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SST Technology Follow-On Program – Phase I

TITANIUM ALLOY 6Al–4V EXTRUSIONS

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FINAL REPORT
Task 1

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Prepared for

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16. Abstract
Various investigations were conducted ~~from 1966 to March of 1971, the SST program cancellation date~~ to characterize and develop Ti-6Al-4V extrusions. In addition to Ti-6Al-4V, the initial developmental studies also included Ti-6Al-6V-2Sn extrustions. Properties evaluated included strength, fracture toughness, stress corrosion resistance (K_{Iscc}), fatigue and metallurgical characteristics. The extrustion properties were highly variable. Strength and fracture property variations were associated with significant variations in chemical composition, microstructure and crystallographic texture. High fracture characteristics were related to relatively low oxygen contents, fully transformed beta microstrucutre and near non-directional textures.

(K sub ISCC),

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PREFACE

This is one of a series of final reports on Titanium Materials Technology submitted in fulfillment of Task 1-A of Department of Transportation contract DOT-FA-SS-71-12, dated 30 June 1971. The report was prepared by the Materials Technology organization of The Boeing Company, Commercial Airplane Group, Seattle, Washington.

The author acknowledges the scores of co-workers and supervisors who assisted or directed parts of this program. Acknowledgement is also given to the titanium extrusion producers, without whom many of the advances made would not have been possible.

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GLOSSARY OF TERMS

CYS	.2% offset compression yield strength
Ec	Modulus of Elasticity for Compression
Et	Modulus of Elasticity for Tension
K_A	Anistrophy factor, determined from X-Ray diffraction pole figure
K_{ADJ}	K_{ISCC} test value adjusted to oxygen content of .20 wt. %
K_{IC}	Plane strain fracture toughness
K_{IE}	Mixed mode fracture toughness values
K_{ISCC}	Stress Corrosion Resistance in 3½% NaCl (Threshold)
K_t	Stress-Concentration Factor
MR	Microstructural Rating, where 0 = bad, 20 = good
R	minimum to maximum stress ratio in a fatigue test
RA	% reduction in area in tension tests
TUS	Ultimate tensile strength
TYS	.2% offset tension yield strength

1.0 BACKGROUND AND INTRODUCTION

Titanium alloys were considered for Supersonic Transport (SST) applications as early as 1958 (ref. 1a). Ti-8Al-1Mo-1V alloy, introduced in 1962, was the leading titanium alloy under consideration until early 1965. At that time, results of a relatively new environmental test using a precracked fracture specimen, demonstrated that Ti-8Al-1Mo-1V was markedly susceptible to stress corrosion cracking in salt water and other aqueous environments. Variations in heat treatments were tested including special processing by the producers which showed unacceptable crack propagation resistance for thicknesses greater than 0.040 in. Also, results of thermal stability tests revealed that the good fracture toughenss of duplex annealed Ti-8Al-1Mo-1V deteriorated during elevated temperature fabrication. It was discovered that an extremely fast cooling rate was necessary to maintain the high fracture toughness condition in Ti-8Al-1Mo-1V. This cooling rate was found difficult to attain in manufacturing processes. The undesirable properties of Ti-8Al-1Mo-1V were found to be primarily related to alloy composition. Metallurgical analysis has shown that the eight percent aluminum content, the highest for a commercial alloy, is sufficient to reduce stress-corrosion resistance and cause an ordering reaction in the alpha phase. This ordering tendency is directly related to the instability and cooling rate sensitivity.

As a result of the problems encountered with the Ti-8Al-1Mo-1V alloy, all candidate alloys were re-evaluated with emphasis on stress corrosion cracking. More than ten different alloy compositions were evaluated in various heat treatment conditions (ref. 1b). Ti-6Al-4V and Ti-4Al-3Mo-1V demonstrated superior properties to the other alloys. At that time, The Boeing Company under FAA sponsorship, initiated an investigation of these two alloys. The goal of this effort was to determine the processing conditions required for the optimum combination of properties including resistance to stress corrosion, strength, fracture toughness, and metallurgical stability. Detailed results of this investigation were reported (ref. 1c and 1d). Based on these results Ti-6Al-4V was selected as the primary structural alloy. Further development was initiated at that time for Ti-6Al-4V extrusions.

The selection of Ti-6Al-4V was based primarily on the achievement of superior fracture toughness and stress corrosion resistance by the beta annealing of plate. Ti-6Al-4V extrusions are generally extruded at temperatures near the beta transus and were at that time assumed to be nearly equivalent to that of the beta annealed Ti-6Al-4V plate. Experience with extrusions procured for the SST prototype construction proved the assumption to be only partly true. Characterization testing of Ti-6Al-4V extrusions demonstrated that extrustions were highly variable in mechanical, fracture and metallurgical properties.

This report summarizes initial development of titanium extrusions for the SST program, specification development, supplier qualification, and the characterization testing of prototype Ti-6Al-4V extrusions. The status of titanium extrustion technology at the time of SST program cancellation is discussed in light of the results of the characterization testing.

Many tests in progress as part of the SST effort were halted at the time of SST program cancellation, March 26, 1971. Some of these tests have been re-initiated under the continued testing part of the DOT Phase I program. The results of these additional tests, along with metallurgical analyses will be covered in a separate report. These reports will provide the titanium technology basis for the preparation of a new titanium extrusion specification prepared under the DOT Phase II program. Procurement of Ti-6Al-4V extrusions possessing a superior balance of properties through controlled chemistry and mill processing variables will be possible.

2.0 PRELIMINARY EVALUATIONS

Initial studies of titanium extrusions included both Ti-6Al-6V-2Sn and Ti-6Al-4V alloys. The higher strength of Ti-6Al-6V-2Sn provided greater potential for weight savings in aircraft applications. In 1966, a test program (ref. 2) was conducted to evaluate the mechanical, fracture, fatigue and metallurgical properties of an extruded Ti-6Al-6V-2Sn "tee" in the annealed condition.

Tensile properties for this extrusion were determined at room temperature, -65°F and 500°F. Compressive yield strength, notched (K_t = 2.58) tension-tension fatigue, fracture toughness and stress corrosion resistance (K_{ISCC}) were determined at room temperature. The extrusion microstructure was typical of a transformed beta (basketweave) microstructure which had been subjected to some high alpha-beta temperature thermal processing. The mechanical test results were comparable to those of annealed Ti-6Al-4V alloy except that mechanical properties were approximately 6% higher and K_{ISCC} values were from 30 to 45% lower.

A second titanium extrusion evaluation (ref. 3) was conducted on two Ti-6Al-4V extrusions heat treated to three strength levels. Two extrusion sizes were evaluated: 1) a "tee" configuration of approximately 6 square inches in cross-section, and 2) an angle cross-section of approximately 1.5 square inches. The heat treatment conditions evaluated were a) annealed, b) solution treated plus aged (STA or Condition III), and c) solution treated plus overaged (STOA or Condition IV). Mechanical, fracture, stress corrosion resistance, fatigue and metallurgical properties were determined.

The extrusion microstructures were characterized by a transformed beta microstructure (basketweave), typical of extruding at or above the beta transus temperature. The tensile properties were not significantly directional and the fracture and stress corrosion properties for all three heat treatment conditions were excellent. The oxygen content of each extrusion was questionable in that chemical analysis results varied by approximately 0.05 wt. %. Notch fatigue characteristics (K_t = 2.58) were typical of other data for Ti-6Al-4V; endurance limits approached 35 ksi gross area stress. The fracture and fatigue results from this study are included in Section 6.0.

3.0 MATERIAL SPECIFICATION

3.1 SPECIFICATION DEVELOPMENT

Ti-6Al-4V extrusions procured for SST prototype construction were purchased to Revision C of the Boeing Material Specification BMS 7-44 (Appendix A). The specification was originally written in 1956 in conjunction with the 110A bomber program and was since periodically modified and upgraded to incorporate developing technology. In 1967, it was revised specifically for the SST program (Revision B) to include several major modifications.

The B revision major changes were as follows:

- Class A extrusions which were close tolerance shapes not requiring surface machining
- Condition IV heat treatment condition for STOA (solution treated and overaged) extrusions
- Specific thermal processing requirements for controlling extrusion straightening and stretching
- Compression yield testing requirements for the control of residual stresses resulting from cold straightening.

The thermal processing requirements associated with straightening and stretching were a result of stretching studies conducted by The Boeing Company in conjunction with the H.M. Harper Company (ref. 4). Ti-6Al-4V extrusions, as-extruded, annealed, solution treated and solution treated and aged, were stretched from 1 to 3% at various temperatures from room temperature to 1000°F. Tension and compression property tests, residual stress measurements, and warping tendency measurements were conducted after stretching and thermal processing to evaluate any effects due to residual cold work.

