 1000° ±25°F for four (4) hours minimum and air cool.
Condition IV	Solution Treat	1650° - 1700°F for fifteen (15) minutes nominally and water quench; age at 1350° ±25°F for four (4) hours and air cool.

*Material purchased in Condition I shall be capable of being heat treated to the properties required of material in Condition III or IV.

b. Furnace tolerances shall be ± 25°F. Temperature control shall be per MIL-H-81200.

3.1.3 Grain Flow - Unless otherwise specified, the grain flow pattern shall conform to the structural shape of the bar or forgings. When specified the grain flow pattern in forgings shall conform to the drawing requirements.

3.2 Chemical Composition - Chemical composition shall meet the requirements of Table D-2. For method of determination and limits, see Section 4.4.1.

TABLE D-2 - CHEMICAL COMPOSITION

ELEMENT	COMPOSITION (WEIGHT PERCENT) MINIMUM	MAXIMUM	
Aluminum	5.7	6.2	
Vanadium	3.6	4.4	
Iron	---	0.25	
Carbon	---	0.05	
Nitrogen	---	0.03	
Hydrogen	---	0.0125	(1)
Oxygen	0.08	0.11	(1)
Other Impurities	---	0.40	(2)
Titanium	Remainder		(3)

(1) Shall be determined after all processing has been completed.

(2) Need not be reported. Any individual element shall not exceed 0.10 percent.

(3) Need not be reported.

3.3 Mechanical Properties - The room temperature tensile properties as determined by the methods in Section 4.4.2 shall meet the requirements given in Table D-3.

TABLE D-3 - MINIMUM TENSILE PROPERTIES (3) (4)

Cond.	Thickness as Forged (2) (inches)	Thickness as Heat Treated (inches)	Ultimate Strength (ksi)	Yield Strength 0.2% Offset (ksi)	Elongation (4D) (%) (L)	(T)	(ST)	Reduction of Area (%) (LT)	(T)	(ST)
I	Up to 2.00	--	125	112	10	10	-	25	25	-
	2.01-6.00	--	122	110	8	8	6	20	20	15
	6.01-8.00	--	120 (1)	108 (1)	8	8	6	15	15	12
	8.01-12.00	--	118 (1)	105 (1)	8	8	6	15	15	12
III	Up to 6.00	Up to .50	150	135	6	6	-	20	20	-
		.51-1.00	147	132	6	6	-	20	20	-
		1.01-1.25	142	127	6	6	-	20	20	-
		1.26-1.50	135	120	6	6	-	20	20	-
		1.51-2.00	130	115	6	6	-	20	20	-
		2.01-3.00	125	112	6	6	-	20	15	-
	6.01-12.00	Up to .50	147	132	6	6	-	20	20	-
		.51-1.00	142	127	6	6	-	20	20	-
		1.01-1.25	135	120	6	6		20	20	-
		1.26-1.50	130	115	6	6	-	20	15	-
		1.51-2.00	125	110	6	6	-	20	15	-
IV	Up to 6.00	Up to 1.00	130	118	10	10	-	25	20	-
		1.01-1.50	125	112	9	9	-	20	20	-
	6.01-12.00	Up to 1.00	125	112	8	8	-	20	20	-

(1) The value is 3 KSI less for the short transverse grain direction when the as-forged (or rolled) width exceeds 3X the thickness.

(2) Thickness is measured in the short transverse direction of the as-forged (or rolled) material with a Width : Thickness Ratio not exceeding 5:1.

(3) Tensile property requirements may be waived for any direction in which the dimension is less than 2½ inches.

(4) The symbols L, T, and ST refer to longitudinal, transverse and short transverse test directions respectively.

3.3.2 Environmental Fracture Requirements - Forgings and barstock (over 1.625 inches diameter or thickness) shall meet the following minimum environmental fracture toughness requirement when tested in accordance with Section 4.4.4

$$K_{salt} = 55 \text{ KSI} \sqrt{\text{in.}}$$

3.3.2 (Continued)

The specimen axis shall be perpendicular to the grain flow of the material unless otherwise noted on the part drawing. For Condition I material, the specimen blanks shall be removed from the bar or forging after annealing. For condition III or IV material, the specimen blanks shall be removed prior to heat treatment and then the blanks annealed to Condition 1 (1350 ± 25°F for two (2) hours minimum and air cool). Two (2) specimens shall be tested per lot.

3.4 Dimensions and Tolerances

3.4.1 Dimensions - The shapes and dimensions shall be specified on the drawing and/or in the purchaser order.

3.4.2 Tolerances - Dimensional tolerances for bar shall be in accordance with AMS 2241.

3.5 Microstructure - Microstructure shall be determined per Section 4.4.3. The microstructure shall consist of basketweave or Widmanstatten morphology (Figure 1) and shall not contain primary or equiaxed alpha phase. The microstructure shall be uniform and shall be fine grain. Prior beta grains exceeding .030 in. in width or .050 in. in length shall constitute no more than 10% of the microstructure when examined at 10-50 magnification. A prior beta grain is a region of basketweave morphology which has transformed from a single beta grain. The microstructure shall show no interstitial surface contamination as evidenced by a different microstructure morphology (stabilized alpha) at the surface.

3.6 Identification of Product - Each bar or forging shall be marked in accordance with FED-STD-184. In addition, each bar or forging shall be marked with the heat number, the number of this specification, drawing number, suppliers identification, heat treatment condition and composition.

3.7 Ultrasonic Inspection - Unless otherwise specified in the purchase order, all bars and forging stock shall be ultrasonically inspected in accordance with MIL-I-8950. The minimum quality level shall conform to Table D-4.

TABLE D-4- ULTRASONIC QUALITY LEVELS

Dimension (Inch)	Ultrasonic Classification
Up to 1-1/2 thickness Incl.	AA
Over 1-1/2 to 9 thickness	A
Larger than 9	B

3.8 Penetrant Inspection - Unless otherwise specified in the purchase order, all die forgings shall be penetrant inspected in accordance with MIL-I-6866.

3.9 Workmanship - Barstock and forged shapes shall be uniform in quality, free from all voids, pipe, laps and porosity as determined by penetrant and ultrasonic inspection methods, in addition to visual inspection.

Material shall not be repaired by plugging or welding.

The material shall be capable of meeting the following requirements:

Surfaces shall be free of scale and oxygen contamination. The outer .005 inches of surface shall contain an average of no more than 0.22 weight percent oxygen when analyzed per Section 4.4.1.

Surface defects such as laps, seams, etc. shall be removed by localized grinding or other suitable methods. If grinding is used on die forgings, .005" minimum shall be removed from the ground surface by chemical milling, etching, or machining.

4.0 QUALITY ASSURANCE PROVISIONS

4.1 Responsibility for Inspection - Unless otherwise specified in the contract or purchase order, the supplier is responsible for the performance of all inspection requirements as specified herein. Except as otherwise specified, the supplier may utilize his own facilities or any commercial laboratory acceptable to the procuring activity. The purchaser reserves the right to perform any of the inspection set forth in the specification where such inspections are deemed necessary to insure supplies and services conform to prescribed requirements.

4.2 Lot - A lot shall consist of bars or forgings submitted for inspection from the same processing lot which are from the same heat of material, rolled or forged at the same nominal temperature, of the same configuration size (for die forgings, forged from identical dies), in the same heat treat condition and from the same heat treatment run.

4.3 Sampling - Except as otherwise specified sampling plans and procedures in the determination of the acceptability of products submitted by a supplier shall be in accordance with the provisions set forth in MIL-STD-105.

4.3.1 Examination of Product

4.3.1.1 Samples for visual examination and dimensional tolerances shall be selected from each lot of bars or forgings of titanium and titanium alloy in accordance with the provisions of MIL-STD-105. Acceptance criteria shall be in accordance with MIL-STD-105, Inspection Level II, Acceptable Quality Level 1.5 percent.

4.3.1.2 Samples shall be visually examined for conformance with requirements for condition, identification, workmanship, and dimensions.

4.4 Quality Conformance Tests

4.4.1 Chemical Analysis

4.4.1.1 Sampling - After all processing has been completed, at least one sample from each lot shall be taken for oxygen and hydrogen analysis as described in Method 111 or Method 112 of Federal Test Method Standard No. 151.

4.4.1.2 Analysis - Chemical composition for all elements except hydrogen shall be determined using ASTM E-120. Analysis for hydrogen shall be performed using the hot extraction method described in ASTM E-146-64T. Check analysis shall be according to AMS 2249. The producer shall not ship material which is outside the limits specified in Section 5.2. The purchaser shall not reject,for chemical composition, material within the check analysis tolerance. Any other analysis methods, having equivalent or better accuracy and precision than the above methods, may be used provided they are approved by the purchaser. Check analysis for oxygen content shall be performed by a technique having a maximum accuracy standard deviation of 50 ppm.

4.4.1.3 The supplier shall furnish adjacent chemical analysis blanks (approximately 1/4 cubic inches) to the purchaser.

4.4.2 Mechanical Testing

4.4.2.1 Tensile Testing

a. The following tensile specimens per ASTM E-8 shall be used.

(1) For material thicknesses of .500 inch and greater - .250 inch diameter specimen.

(2) For material thicknesses less than 0.500 inch - specimen to be agreed upon by suppliers and users.

(3) The supplier shall furnish adjacent test blanks for tensile and environmental fracture testing to the purchaser.

b. Tensile testing shall be done in accordance with ASTM E-8. The strain rate shall be .003 - .007 inch per minute through 0.2% offset strain. The crosshead speed shall then be increased to .075 - .125 inch per minute per inch of gage length. When a dispute occurs between purchaser and supplier over the yield strength values, a referee test shall be performed on a machine having a strain rate indicator or controller, using a strain rate of .005 inch per inch per minute through the yield strength. Three (3) specimens shall be tensile tested from each lot of material.

c. The drawing may specify integrally forged specimen blanks, the areas of the forgings from which to take test specimens and the direction of the major axis of the specimens. In forged bar, the specimen shall be a long transverse specimen where size of bar permits.

d. Test specimens for bars shall be taken from the center of the cross section of the bar.

4.4.3 Determination of Microstructure - Microstructure shall be determined on at least two specimens per lot, including each K_{salt} specimen. Examination shall be conducted at a magnification of 500X. Specimens shall be taken with the specimen surface parallel to the longitudinal grain direction. The etching shall be accomplished by immersion in Krolls etch (2% HF, 10% HNO_3, 88% H_2O) for approximately 15 seconds followed by a water rinse, then a second etching by immersion in a 0.5% HF solution for approximately 5-10 seconds. The microstructural specimen shall have been annealed at 1350°F for at least two hours.

4.4.4 Test for Environmental Fracture Toughness (K_{SALT}) - This testing procedure covers the determination of fracture toughness for Ti-6Al-4V bar and forging material in environment of salt water.

4.4.4.1 List of Terms

K_{SALT}	A measure of fracture toughness in an environment of salt water.
K	A stress intensity factor derived from fracture mechanics
K_{SL}	A stress intensity factor sustained at a specified level for 20 minutes in aqueous 3-1/2% NaCl
B	Specimen thickness
W	Specimen width
a	Total crack length (sum of notch and fatigue crack length)

4.4.4.2 Apparatus - The K_{SALT} test shall be conducted on any tensile machine capable of developing 30,000 pounds load, and conforming in other respects to ASTM E4, Verification of Testing Machines. The machine shall also be capable of sustaining load at a specified level within ± 2 percent for a period of twenty minutes.

Test fixtures shall be capable of maintaining alignment in the transfer of load from the machine to the specimen. Apply load at points indicated in Figure D-2 for Notched Bend test specimens. For Short Notched Bend specimens using specimen grips apply load per Figure D-3.

It is required that the precracked area of the specimen be completely immersed throughout the test in aqueous 3.5% sodium chloride.

4.4.4.3 Test Specimen - Notch Bend specimens shall be prepared per Figure D-5 or 6. The thickness of the specimen shall be that of the product for thicknesses to 1/2 inch. Specimens 1/2 inch thick shall be prepared from products whose thickness exceeds 1/2 inch.

The notch may be prepared by mill cutting. It is mandatory that the root radius be no larger than 0.015 inches or fatigue precracking is extremely difficult to control. Any procedures which reduce the size of the root radius are permissible.

The specimens shall be precracked by fatigue loading until the crack extends a minimum of .050" and a maximum of .200" on each side of the specimen. The crack may be started at higher K values, but during the final 0.050 inches of extension, the maximum K should not exceed 2/3 of K_{SL}.

4.4.4.4 Test Procedures

a. Measure the specimen's thickness at two points, one on each side of the notch. Average the measurements.

b. Measure the specimen's width from edge to edge on each side surface along the crack plane. Average the measurements.

c. Measure the crack length from the edge to the crack tip on each surface of the specimen. Average the measurements.

d. Calculate the load required to develop K_{SL} using the equation of step h.

e. Assemble a saltwater reservoir enclosing the pre-cracked area.

f. Fill the reservoir with saltwater making sure that the crack tip is completely immersed.

g. Load the specimen to $K_{SL} = 55$ ksi $\sqrt{in}$ at a crosshead separation rate of approximately .05 inches per minute. Hold the load at K_{SL} for 20 minutes. If the specimen has not failed after 20 minutes at K_{SL}, raise the load so that K increases 15 ksi $\sqrt{in}$. and hold at this new level for 7 minutes. If the specimen does not fail at this level (K_{SL} + 15) continue this procedure with increases of 15 ksi $\sqrt{in}$ for 7 minute periods until failure.

h. Calculate K_{SL} and all other K-values using the following:

$$K_{SL} \text{ or } K = \frac{1.5P(S-s)\sqrt{a}}{BW^2}\left[1.99 - 2.47\,(a/w) + 12.97\,(a/w)^2 - 23.17\,(a/w)^3 + 24.8\,(a/w)^4\right]$$

where:

P is the load required to develop a desired K-level

S is the distance between the upper load points

s is the distance between the lower load points

a is the crack length

w is the specimen width

i. Record the following results:

(1) If the specimen passes K_{SL} but fails the next 7 minute K level, report the value of K_{SL}.

(2) If the specimen passes K_{SL} and subsequent 7 minute K levels, report the highest 7 minute level passed.

(3) The test values obtained shall be reported on the material certification as K_{SALT} values in ksi $\sqrt{in.}$

4.4.5 Ultraonsic Inspection - Ultrasonic inspection shall be performed in accordance with MIL-I-8950. Surface roughness shall not exceed 125 roughness height rating (RHR) at 5 megahertzen (mhz) and 250 RHR at 2.25 mhz and lower frequencies. The surface roughness of the reference standards shall not vary more than ± 25 RHR from the surface roughness of material being tested.

4.4.6 Penetrant Inspection - Penetrant inspection shall be per MIL-I-6866.

5.0 PREPARATION FOR DELIVERY

5.1 Identification - Each bar and forging shall be marked in accordance with Federal Standard No. 184. In addition, each bar and forging shall be marked with heat number, lot, condition, type and the number of this specification, including the applicable revision letter.

5.2 Packaging and Marking

a. Packaging shall be such as to assure safe delivery.

b. Each container shall be durably and legibly marked with the following information:

Material specification number including the applicable revision letter, the appropriate condition and type, the supplier's name, product designation, lot number, purchaser order number and quantity.

6.0 NOTES

6.1 Intended Use - The materials procurable under this specification are intended for structural application in airborne vehicles and equipment where high fracture toughness is required. The materials are weldable by electron beam, plasma arc, friction, and diffusion welding processes.

6.2 Ordering Data - Procurement document should state the following:

(a) Title, number, and date of this specification.

(b) Composition or commercial alloy designation.

(c) Heat treatment condition (see 3.1.2).

(d) Size and thickness.