The extrusion producers were unable to meet the requirements for close tolerance extrusions (Class A). Revision C was written to exclude this extrusion class and to incorporate additional specification improvements. The major improvement of Revision C included higher mechanical properties for annealed extrusions and a "Qualified Products List" (QPL). The QPL, a list of approved extrusion producers that had demonstrated the capability to produce Ti-6Al-4V extrusions meeting the specification requirements, was necessary to minimize the incidence of material rejections and the corresponding impairment of production schedules.

For the procurement of prototype extrusions, additional modifications to Revision C specification were required as a result of purchasing problems. These changes were enacted by attachments to individual purchase orders. Thermal processing requirements were modified to better control residual stresses in annealed extrusions. These requirements were necessary as a result of distortion encountered during the machining of annealed extrusions.

The requirements for annealed properties were reduced because of the inability of extrusion producers to meet the higher requirements of Rev. C. A surface oxygen limit was added to eliminate the occurrence of contaminated surfaces. Later deviations included the option to stretch and anneal simultaneously and to allow the use of a 200 lb. maximum pressure to aid in measuring straightness.

3.2 QUALIFICATION OF SUPPLIERS

The QPL section of BMS 7-44C required that each supplier desiring to produce Ti-6Al-4V extrusions for SST prototype construction must have been first qualified by The Boeing Company. The qualification procedure generally required: a) that the supplier provide test data and sample extrusions demonstrating compliance with the specification requirements, b) a survey of the suppliers facilities by representatives from Boeing Quality Control and Engineering Departments, c) verification testing by Boeing of the supplied extrusion samples and d) an overall evaluation by Boeing Engineering of the test data and supplier's production capability.

Emphasis in verification testing was to demonstrate that a supplier could produce extrusions sufficiently free of residual stresses such that excessive warping would not occur during machining. Excessive warping was defined as dimensional changes which were beyond specification tolerance limitations for angularity, straightness, twist and transverse flatness. The STA condition is more prone to the occurrence of residual stresses due to the marginal stress relief provided by the 1000°F age temperature. Qualification granted for STA extrusions automatically included also the annealed and STOA conditions. In later qualification exercises, chemical milling was used in place of machining to preclude the possibility of additional residual stresses induced during machining.

Upon successful completion of the qualification requirements, the qualified suppliers were added to the QPL of BMS 7-44. In cases where suppliers had been successfully producing Ti-6Al-4V extrusions to the specification requirements prior to the incorporation of the QPL, they were granted qualification based on this prior experience. Qualification by this means was limited, however, to the maximum sizes covered by the prior experience. No changes in raw materials or extrusion manufacturing methods were allowed after qualification without prior written approval of The Boeing Company Engineering Department.

4.0 DESIGN AND MANUFACTURING CONSIDERATIONS

The use of Ti-6Al-4V extrusions for SST Prototype applications required first the evaluation of cost, design efficiency, and extrusion producibility. For some applications, overall costs were reduced by the use of Ti-6Al-4V bar or formed sheet sections in lieu of the use of extrusions. However, machined extrusion shapes generally provided the best design efficiency.

Each extrusion section shape was determined through a rigorous procedure that added excess metal to the machined part shape. The excess material was necessary to allow for 1) extrusion dimensional tolerances, 2) machining tolerances, and 3) hot forming or manufacturing tolerances. In many cases excess material added to the original shape amounted to more than 100% increase.

An important manufacturing factor involving the machining of titanium extrusions was excessive tool wear caused by contaminated surfaces (alpha case). Excessive tool wear was minimized in this program by the procurement of contamination free extrusions. Extrusions were purchased with a maximum surface oxygen content of the outer surface (.005 inches in thickness) of 0.22 wt. % maximum. Contamination was minimized for inplant manufacturing, i.e., elevated temperature forming, etc. by the control of chemical milling subsequent to thermal processing.

5.0 CHARACTERIZATION TESTING

Ti-6Al-4V extrusions were characterized with respect to the following properties: tension and compression strength, fracture toughness, stress corrosion resistance (K_{ISCC}), fatigue, microstructure and chemical composition. The majority of the tension and compression testing and chemical composition determinations were conducted by the suppliers and the Boeing Company's Quality Control Department. These evaluations were necessary on each heat-lot of extrusions to insure conformance to BMS 7-44 specification requirements. The Engineering Department conducted various evaluations for fracture, fatigue, mechanical and metallurgical properties. Microstructures were characterized for morphology, prior beta grain size and crystallographic texture.

The data generated by the quality control testing provided a unique opportunity to evaluate extrusions based on a large sample population from approximately 650,000 lbs of extrusions, representing material from all major producers. The data generated by the engineering tests, although smaller in population, provided supplemental information on characteristics not evaluated for specification conformance.

The extrusions selected for the various engineering evaluations were primarily from two overlapping categories: a) extrusions which were to be used for SST Prototype wing lower spar chords and b) extrusions selected at random representative of all sized and conditions purchased for prototype construction. Attempts were made to obtain material produced by all major suppliers. Five suppliers produced extrusions for the SST Prototype program: Curtiss-Wright (C-W), Armco Steel Corp. (ARMCO), Titanium Metals Corporation of America (TMCA), Harvey Aluminum, Inc. (HARVEY), and H.M. Harper Company (HARPER). Due to availability of test samples, engineering tests were primarily conducted on C-W, TMCA and HARVEY material.

Particular concern developed concerning the fracture characteristics of lower wing spar chord extrusions. This was an outgrowth of the discovery that the initial lower wing skin plate material possessed unanticipated low fracture properties. Fracture toughness and stress corrosion resistance were important criteria in the design of wing lower surface structure. An attempt was made to determine or estimate the K_{ISCC} value of each lower wing spar chord extrusion. Completion of this evaluation was prevented by the cancellation of the SST program.

5.1 TEST PROCEDURES AND TECHNIQUES

Tension and compression testing were conducted in accordance with the methods described by ASTM E8 and the requirements of the material specification, BMS 7-44 (Appendix A). Chemical compositions were also determined per the requirements of this specification.

Fracture toughness was determined using the four-point loaded notched bend specimens precracked by fatigue cycling. Detailed test procedures are given in Appendix B. Generally, the 0.480-inch thich specimen was used to allow a direct comparison with previously generated data on titanium plate and bar. Thinner specimens were utilized where extrusion thicknesses were not sufficient to obtain the 0.480-inch thickness. In most cases the specimen configuration did not meet the recommendations of ASTM for validity. Mixed mode fractures were encountered rather than plane strain fractures. Because of this, fracture toughness values are referred to as K_{IE} rather than K_{IC}. The specimen thickness, however, was considered to be representative of those encountered in SST prototype construction.

Stress corrosion resistance, K_{ISCC}, was determined using the same specimen configuration as was used to determine fracture toughness, i.e., the four-point-load notch bend specimen. The specimens were precracked by fatigue prior to sustained loading in 3.5% salt water (NaCl). The detailed test procedures are given in Appendix B. Metallurgical analyses were conducted on various Ti-6Al-4V extrusions. The evaluations characterized the extrusion microstructures for alpha phase morphology, prior beta grain size, crystallographic texture, dispersion of textured alpha basal planes and fracture mode. The chemical composition of each extrusion was analyzed for correlations to mechanical and fracture characteristics. The techniques used were: optical metallography, crystallographic texture analysis by computerized x-ray pole figure determination and color metallography, and macrofractography. Detailed test procedures are described in an associated DOT report for Beta Rolled Ti-6Al-4V Plate (ref. 5).

Tension-tension fatigue characteristics were determined using notched fatigue specimens with a stress concentration factor (K_t) of 2.58. The specimen, a flat specimen configuration containing a 0.25-inch diameter center hole (fig. 1) was selected to represent approximate conditions in aircraft structure. Three Ti-6Al-4V heat treatment conditions were evaluated: a) annealed (Condition I), b) solution treated and aged (Condition III), and c) solution treated and overaged (Condition IV).

Fatigue testing was conducted at room temperature in tension-tension with a maximum gross area stress of 60 ksi and an R value of 0.06 (minimum stress/maximum stress). The fatigue cycling rate was 1800 cycles per minute.