(e) Marking requirements (see 3.6)

FIGURE D-1.—Ti-6Al-4V MICROSTRUCTURE TYPICAL OF A BASKETWEAVE OR WIDMANSTATTEN MORPHOLOGY
(MAG. 5000X)

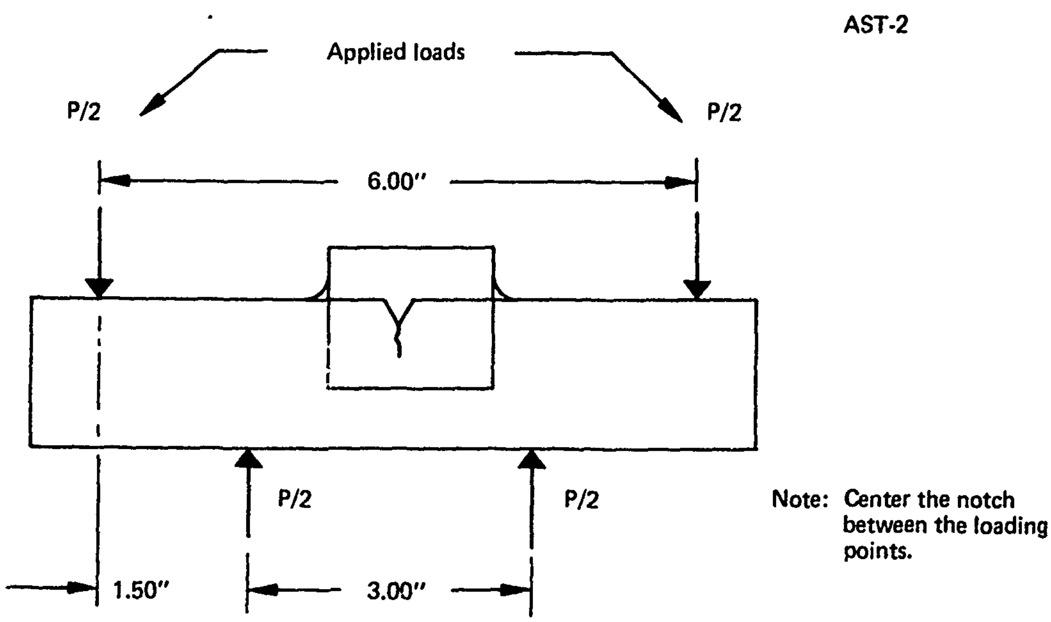


FIGURE D-2.–LOAD APPLICATION TO NOTCH BEND SPECIMEN

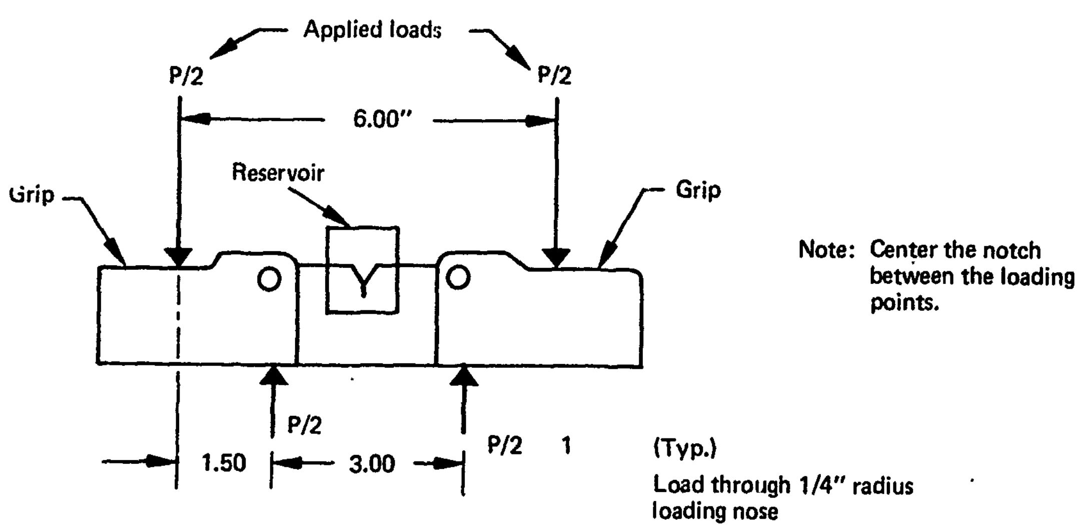
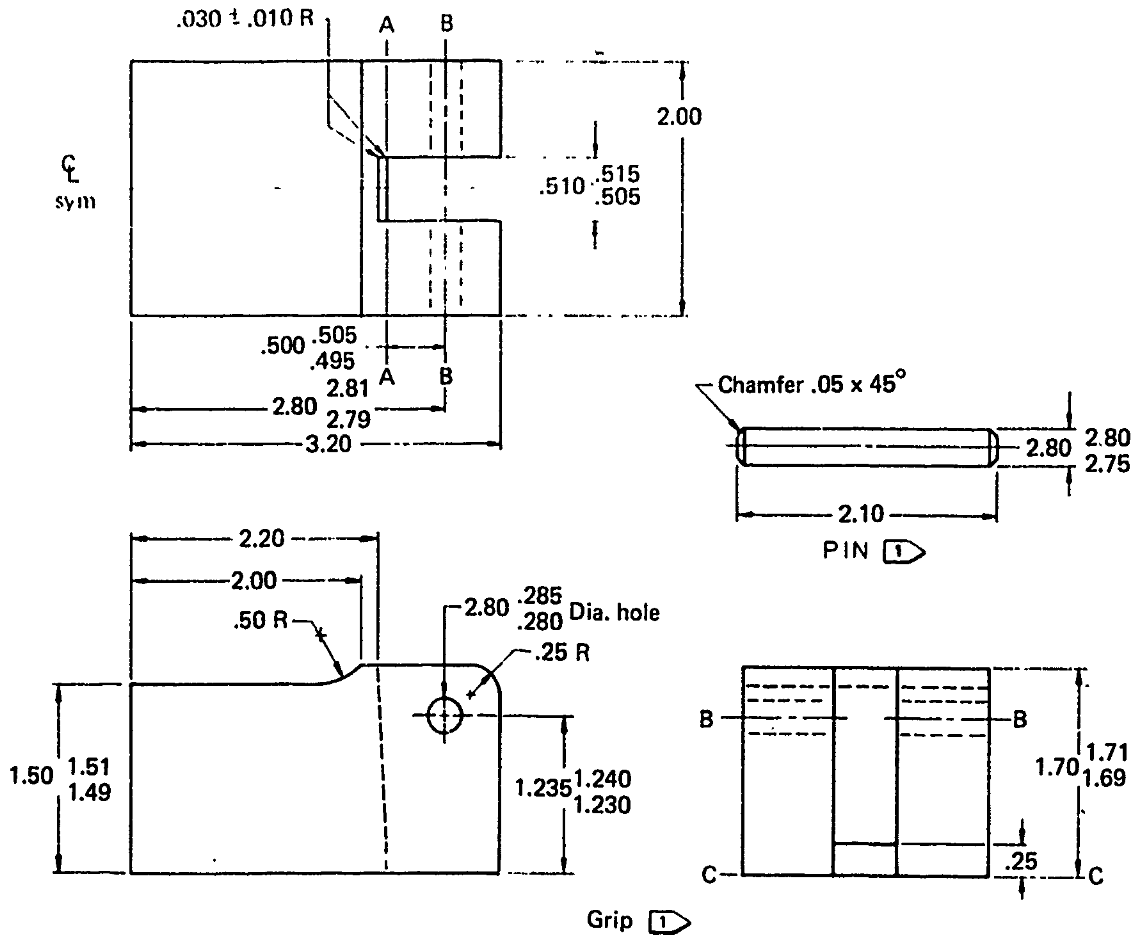


FIGURE D-3.–LOAD APPLICATION TO SHORT NOTCH BEND SPECIMEN

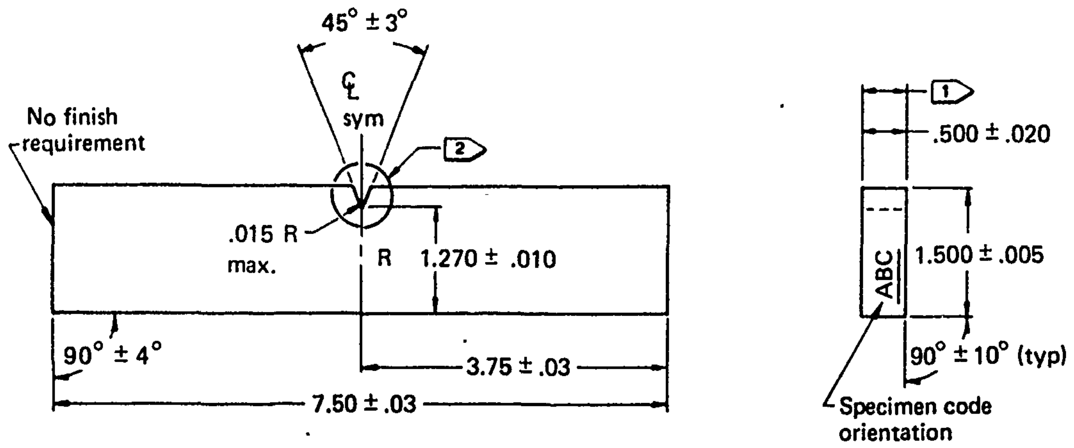


Line A-A to be parallel to line B-B within 0.001 inch.
Line B-B to be parallel to line C-C within 0.091 inch.