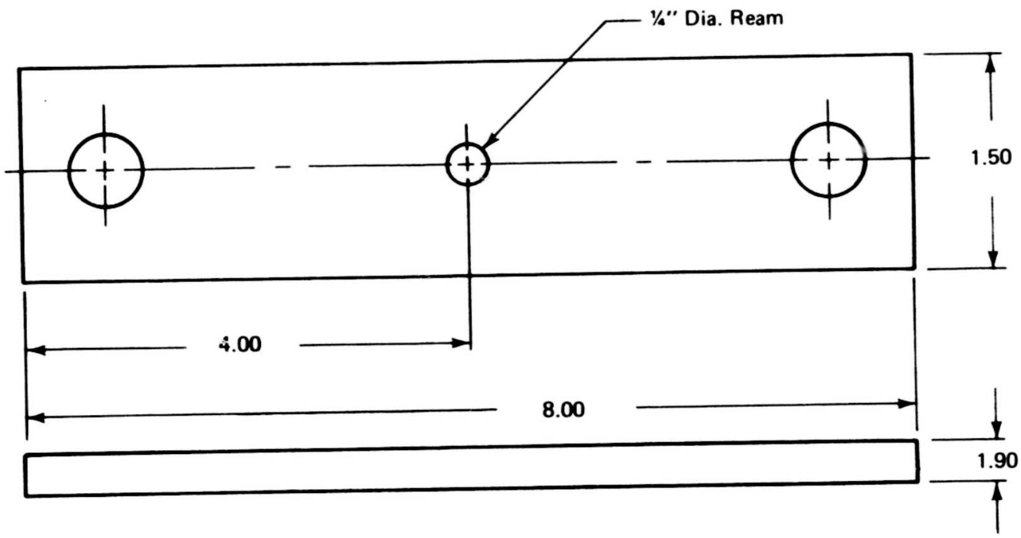

FIGURE 1.–NOTCHED FATIGUE SPECIMEN

5.2 QUALITY CONTROL TESTS

The Quality Control departments of each extrusion supplier and The Boeing Company conducted tension and compression tests and chemical analyses to verify conformance to specification BMS 7-44 requirements. Samples from approximately 650,000 lbs. of Ti-6Al-4V extrusions were evaluated. The mechanical property tests were made in the longitudinal grain direction. Most of the data was generated at the suppliers as the tests conducted by The Boeing Company were for the purpose of verifying the testing accuracy of the suppliers.

The large quantity of data was computerized to allow efficient analysis. The data was grouped into various categories to allow the evaluations of the effects of heat treatment condition and oxygen content on TUS, TYS, Elongation, Reduction in Area (RA) and CYS. Mean, maximum, minimum, standard deviation, number of data points and number of heat-lots were determined by the computer. Statistical data was also determined for elastic modulii (E and E_C).

5.3 ENGINEERING EVALUATIONS

5.3.1 Evaluation of Lower Wing Surface Extrusions

An evaluation was conducted to determine or estimate the fracture characteristics of lower wing spar chord extrusions. Primary effort was directed toward obtaining a K_{ISCC} value for each extrusion. The SST wing design concept required that the lower spar chords possess adequate fracture properties to safely carry structural loads in the event of a skin panel fracture. The discovery of unanticipated low K_{ISCC} values for some Ti-6Al-4V plates used for skin panels led to greater emphasis on the fracture properties of lower spar chord extrusions.

K_{ISCC} tests were conducted where adequate excess material was available. On spar chords where sufficient material was not available, K_{ISCC} values were estimated using microstructure, chemical composition and metallurgical relationships established from beta processed plate. Transformed beta microstructures (basketweave morphology) combined with moderately low oxygen contents (.13 to .15 wt. %) were associated with adequate values of K_{ISCC} (35 to 50 ksi$\sqrt{}$in). Alpha-beta worked microstructures, as evidenced by equiaxed or elongated primary alpha phase, combined with high oxygen contents (.18 to .20 wt. %) were found to be related to low values of K_{ISCC} (22 ksi$\sqrt{}$in).

Two of the most heavily loaded spar chord extrusions were tee extrusions identified as BAC 1671-26 and -51. The -26 extrusions were for the fabrication of inboard chords and the -51 extrusions were for outboard chords. The majority of the testing in this evaluation for all lower chord extrusions was interrupted by the cancellation of the SST program.

5.3.2 Evaluation of SST Extrusions Selected at Random

Extrusion samples were evaluated for microstructure and stress corrosion behavior (K_{ISCC}). The samples were selected at random from available excess material cut from prototype extrusions. The extrusion pieces were originally intended for verification testing for conformance to specification requirements. Selection of samples was made to obtain extrusion material representative of all sizes and conditions to be used for prototype construction.

Notched bend specimens from both the transverse and longitudinal grain directions were fabricated from 25 extrusion heat-lots for K_{ISCC} testing. Microstructures were examined and rated for 13 of these extrusions.

5.3.3 Fracture and Fatigue Evaluation of Annealed and Heat Treated Extrusions

Two Ti-6Al-4V extrusions, a tee shape of approximately 6 square inches cross-section and an angle shape of 1.5 square inches, were evaluated for K_{IC}, K_{ISCC} and notched tension-tension fatigue. The extrusions were evaluated in the annealed, STA and STOA heat treatment conditions. Flat fatigue specimens with a 0.25-inch diameter center hole (K_t of 2.58) were cycled at 1800 cycles per minute with a stress ratio, R = 0.06. Microstructures were studied with optical metallography for each heat treatment condition.

6.0 RESULTS AND DISCUSSION

The test data and metallurgical information generated by the various extrusion evaluations described previously in section 5.0 are discussed in this section as related to individual design properties. The test results from each evaluation are grouped together for each design property to provide an overall view of the factors controlling individual property variations. The effects of variations in chemical composition, microstructure and texture are discussed for mechanical and fracture properties. The effects of heat treatment strength level on fatigue characteristics are included.

6.1 MECHANICAL PROPERTIES

Annealed tension strength properties of SST prototype extrusions varied as much as 35% for TYS and 23% for TUS based on observed minimum values (table 1). Compression yield strength, CYS, varied 23%. Wide ranges in chemical composition were associated with these property variations (table 1). Variations in tension and compression properties for STA extrusions were not as large as those for annealed extrusions (table 2), however, the quantity of data is also less.

The data was also grouped by oxygen content (.130 and under, .131 to .169 and .170 wt. % and over) and analyzed to determine effects of oxygen content on mechanical properties (table 3). The effects are demonstrated in figure 2 where mean TUS and TYS are plotted

TABLE 1.–STATISTICAL CHARACTERISTICS FOR ALL SST Ti-6Al-4V EXTRUSION DATA, ANNEALED CONDITION, 205 HEAT-LOTS*

Properties	Mean	Maximum	Minimum	Standard Deviation	Number of Data
UTS	142.2	157.0	128.3	4.5	746
TYS	129.2	152.0	117.5	4.6	746
Elongation	13.2	20.0	5.0	2.3	746
RA	29.0	40.5	15.4	4.8	454
CYS	137.5	153.4	123.9	4.5	742
Composition (Wt. %)					
Oxygen	.174	.218	.100	.020	~250
Nitrogen	.013	.027	.005	.004	~250
Hydrogen	.0063	.0120	.0006	.0020	~250
Carbon	.028	.074	.005	.011	~250
Aluminum	6.3	6.8	5.5	.2	~250
Vanadium	4.1	4.4	3.5	.1	~250
Iron	.19	.28	.06	.03	~250

*Data summarized from Q.C. Receiving and Inspection certification data, longitudinal grain direction

*TABLE 2.–STATISTICAL CHARACTERISTICS FOR SST Ti-6Al-4V EXTRUSION DATA**, SOLUTION TREATED AND AGED CONDITION, 8 HEAT-LOTS*

Properties	Mean	Maximum	Minimum	Standard Deviation	Number of Data
UTS	168.1	176.4	158.5	6.0	38
TYS	153.2	160.1	142.5	5.8	38
Elongation	11.0	13.0	9.0	.9	38
RA	23.8	31.3	13.8	3.9	32
CYS	163.3	172.1	152.3	5.8	36
Oxygen (Wt. %)	.174	.200	.140	.019	~10

*Data summarized from Q.C. Receiving Inspection Certification Data, longitudinal grain direction

TABLE 3.–STATISTICAL CHARACTERISTICS FOR TWO RANGES OF OXYGEN CONTENT FOR ANNEALED Ti-6Al-4V EXTRUSIONS

Oxygen Content (Wt. %)	Statistical Information	TYS (ksi)	TUS (ksi)	Elong (%)	RA (%)	CYS (ksi)	Al (wt. %)
0.130 and Under	Mean	127.9	139.6	11.9	28.9	136.9	6.5
	Maximum	135.8	146.0	15.0	36.5	142.7	6.6
(.124 mean)	Minimum	122.0	135.0	10.0	20.0	129.9	6.2
	No. of Data	35	35	35	32	35	~ 15
	Std. Deviation	2.7	2.7	1.3	3.2	3.4	.1
	No. of Heat-Lots	12	12	12	12	12	12
0.170 and Over	Mean	129.5	142.7	13.7	29.4	137.3	6.3
	Maximum	144.5	157.0	20.0	40.5	153.0	6.8
(.186 mean)	Minimum	117.5	128.3	5.0	15.5	128.0	5.5
	No. of Data	517	517	517	313	515	~180
	Std. Deviation	4.5	4.3	2.4	5.1	4.3	.2
	No. of Heat-Lots	133	133	133	133	133	133