Notes: Remove all burrs.
125 finish all over.
Spray all of Grip (except inside of hole) with teflon spray
Tolerances ± .03 inch except as noted.
All linear dimensions in inches.
For use with short notch bend K_{salt} specimen shown in figure D-6

1 Pin and Grip should be fabricated from a high strength steel, ultimate tensile strength of 200 ksi minimum (e.g., AISI 4340).

FIGURE D-4.–SHORT NOTCH BEND SPECIMEN GRIP



Notes:

125 Finish all over except as noted.

Remove burrs but do not break off chamfer edges.

1. Remove an equal amount of material from each surface. The specimen shall be free from interstitial contamination.

2. Optional notch configuration as shown below (drawing not to scale)

All linear dimensions in inches.

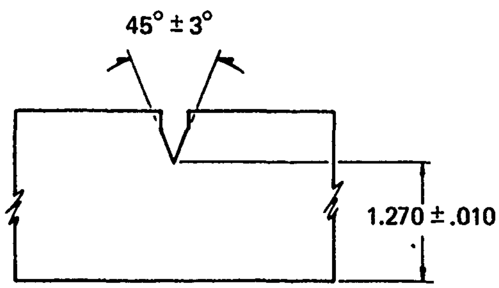
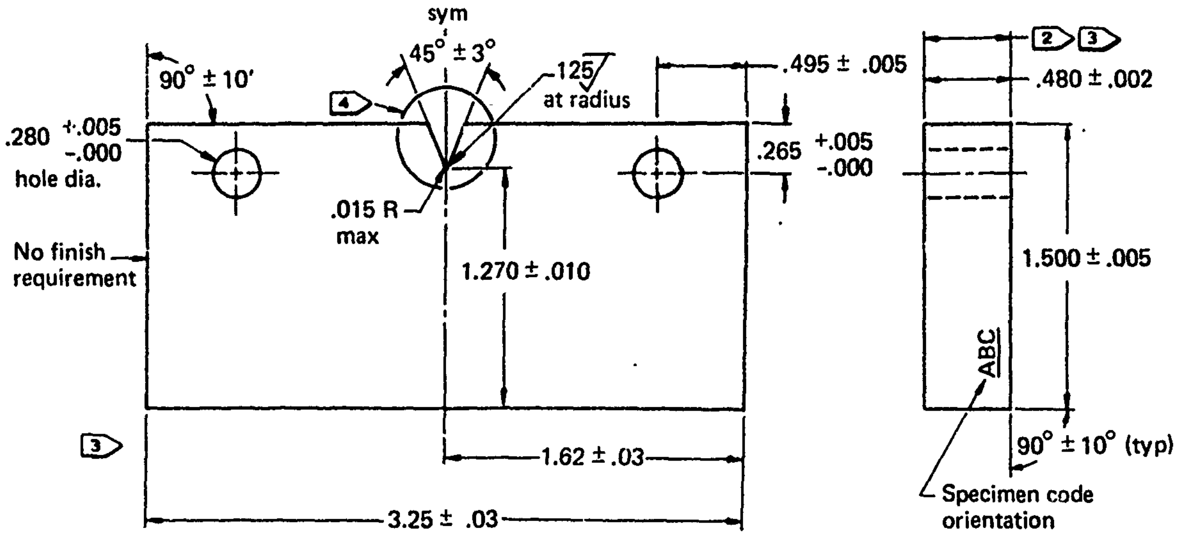


FIGURE D-5.—NOTCHED BEND SPECIMEN



1. 125 finish all over except as noted.
2. Remove burrs but do not break or chamfer edges.
3. All linear dimensions in inches.
4. This specimen shall be used with the grip shown in figure D-4.

1 Steel stamp or vibro-scribe (both ends)

2 Remove an equal amount of material from each surface. The specimen shall be free from interstitial contamination.

3 Perpendicular to surface within .003.

4 Optional notch configuration as shown below (drawing not to scale):

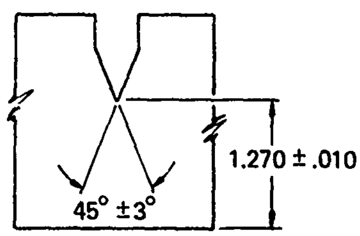


FIGURE D-6.–SHORT NOTCHED BEND SPECIMEN

APPENDIX E
PROPOSED
ADVANCED SUPERSONIC TRANSPORT
MATERIAL SPECIFICATION

(Prepared for the Federal Aviation Administration)

TITANIUM ALLOY 6Al-4V BETA PROCESSED EXTRUSIONS

1.0 SCOPE

1.1 Scope - This specification covers Titanium -6 Aluminum -4 Vanadium alloy extruded and hot rolled structural shapes for high toughness applications.

1.2 Classification

1.2.1 Conditions

Condition I - Mill Annealed
Condition III - Solution Treated and Aged at 1000F

1.2.2 Forms

Extruded or rolled structural shapes.

2.0 APPLICABLE DOCUMENTS

Except where a specified issue is indicated, the issue of the following documents in effect on the date of invitation for bid shall form a part of this specification to the extent indicated herein.

a. AMS 2249, Chemical Check Analysis Limits

b. ASTM E-8, Tension Testing of Metallic Materials

c. ASTM E-9, Compression Testing of Metallic Materials

d. ASTM E-120, Methods of Chemical Analysis for Titanium and Titanium Alloys

e. ASTM E-146, Hot Extraction of Hydrogen

f. Federal Standard No. 184 - Identification Markings for Aluminum, Titanium and Magnesium

g. Federal Test Method Standard No. 151 - Metals, Test Methods

h. MIL-H-81200 - Heat Treatment of Titanium and Titanium Alloys

i. MIL-I-8950 - Inspection, Ultrasonic Wrought Metals, Process

3.0 REQUIREMENTS

3.1 Material

3.1.1 Melting and Fabrication Practice - The material shall be produced by multiple melting under vacuum or inert gas atmosphere. Melting processes shall include either singly or in combination, electro-consumable arc, electron beam, or other vacuum melting processes suitable for the production of materials meeting the requirements of this specification. Extrusion and rolling temperatures must be maintained above the beta transus (1800 to 1900°F). Starting stock prior to extruding or rolling shall be primarily worked below the beta transus.

3.1.2 Heat Treatment Conditions

a. Material shall be furnished in the following condition as specified on the purchase order.

Condition	Heat Treatment	Time and Temperature	
I	Mill Anneal	1350° ± 25°F for two hours nominally and air cool	(1)
III	Solution Treatment	1675° ± 25°F for nominally 1 hour and water quench 1000° ± 25°F for four hours and air cool	

(1) Extruded shapes may be stretch annealed at 1350° ± 25°F for a minimum of 30 minutes at temperature following by air cooling. If temperatures in excess of 1350°F are required to straighten parts, this temperature must be lowered to 1350° ± 25°F and held there for 10 minutes minimum prior to air cooling to room temperature.

(2) For section thicknesses (see note) greater than one inch, the solution treating time shall be based on one hour per inch (or fraction of an inch) of thicknesses.

NOTE: A complex shape may be considered as being comprised as a series of blocks; each block having a given length, width, and thickness as the largest thickness in this series of blocks - for single layer loading. For multi-layer loading, thickness is defined as the minimum dimension of the load. If straightening fixtures are used during heat treatment, consider the section thickness of the fixture in addition to that of the part.

3.1.2 (Continued)

b. Mechanical deformation or straightening shall meet the following requirements:

(1) Condition I material straightened after final heat treatment must be straigntened at 1200° to 1350°F for a minimum of 10 minutes.

or

Material straightened after final heat treatment at a temperature below 1200°F shall be stress relieved at 1250° to 1350°F for a minimum of 30 minutes.