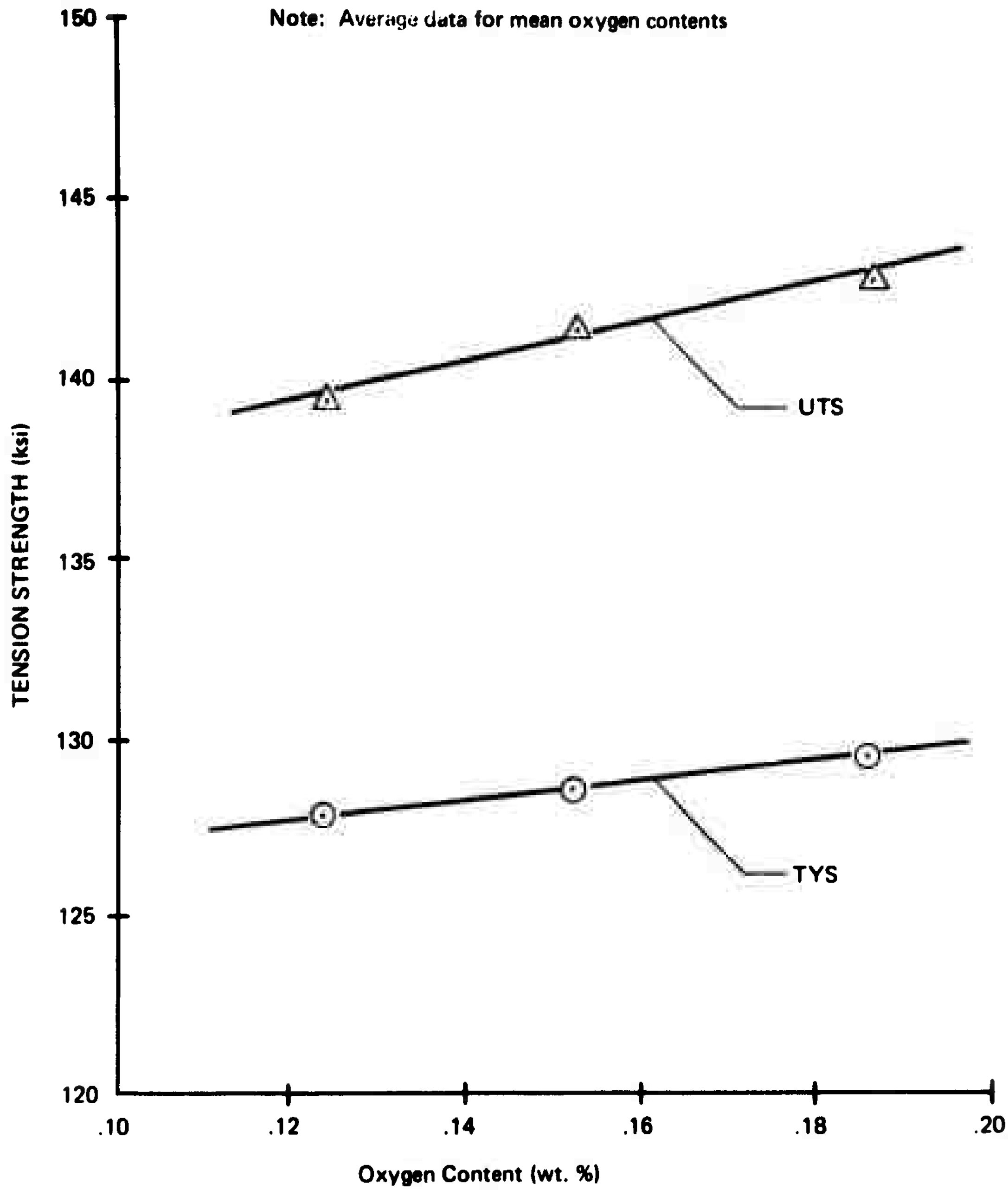

FIGURE 2.–EFFECT OF OXYGEN CONTENT ON TENSION STRENGTH FOR Ti-6Al-4V ANNEALED EXTRUSIONS

versus the mean oxygen content of each data group. Oxygen increases the strength properties of Ti-6Al-4V extrusions, but the effect was much less than expected. The slope for TUS is 0.57 ksi/.010 wt % oxygen. Similar data for Ti-6Al-4V sheet had a slope of 1.5 (ref.6). This difference in oxygen effect is probably related to other metallurgical factors. For example, the average aluminum content of the lower oxygen data group was 3% higher than that of the high oxygen group (table 3). Microstructure is probably another important factor. The sheet data represented a cross-rolled, alpha-beta rolled microstructure and the present data generally is based on extruded transformed beta structures.

Average values were also determined for tension and compression moduli, E and E_C. The results of 16.8 and 17.1 x 10^6 psi respectively were markedly higher than those generally reported for Ti-6Al-4V mill products. MIL-H-5 reports E = 16.0 and E_C = 16.4 for Ti-6Al-4V sheet, plate, bar and forgings. This 5% increase can provide a significant weight savings in the design of stiffness critical structure.

6.2 FRACTURE PROPERTIES

The fracture properties, K_{IE} and K_{ISCC}, of Ti-6Al-4V extrusions were found to be highly variable. The majority of test data generated was for stress corrosion resistance K_{ISCC}.

6.2.1 Stress Corrosion Resistance K_{ISCC}

Values of K_{ISCC} for Ti-6Al-4V extrusions were found to vary nearly 300%. They ranged from a low of 20 ksi$\sqrt{in}$ to a high of 59 ksi$\sqrt{in}$ (table 4). The primary factors causing variations in K_{ISCC} were chemical composition, microstructure and crystallographic textures.

The relationship between chemical composition variations and variations in K_{ISCC} values for extrusions followed in general the relationship established for beta annealed Ti-6Al-4V plate. Regression analysis of plate K_{ISCC} data and composition resulted in the following equation (ref. 5):

$$K_{ISCC} = 171 - 320\, O_2\% + 60Fe\% - 16\, Al\% + 1.4MR^*$$

Examples demonstrating the general effect of oxygen for extrusion data are shown in the data summary, table 5. Specifically, K_{ISCC} values predicted from the equation for specimens FM 959-4 and FM 962-9 were 45 and 19 ksi$\sqrt{in}$ respectively. Actual test values were 46 and 21 ksi$\sqrt{in}$ respectively. Agreement between predicted values and test values are not usually this close.

Since the oxygen content is the major factor influencing predicted values, the accuracy of the oxygen analysis is very important. The above predictions were based on oxygen contents determined at Boeing from broken fracture specimens by using the neutron activation method. Discrepancies in oxygen content are noted between neutron activation values (Boeing analyses) and inert gas fusion values determined from the Ti-6Al-4V ingot material by the vendor (table 5).

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*Microstructural Rating where 0 = alpha-beta worked microstructure and 20 = good transformed beta microstructure.

TABLE 4.–SUMMARY OF STRESS CORROSION RESISTANCE, K_{ISCC} (3.5 % NaCl) FOR Ti-6Al-4V EXTRUSIONS (MILL ANNEALED, CONDITION I)

Number of Extrusions Evaluated:	34
Number of Test Values:	77
Transverse Tests (59 tests)	K_{ISCC} (ksi√in)
Maximum	59
Minimum	20
Average	35
Std. Deviation	9.2
Longitudinal Tests (18 tests)	
Maximum	59
Minimum	34
Average	41
Std. Deviation	7.2
Directionality (ave. Difference, L minus T)	+ .9

The importance of accuracy in chemical analysis is also apparent from the data plotted in figures 3, 4 and 5. Here the K_{ISCC} values determined by test are adjusted (K_{ADJ}) to an oxygen content of 0.20 wt. % and then plotted versus aluminum, iron and vanadium. The lack of correlation shown by these curves can be explained by inaccuracies in chemical analysis. In addition, the scatter in data can also be attributed to a) inaccuracy of the oxygen coefficient used for adjusting K values, and b) ignoring correction factors for microstructure, texture, distribution of basal planes, prior beta grain size and degree of ordering of the alpha phase (Ti_3 Al).