(2) Condition III material may be straightened during aging. Total time at 1000°F must be within 3 to 4 hours.

or

Material straightened after aging or partial aging at a temperature below 1000°F shall be stress relieved at 1000°F for 1 hour. Total time at 1000°F must be within 3 to 4 hours.

(3) Condition IV material may be straightened during aging. Total time at 1250°F must be within 3 to 4 hours.

or

Material straightened after aging or partial aging at a temperature below 1250°F shall be stress relieved at 1225°F for nominally 30 minutes. Total time at 1250°F must be within 3 to 4 hours.

All straightening, stress-relieving operations conducted at the aging temperature shall be considered as part of the aging cycle. Straightening at temperatures to 900°F for a maximum of 8 hours is not to be considered as part of the aging cycle.

c. Temperature control shall be per MIL-H-81200.

3.2 Chemical Composition - For method of determination and limits, see Section 4.3.1.

Element	Composition (Weight Percent)		
	Minimum	Maximum	
Aluminum	5.7	6.2	
Vanadium	3.6	4.4	
Iron	-	0.25	
Carbon	-	0.05	
Nitrogen	-	0.03	
Hydrogen	-	0.0125	(2)
Oxygen	0.08	0.11	(2)
Other Impurities	-	0.40	(1)
Titanium	Remainder		

(1) Need not be reported. Any individual element shall not exceed 0.10 percent.

(2) Shall be determined after all thermal and cleaning processing has been completed.

3.3 Mechanical Properties - The room temperature mechanical properties, as determined by the methods in Section 4.3 shall meet the requirements in Table E-1.

TABLE E-1. MECHANICAL PROPERTIES (MINIMUM)

Condition	Thickness (inches)	TUS (psi)	TYS 0.2% Offset (psi)	Elongation (Percent) (2)	CYS 0.2% Offset (psi) (3)
I (1)	0.188-2.000	125,000	112,000	10.0	122,000
	2.000	120,000	108,000	10.00	120,000
III	0.188-0.500	150,000	135,000	7.0	150,000
	0.501-0.750	145,000	130,000	7.0	145,000
	0.751-1.000	140,000	125,000	6.0	140,000
	1.001-2.000	130,000	120,000	6.0	130,000
	Over 2.000	125,000	112,000	6.0	

(1) Condition I material shall be capable of being heat treated to the minimum mechanical properties for Condition III and Condition IV materials when solution treated and aged per Section 3.1.2.

(2) Elongation is measured over a 1 inch gage length for .25 inch diameter test specimens and over a 2 inch gage length for flat specimens.

(3) Compression yield strength is determined using the 1 inch gage length.

3.4 **Dimensional Tolerances** - Unless otherwise specified, the following tolerances apply.

3.4.1 Cross Sectional Dimensions

Ordered Dimension	TOLERANCE (Inch) Cross Section Area 5 Sq. In.	Cross Section Area 5 Sq. In.
0 - 1" Incl.	+ .040 - .000	+ .060 - .000
Over 1" - 2" Incl.	+ .060 - .000	+ .090 - .000
Over 2" - 3" Incl.	+ .080 - .000	+ .125 - .000
Over 3"	+ .125 - .000	+ .02 x Drawing Dimension or + .125 - .000 whichever is greater

3.4.2 Length

Length	Tolerance (Inch) Over	Under
Up to 12 feet inclusive	0.25	0
Lengths over 12 feet	0.50	0

3.4.3 Corner and Filler Radii

Radii	Tolerance (Inch) Cross-Section Area 5 Sq. In.	Cross Section Area 5 Sq. In.
Fillet	± .060	± .250
Corner	± .030	± .125

3.4.4 Angles - Angles shall be ± 2 degrees.

3.4.5 Straightness - Deviation of any edge from a flat surface shall not exceed 0.125 inches in any 5 foot length. A force not to exceed 200 pounds may be used to hold the part down during the straightness measurement.

Local grindouts shall not be included in the measurement.

3.4.6 Twist - Twist shall not exceed three degrees in any 5-foot length with a maximum of 5 degrees in the full length.

3.4.7 Transverse Flatness - Deviation from flat shall not exceed 0.010 inch per inch of width with a maximum deviation of 0.050 inches for widths over 5 inches.

3.4.8 Workmanship - Extruded and rolled shapes shall be uniform in quality, free from all voids, pipe, kinks, or damaged ends as determined by visual and ultrasonic inspection methods.

3.5 Ultrasonic Inspection - Unless otherwise specified in the purchase order, all material prior to extruding or rolling shall be ultrasonically inspected in accordance with MIL-I-8950 and Section 4.4.5. The minimum quality level shall conform to Table E-2. Extrusions and rolled shapes with a minimum thickness greater than 1.0 inch shall meet Class A quality level of MIL-I-8950.

TABLE E-2 - ULTRASONIC QUALITY LEVELS

Dimension (Inch)	Ultrasonic Classification
Over 1-1/2 to 9 thickness	A
Larger than 9	B

3.6 Microstructure - Microstructure shall be determined per Section 4.3.4. The microstructure shall consist of basketweave or Wiedmanstatten morphology (Figure E-1) and shall not contain primary or equiaxed alpha phase (Figure E-2). The microstructure shall be uniform and shall be fine grain. **Prior beta grains exceeding .030 in. in maximum dimension shall constitute no more than 10% of the microstructure when examined at 10-50 magnification. A prior beta grain is a region of basketweave morphology which has transformed from a single beta grain.**

The microstructure shall show no surface oxygen contamination as evidenced by different microstructure morphology (stabilized alpha phase) at the surface.

3.7 Saltwater Fracture Test - All shapes with a maximum width dimension of 1.7 inches and greater shall meet the following minimum saltwater fracture toughness (K_{SALT}) requirement when tested in accordance with Section 4.3.4.

$$K_{SL} = 55 \text{ ksi } \sqrt{\text{in.}}$$

The notched bend specimen axis (longest dimension) shall be parallel to the rolled or extruded direction for shapes under 3.5 inches in maximum widths. For shapes 3.5 inches and over in maximum width, the specimen axis shall be perpendicular to the rolled or extruded direction.

For Condition I material, the specimen blanks shall be removed after annealing. For Condition III or IV material, the specimen blanks shall be removed after heat treatment and then the blanks annealed to Condition I (1350 $\pm$ 25°F for one hour minimum and air cool). One specimen shall be tested per lot.

3.8 Surface Condition - The surface shall be descaled, pickled and free of interstitial surface contamination. The material shall be capable of meeting the following requirement: The outer .005 inches of surface shall contain an average of no more than 0.22 weight percent oxygen when analyzed per Section 4.3.1.

Surface defects such as laps, seams, etc. shall be capable of being removed by localized grinding or machining to not less than the minimum drawing dimension in that area.

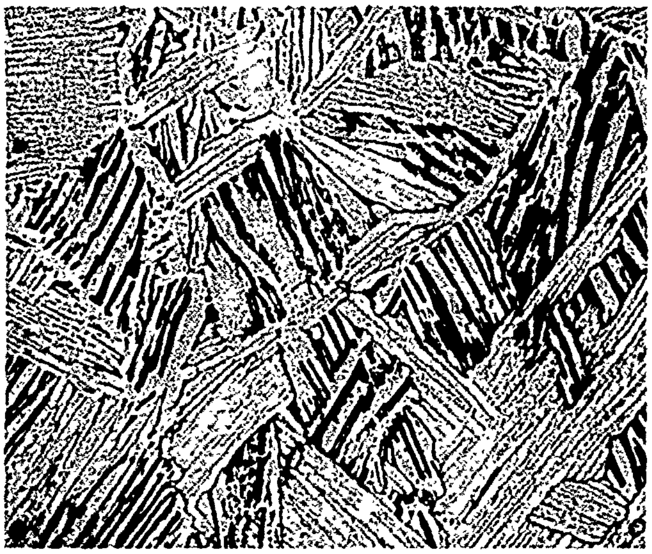


FIGURE E-1.—AN EXAMPLE OF AN ACCEPTABLE Ti-6Al-4V EXTRUSION MICROSTRUCTURE.

(MAG. 500X)

FIGURE E-2.—AN EXAMPLE OF AN UNACCEPTABLE Ti-6Al-4V EXTRUSION MICROSTRUCTURE

(MAG. 500X)

3.9 Identification of Product - Each shape shall be marked in accordance with FED-STD-184. In addition, each shape shall be continuously marked with the material specification number, revision letter, the condition, heat number, lot number, the supplier's identification, and the drawing number.

4.0 QUALITY ASSURANCE PROVISIONS

4.1 Responsibility for Inspection - Unless otherwise specified in the contract or purchase order, the supplier is responsible for the performance of all inspection requirements as specified herein. Except as otherwise specified, the supplier may utilize his own facilities or any commercial laboratory acceptable to the procuring activity. The purchaser reserves the right to perform any of the inspections, set forth in the specification where such inspections are deemed necessary to insure supplies and services conform to prescribed requirements. The supplier shall furnish three copies of a report of the individual test results including photomicrographs for each lot shipped.

4.2 Lot - A lot is defined as all lengths of a given drawing number which are produced from the same heat of material and heat treated in a single batch.

4.3 Sampling - Except as otherwise specified sampling plans and procedures in the determination of the acceptability of products submitted by a supplier shall be in accordance with the provisions set forth in MIL-STD-105.

4.3.1 Examination of Product - Samples for visual and dimensional tolerances shall be selected from each lot in accordance with the provisions of MIL-STD-105.

Acceptance criteria shall be in accordance with MIL-STD-105, Inspection Level II, Acceptable Quality Level 1.5 percent.

Samples shall be visually examined for conformance with requirements for condition, identification, workmanship, and dimensions.

4.4 Quality Conformance Tests

4.4.1 Chemical Analysis

4.4.1.1 Sampling - After all processing has been completed, at least one sample from each lot shall be taken for oxygen and hydrogen analysis as described in Method 111 or Method 112 of Federal Test Method Standard No. 151.

4.4.1.2 Analysis - Chemical composition for all elements except hydrogen shall be determined using ASTM E-120. Analysis for hydrogen shall be performed using the hot extraction method described in ASTM-E-146. Check analysis shall be according to AMS 2249. The producer shall not ship material which is outside the limits specified in Section 5.2. The purchaser shall not reject,for chemical composition, material within the check analysis tolerance. Any other analysis methods, having equivalent or better accuracy and precision than the above methods, may be used provided they are approved by the purchaser. Check analysis for oxygen content shall be performed by a technique having a maximum accuracy standard deviation of 50 ppm.

The supplier shall furnish adjacent chemical analysis blanks (approximately 1/4 cubic inches) to purchaser.

4.4.2 Mechanical Pfoperties

4.4.2.1 Tensile Testing - The following tensile specimens per ASTM E8 shall be used:

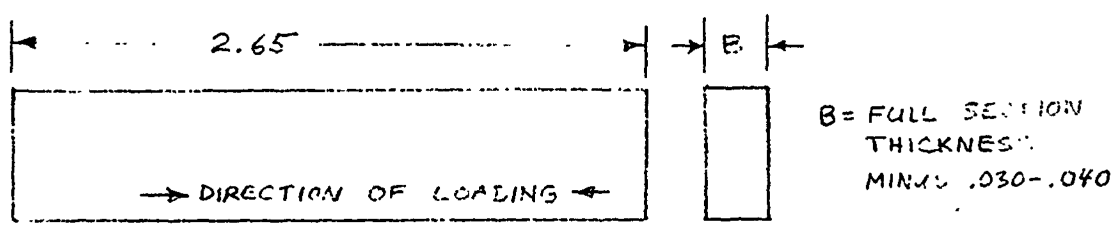
(1) Material thickness less than .375 inch - Figure 7 specimen with surface machined.

(2) Material thickness greater than .375 inch - .250 inch diameter specimen.

(3) When thickness permits, .500 inch diameter specimen may be used.

Tensile testing shall be done in accordance with ASTM E8 with the loads applied parallel to the length of the shape. The strain rate shall be .003 - .007 inch per inch per minute through 0.2% offset strain. The crosshead speed shall then be increased to .075 - .125 inch per minute per inch of gage length. Wehn a dispute occurs between purchaser and supplier over the yield strength values, a referee test shall be performed on a machine having a strain rate indicator or controller, using a rate of .005 inch/inch/minute through the yield strength. Three coupons, taken from the thickest section, shall be tested from each lot of material, until the quality level justifies reduced testing in accordance with an approved reduced sampling plan. Where possible, one specimen shall be prepared from each of three lengths selected at random.

4.4.2.2 Compression Yield Testing - Compression yield testing shall be done per ASTM E9 with the loads applied parallel to the length of the shape. The strain rate shall not exceed 0.010 inch per inch per minute through 0.2% offset strain. Three samples shall be tested from each lot of material. Shapes greater than 1/2 inch section thickness shall use the 1/2 inch diameter round type specimen described in ASTM E9. Shapes with section thicknesses less than 1/2 inch will use the flat type specimen as shown in Figure E-3. Gage length of both specimens is one inch. The as extruded surfaces shall be removed by grinding or milling to a thickness of the drawing dimension minus 0.030 to 0.040 inch.



END SQUARE AND PARALLEL WITHIN ± .0005 IN.

FIGURE E-3

4.4.3 Test for Environmental Fracture Toughness (K_{SALT}) - This testing procedure covers the determination of fracture toughness for Ti-6Al-4V extrusions and rolled shapes in environment of salt water.

4.4.3.1 List of Terms

K_{SALT}	A measure of fracture toughness in an environment of salt water.
K	A stress intensity factor derived from fracture mechanics
K_{SL}	A stress intensity factor sustained at a specified level for 20 minutes in aqueous 3-1/2% NaCl
B	Specimen thickness
W	Specimen width
a	Total crack length (sum of notch and fatigue crack length)

4.4.3.2 Apparatus - The K_{SALT} test shall be conducted on any tensile machine capable of developing 30,000 pounds load, and conforming in other respects to ASTM E4, Verification of Testing Machines. The machine shall also be capable of sustaining load at a specified level within ± 2 percent for a period of twenty minutes.

Test fixtures shall be capable of maintaining alignment in the transfer of load from the machine to the specimen. Apply load at points indicated in Figure 4 for Notched Bend test specimens. For Short Notched Bend specimens using specimen grips apply load per Figures E-5 and 6.

It is required that the precracked area of the specimen be completely immersed throughout the test in aqueous 3.5% sodium chloride.

4.4.3.3 Test Specimen - Notch Bend specimens shall be prepared per figure E-7 or 8. The thickness of the specimen shall be that of the product for thicknesses to 1/2 inch. Specimens 1/2 inch thick shall be prepared from products whose thickness exceeds 1/2 inch.

The notch may be prepared by mill cutting. It is mandatory that the root radius be no larger than 0.015 inches or fatigue precracking is extremely difficult to control. Any procedures which reduce the size of the root radius are permissible.

The specimens shall be precracked by fatigue loading until the crack extends a minimum of .050" and a maximum of .200" on each side of the specimen. The crack may be started at higher K values, but during the final 0.050 inches of extension, the maximum K should not exceed 2/3 of K_{SL}.

4.4.3.4 Test Procedures

a. Measure the specimen's thickness at two points, one on each side of the notch. Average the measurements.

b. Measure the specimen's width from edge to edge on each side surface along the crack plane. Average the measurements.

c. Measure the crack length from the edge to the crack tip on each surface of the specimen. Average the measurements.

d. Calculate the load required to develop K_{SL} using the equation of step h.

e. Assemble a saltwater reservoir enclosing the pre-cracked area.

f. Fill the reservoir with saltwater making sure that the crack tip is completely immersed.

g. Load the specimen to K_{SL} = 55 ksi $\sqrt{in}$ at a crosshead separation rate of approximately .05 inches per minute. Hold the load at K_{SL} for 20 minutes. If the specimen has not failed after 20 minutes at K_{SL}, raise the load so that K increases 15 ksi $\sqrt{in}$. and hold at this new level for 7 minutes. If the specimen does not fail at this level (K_{SL} + 15) continue this procedure with increases of 15 ksi $\sqrt{in}$ for 7 minute periods until failure.

h. Calculate K_{SL} and all other K-values using the following:

$$K_{SL} \text{ or } K = \frac{1.5P(S-s)\sqrt{a}}{BW^2}\left[1.99-2.47\,(a/w) + 12.97\,(a/w)^2 - 23.17\,(a/w)^3 + 24.8\,(a/w)^4\right] \quad (1)$$

where

P is the load required to develop a desired K-level

S is the distance between the upper load points

s is the distance between the lower load points

a is the crack length

w is the specimen width

i. Record the following results:

(1) If the specimen passes K_{SL} but fails the next 7 minute K level, report the value of K_{SL}.