The microstructural rating, MR, included in the equation for K_{ISCC} has a potential effect of causing the K_{ISCC} to vary 28 units (MR = 20). The highest MR rating determined in this study was 14 for specimen 7M-1. The corresponding microstructure is shown in figure 6. This microstructure is considered an example of good extruded transformed beta microstructure. Examples of the wide variations in microstructure associated with Ti-6Al-4V extrusions purchased to the same specification are shown in figures 7, 8 and 9. A particular microstructure type was not identified to a particular supplier and extrusions from individual suppliers were found to have extreme variations in microstructure.

Crystallographic texture also appeared to have a pronounced effect on stress corrosion resistance. Specimen 2M-1 of table 5 would be expected to yield a lower K_{ISCC} value of approximately 35 ksi√in. The texture of this specimen as denoted by a K_A* of -12 is less favorable for stress corrosion cracking than a high positive value. This is also demonstrated by specimen 6M-1 where a high K_A value of 141.9 is associated with a low K_{ISCC} value. However, since the microstructures and compositions of these two specimens are not identical, the correlation of texture and K_{ISCC} must be considered only qualitative. The limited

*K_A - Anisotrophy factor which measures the relative difference in basal plane orientation between the transverse and longitudinal grain directions (ref. 5).

TABLE 5.– SUMMARY OF FRACTURE, CHEMICAL AND METALLURGICAL DATA FOR SELECTED Ti-6Al-4V EXTRUSIONS

Specimen Number	Extrusion Shape (BAC No.)	Grain Direction	K_{ISCC} (ksi√in)	Oxygen (wt. %)		Al (wt. %)	MR*	Beta G.S.**	Primary Alpha %	Color Anodize***	Texture K_A	Fracture Appearance
				Boeing	Vendor							
2M-1	1670-50	T	41	.213	.190	6.3	10	.01		Dispersed	-12.0	Faceted
3M-2	1671-62	T	46	.154	.160	6.4	10	.01		Dispersed		Faceted
4M-2	1670-50	T	43	.182	.170	6.3	7	.005		Dispersed		Faceted
5M-2	1671-51	T	32	.212	.170	6.3	0		80%	Dispersed	58.5	Flat
6M-1	1671-51	T	21	.185	.180	6.2	0		80%	Banded	141.9	Flat
7M-1	1673-22	T	34	.194	.190	6.3	14	.005		Dispersed	-9.1	Faceted
8M-1	1671-26	T	44	.162	.160	6.2	7	.005		Dispersed	-8.1	Faceted
9M-1	1671-51	T	22	.194	.190	6.2	0		50%	Dispersed		Flat
10M-1	1671-51	T	22	.185	.180	6.3	0		70%	Banded		Flat
11M-1	1671-51	T	21	.218	.200	6.2	0		85%	Banded	92.9	Flat
12M-2	1671-51	T	21	.196	.190	6.2	0		50%	Dispersed	55.0	Flat
13M-1	1671-51	T	34	.205	.200	6.3	0		80%	Dispersed	77.0	Flat
15M-1	1670-48	T	34	.200	.180	6.3	8	.005		Dispersed		Faceted
FM 959-1	1671-50	T	44	.158	.170	6.6	9	.025		Dispersed		
FM 959-2	1671-50	T	43	.164	.170	6.6	9	.025		Dispersed		
FM 959-3	1671-62	T	48	.153	.160	6.4	10	.025		Dispersed		
FM 959-4	1671-62	L	46	.149	.160	6.4	8	.035		Dispersed		
FM 959-5	1671-62	L	49	.144	.160	6.4	8	.035		Dispersed		
FM 959-6	1671-62	L	35	.194	.190	6.4	6					
FM 962-2	1671-26	T	35	.176	.170	6.2	7					
FM 962-7	1671-26	T	31	.200	.190	6.5	6					
FM 962-9	1671-26	T	20	.195	.170	6.2	0					
FM 962-10	1671-26	T	21	.196	.140	6.0	8					