(2) If the specimen passes K_{SL} and subsequent 7 minute K levels, report the highest 7 minute level passed.

(3) The test values obtained shall be reported on the material certification as K_{SALT} values in ksi $\sqrt{in.}$

4.4.4 Determination of Microstructure - One microstructural determination shall be made for each lot. The specimen shall be taken with the specimen surface parallel to the extrusion or rollling direction (transverse view). Examination shall be made by traversing the whole thickness at a magnification of 500X. Etching shall be accomplished by immersion in Kroll's etch (2% HF, 10% HNO_3, 88% H_2O) for approximately 15 seconds iwth a water rinse followed by immersion in 0.5% HF solution for 5-10 seconds. One photograph of the microstructure shall be taken at 500 magnification showing representative microstructure.

4.4.5 Ultrasonic Test - Ultrasonic inspection shall be performed in accordance with MIL-I-8950. Surface roughness shall not exceed 125 roughness height rating (RHR) at 5 megahertzen (mhz) and 250 RHR at 2.25 mhz and lower frequencies. The surface roughness of the reference standards shall not vary more than $\pm$ 25 RHR from the surface roughness of material being tested.

4.4.6 Adjacent Test Blanks

The supplier shall furnish adjacent test blanks for mechanical and saltwater fracture toughness testing to the purchaser.

5.0 PREPARATION FOR DELIVERY

5.1 Identification - Each extrusion or part shall be marked in accordance with Federal Standard No. 184. In addition, each extrusion or part shall be marked with heat number, lot, condition, type and the number of this specification, including the applicable revision letter.

5.2 Packaging and Marking -

a. Packaging shall be such as to assure safe delivery.

b. Each container shall be durably and legibly marked with the following information:

   Material specification number including the applicable revision letter, the appropriate condition and type, the supplier's name, product designation, lot number, purchase order number and quantity.

6.0 NOTES

6.1 Intended Use - The materials procurable under this specification are intended for structural applications in airborne vehicles and equipment where high fracture toughness is required. The materials are weldable by electron beam, plasma arc, friction, and diffusion welding processes.

6.2 Ordering Data - Procurement document should state the following:

a. Title, number, and date of this specification.

b. Composition of commercial alloy designation.

c. Heat treatment condition (see 3.1.2).

d. Marking requirements (see 3.9).

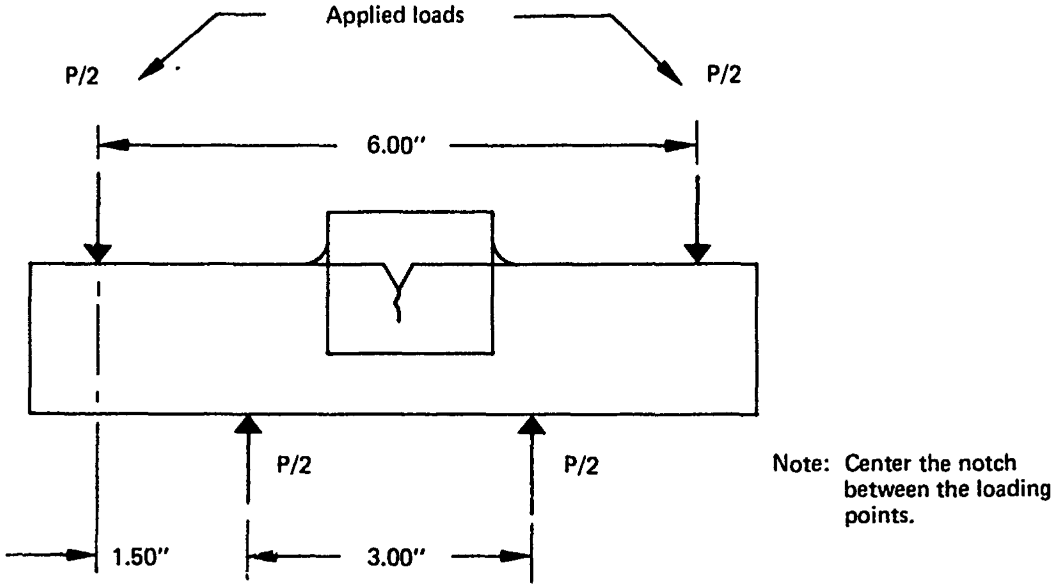


FIGURE E-4 –LOAD APPLICATION TO NOTCH BEND SPECIMEN

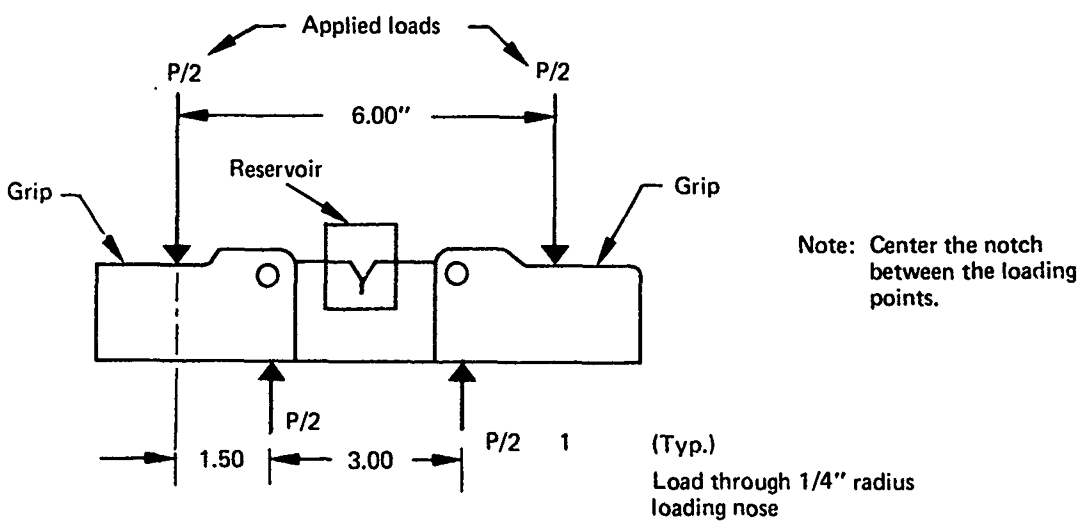
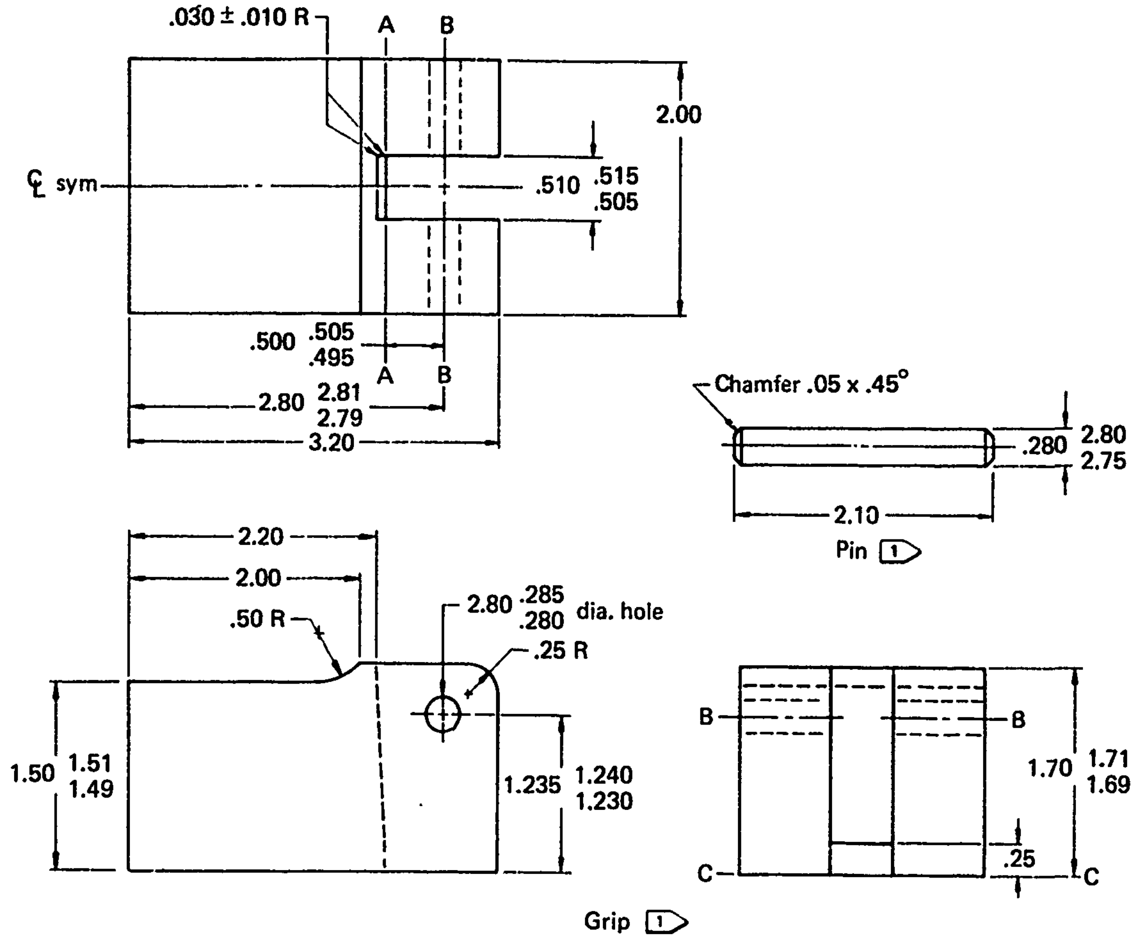