*Microstructural rating where 0 = bad and 20 = good

**Average grain size of prior beta grains

***Distribution of basil planes as shown by color anodize etching

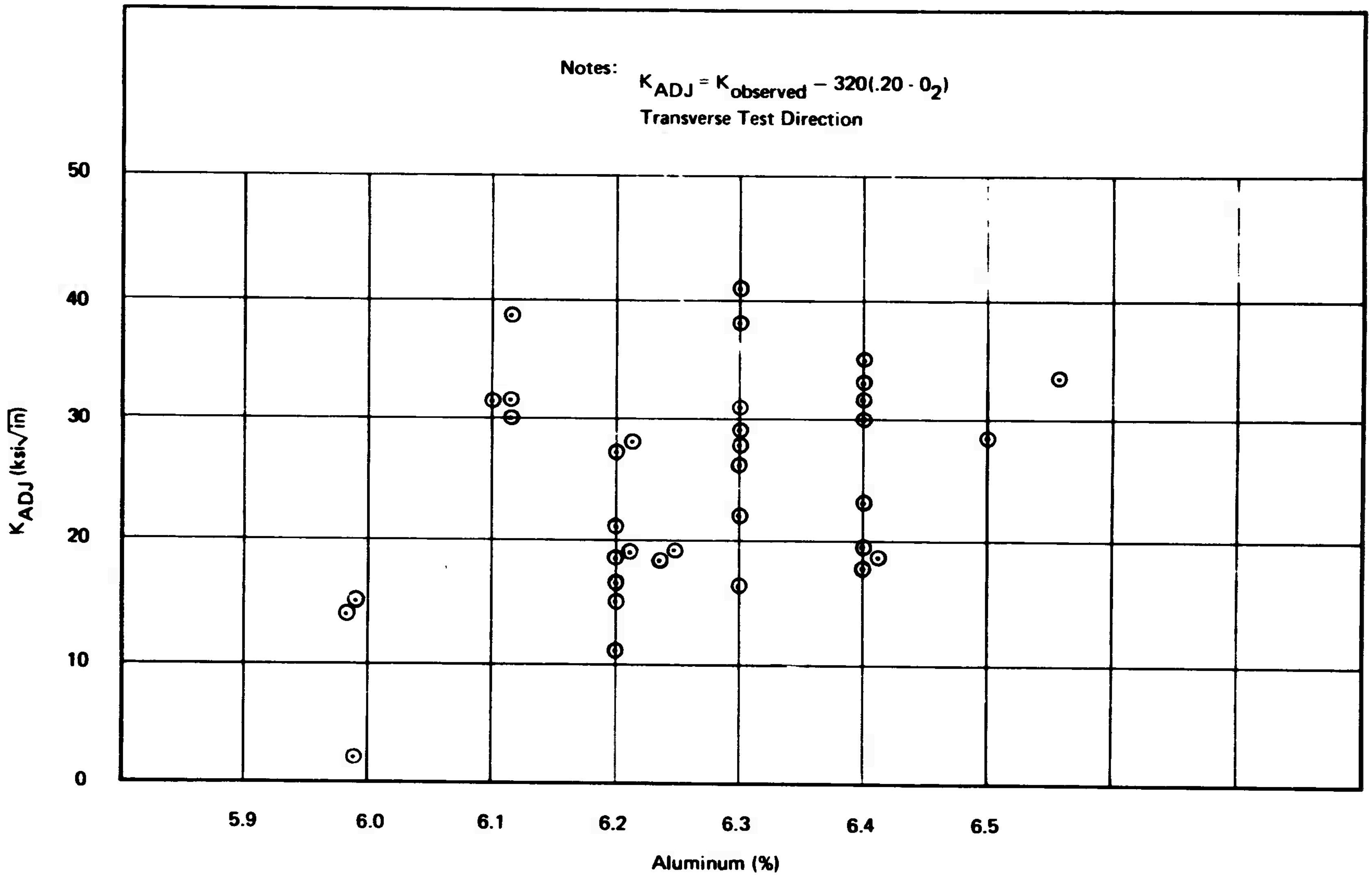


FIGURE 3.—LACK OF CORRELATION OF ALUMINUM CONTENT AND K_{ISCC} ADJUSTED FOR OXYGEN

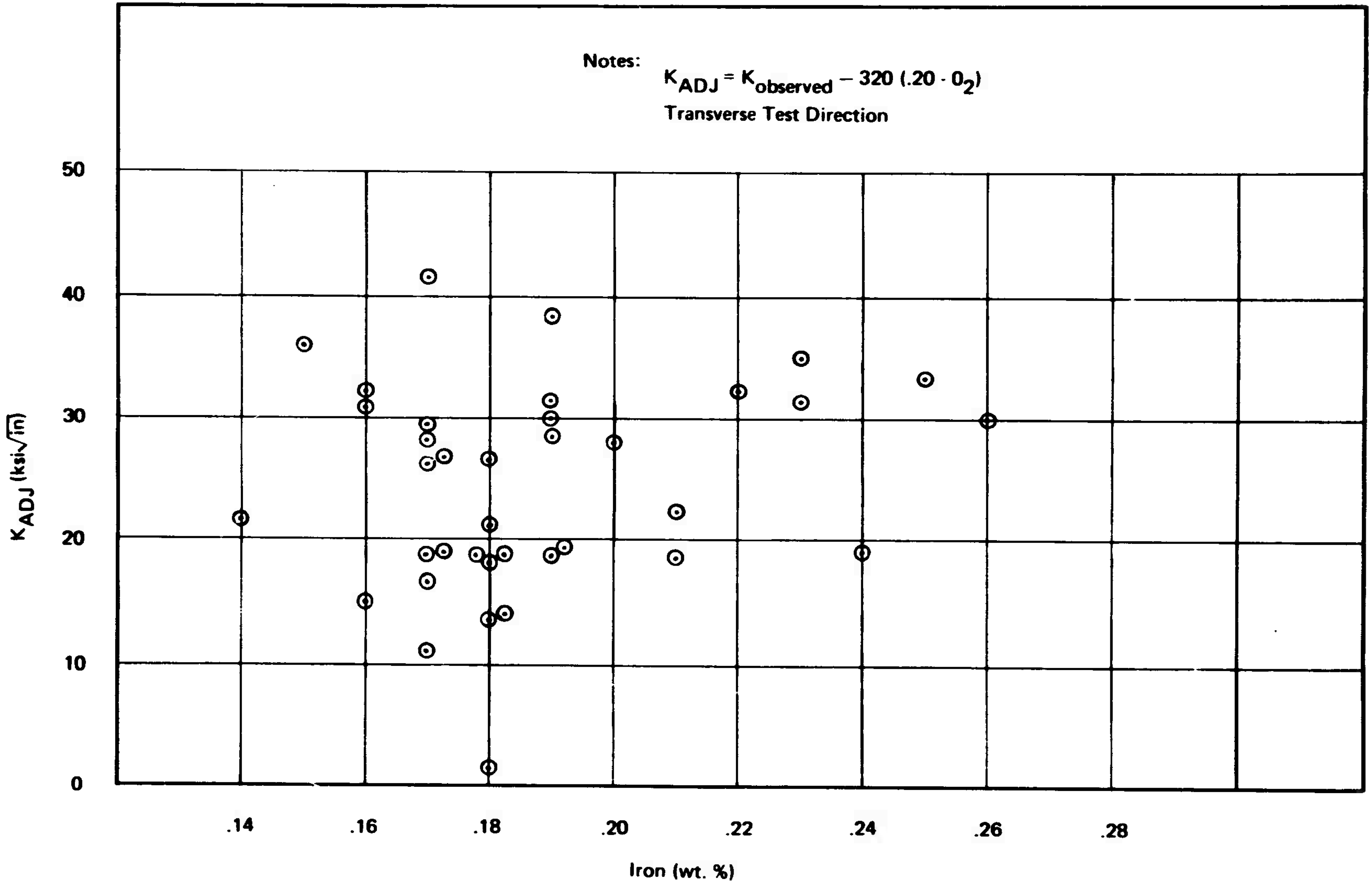


FIGURE 4.–LACK OF CORRELATION OF IRON CONTENT AND K_{ISCC} ADJUSTED FOR OXYGEN

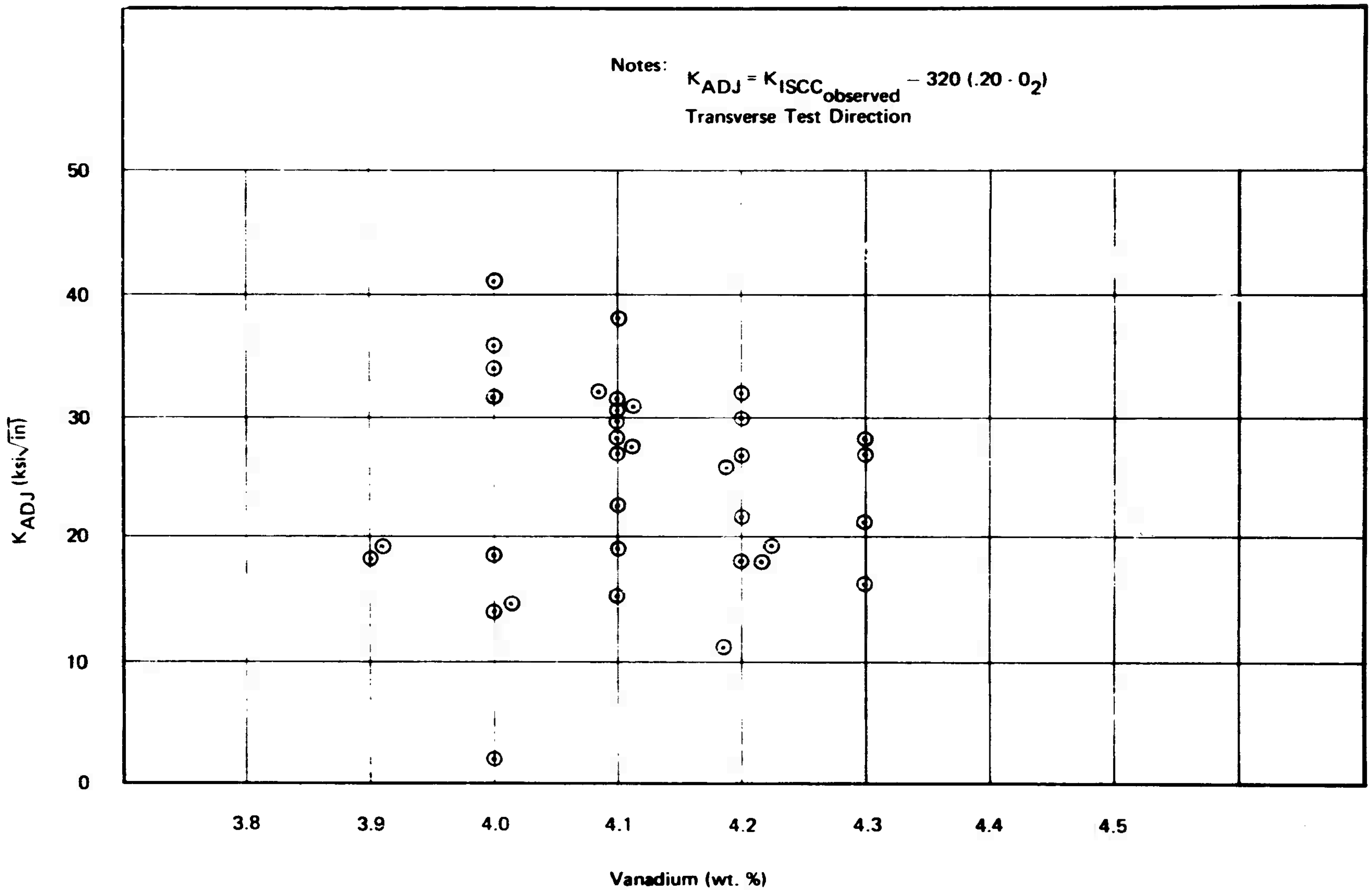
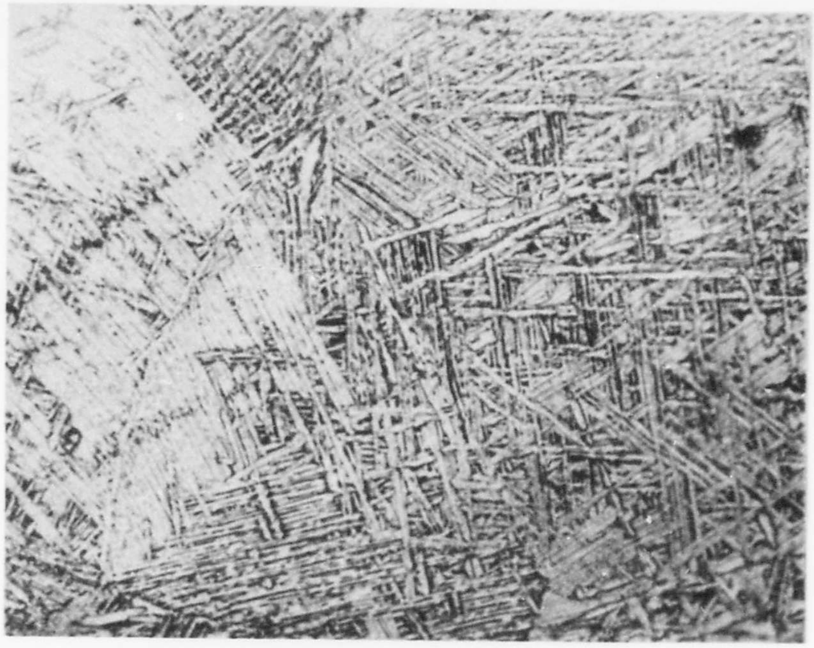
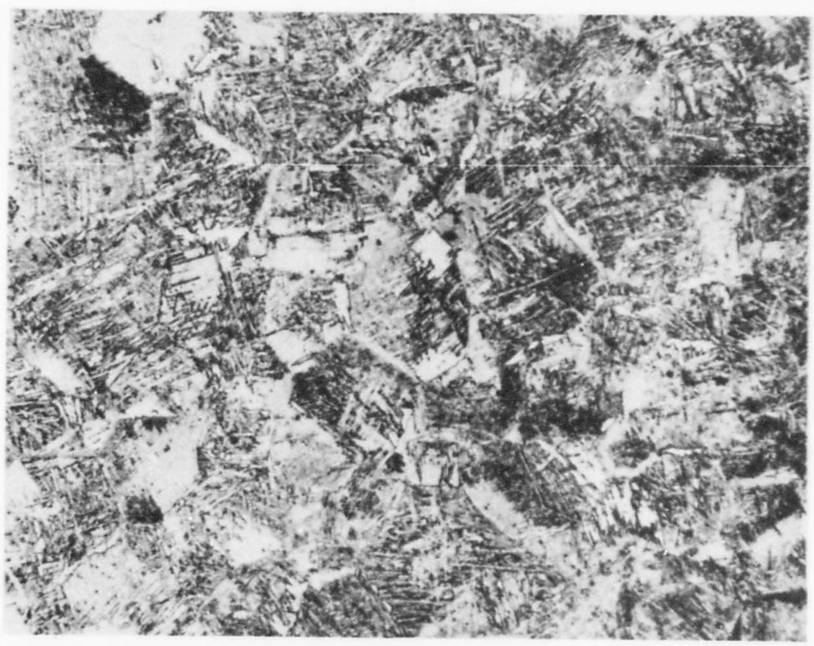