FIGURE E-5 –LOAD APPLICATION TO SHORT NOTCH BEND SPECIMEN



Line A-A to be parallel to line B-B within 0.001 inch.

Line B-B to be parallel to line C-C within 0.001 inch.

Notes: Remove all burrs.

125 finish all over.

Spray all of grip (except inside of hole) with teflon spray

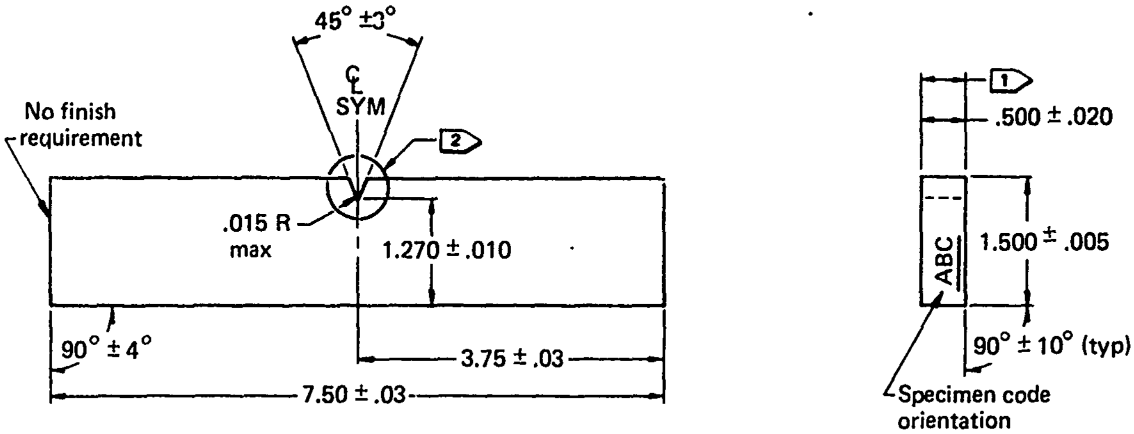
Tolerances ± .03 inch except as noted.

All linear dimensions in inches.

For use with short notch bend K_{salt} specimen shown in figure E-5

[1] Pin and grip should be fabricated from a high strength steel, ultimate tensile strength of 200 ksi minimum (e.g., AISI 4340).

FIGURE E-6.–SHORT NOTCH BEND SPECIMEN GRIP



Notes:

125 Finish all over except as noted.

Remove burrs but do not break off chamfer edges.

1 Remove an equal amount of material from each surface. The specimen shall be free from interstitial contamination.

2 Optional notch configuration as shown below (drawing not to scale)

All linear dimensions in inches.

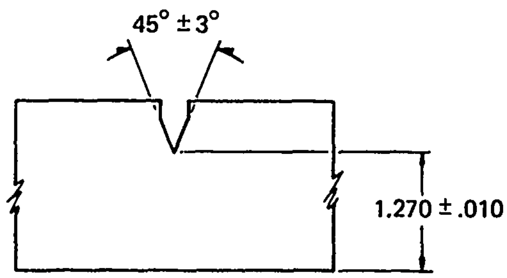
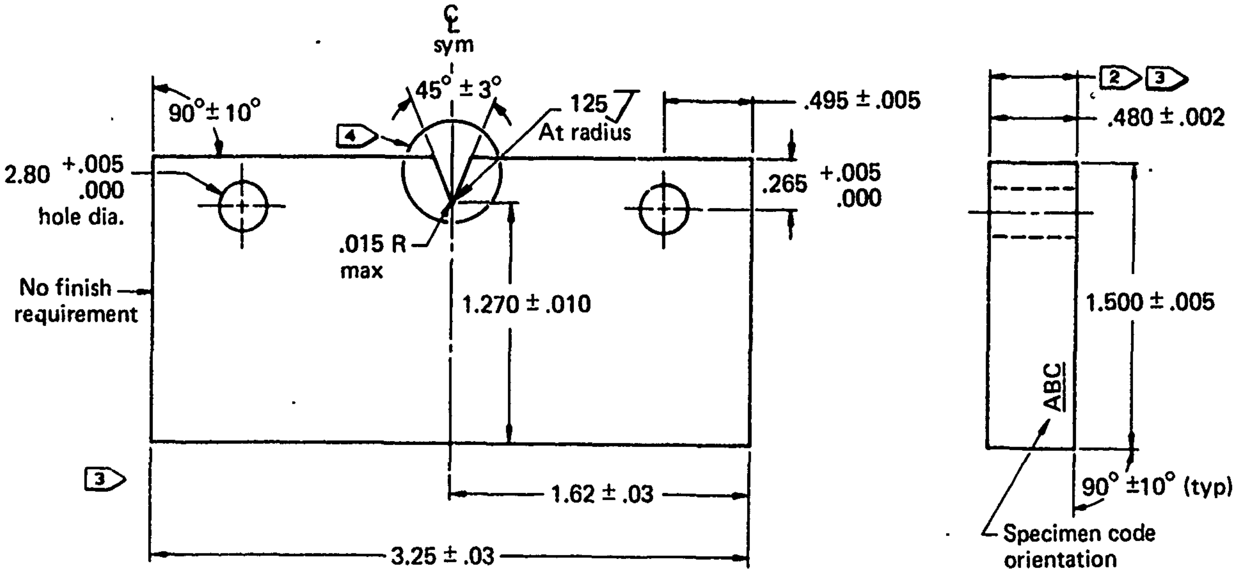


FIGURE E-7.—NOTCHED BEND SPECIMEN



1. 125 finish all over except as noted.
2. Remove burrs but do not break or chamfer edges.
3. All linear dimensions in inches.
4. This specimen shall be used with the grip shown in figure E-6.

1 Steel stamp or vibro-scribe (both ends).

2 Remove an equal amount of meterial from each surface. The specimen shall be free from interstitial contamination.

3 Perpendicular to surface within .003.

4 Optional notch configuration as shown below (drawing not to scale)

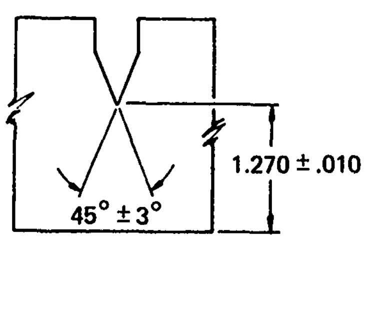


FIGURE E-8. – SHORT NOTCHED BEND SPECIMEN

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2. F. L. Parkinson and W. F. Spurr, "SST Technology Follow-On Program–Phase I, Titanium Alloy 6Al-4V Mechanical-Metallurgical Testing," Report FAA-SS-72-13 (Boeing document D6-60213) July 15, 1972.

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