FIGURE 5.— LACK OF CORRELATION OF VANADIUM CONTENT AND K_{ISCC} ADJUSTED FOR OXYGEN



500X



100X

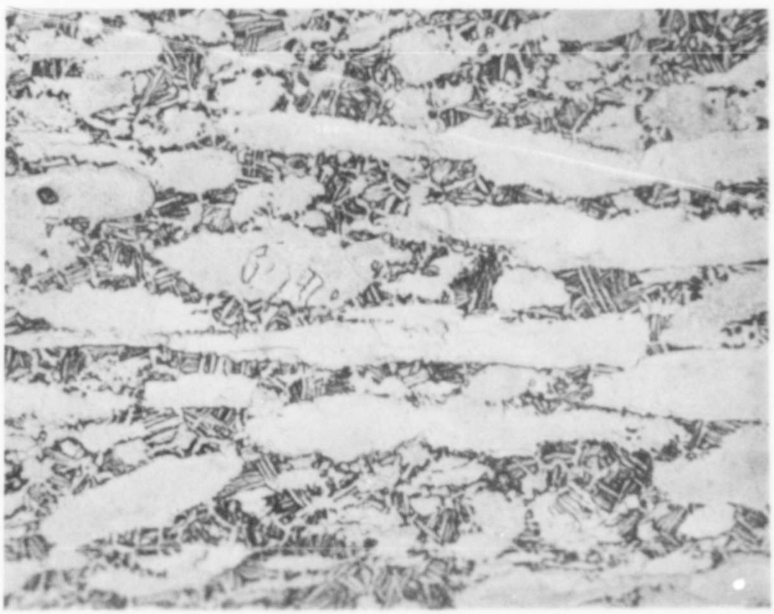
Extrusion No. BAC 1673-22
Specimen No. 7M-1

Etchant Kroll's
MR = 14

FIGURE 6.–EXAMPLE OF EXTRUDED TRANSFORMED BETA MICROSTRUCTURE FOR Ti-6Al-4V

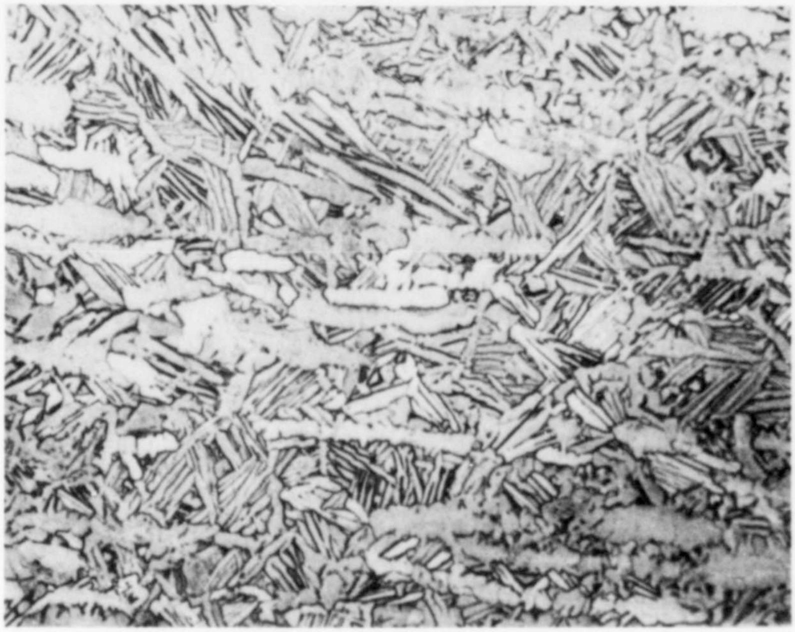
500X

FIGURE 7.—EXAMPLE OF AS-RECEIVED EXTRUSION MICROSTRUCTURE, Ti-6Al-4V ANNEALED, SPECIMEN 2103-4-1 (MR = 0)



500X

FIGURE 8.—EXAMPLE OF AS-RECEIVED EXTRUSION MICROSTRUCTURE, Ti-6Al-4V ANNEALED, SPECIMEN 2103-2-1 (MR = 0)



500X

FIGURE 9.—SPECIMEN 6M-1, ANNEALED Ti-6Al-4V EXTRUSION MICROSTRUCTURE, AS-RECEIVED (MR = 0)

quantity of extrusion data precluded a more quantitative analysis. A regression analysis including texture was conducted for SST Ti-6Al-4V sheet (ref. 6) and texture was determined to be a major factor affecting stress corrosion resistance.

Three pole figures demonstrating typical variations in texture for Ti-6Al-4V extrusions are shown in figures 10, 11 and 12. K_A values for these pole figures are listed in the figures.

6.2.2 Fracture Toughness K_{IE}

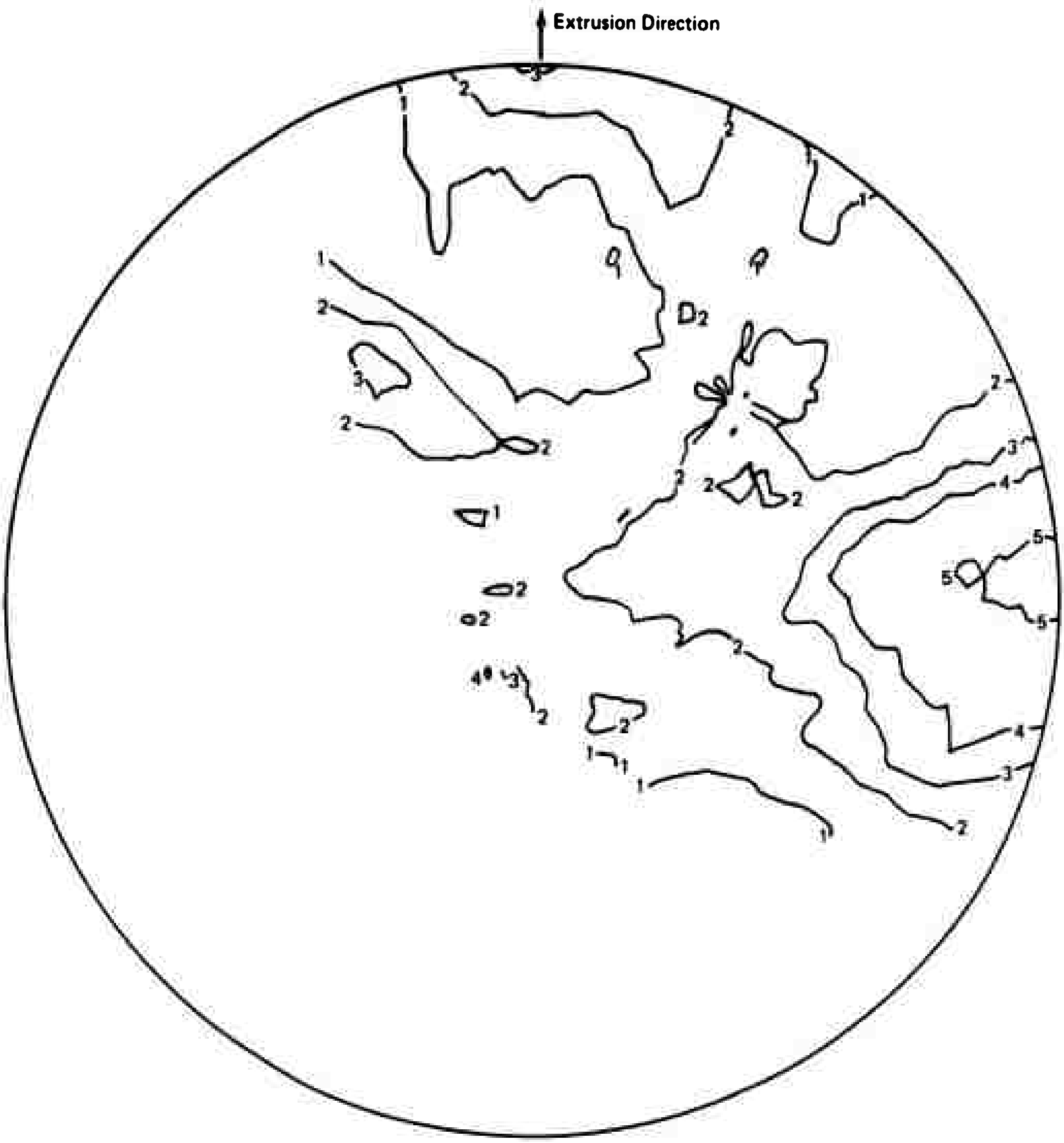
Fracture toughness values, K_{IE}, were determined for two Ti-6Al-4V extrusions heat treated to the annealed, STA and STOA conditions. The data along with K_{ISCC} values and average tensile properties are listed in table 6. K_{IE} values varied with heat treatment strength level in that the higher strength STA conditions had lower fracture roughness. The transverse grain direction had slightly higher toughness characteristics than did the longitudinal direction. The tee extrusion with an average oxygen content of .12 wt. % had also slightly higher average fracture toughness than the angle extrusion with a higher oxygen content (.175 wt. %). Both extrusion microstructures were the fully transformed beta type (basketweave) with the tee extrusion microstructure being slightly coarser.

The small quantity of extrusions tested for K_{IE} was not sufficient for a quantitative analysis of the various metallurgical factors affecting fracture toughness. However, the major variables of composition, texture and microstructure that influence K_{ISCC} would be expected to have similar effects on K_{IE}. Failure modes for both K_{IE} and K_{ISCC} have similar characteristics.

Contour Lines	1	2	3	4	5	6
Times Random Intensity	0.5	1.0	1.5	2.0	4.0	8.0

$K_A = -12$

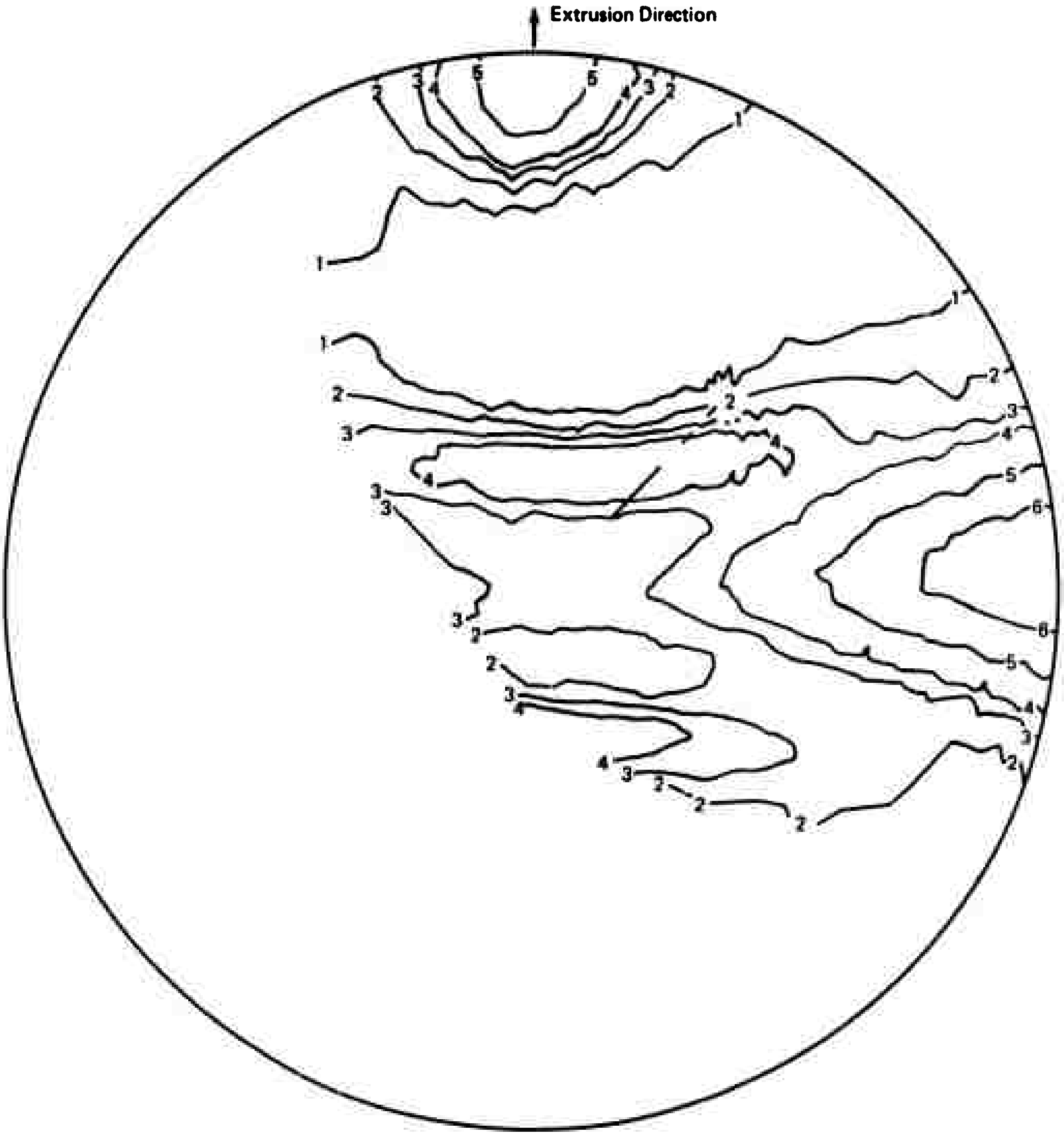
FIGURE 10.—POLE FIGURE FOR SPECIMEN 2M-1, ANNEALED Ti-6Al-4V EXTRUSION BAC 1670-50



Contour Lines	1	2	3	4	5	6
Times Random Intensity	0.5	1.0	1.5	2.0	4.0	8.0

$K_A = 55$

FIGURE 11.—POLE FIGURE FOR SPECIMEN 12M-2, ANNEALED Ti-6Al-4V EXTRUSION BAC 1671-51



Contour Lines	1	2	3	4	5	6
Times Random Intensity	0.5	1.0	1.5	2.0	4.0	8.0

$K_A = 141.8$

FIGURE 12.—POLE FIGURE FOR SPECIMEN 6M-1, ANNEALED Ti-6Al-4V EXTRUSION BAC 1671-51

TABLE 6.–EXTRUSION FRACTURE DATA FOR Ti-6Al-4V

Extrusion Shape	Heat Treatment	Grain Direction	K_{IE} (ksi $\sqrt{in}$)	K_{ISCC} (ksi $\sqrt{in}$)	Tensile Properties*			
					UTS (ksi)	TYS (ksi)	Elong (%)	RA (%)
Tee (P-241-1)	Annealed	L	88.4	65	139.1	121.2	14.2	33.5
			86.9					
			93.5					
		T	95.8					
			92.8					
			93.5					
	STA	L	59.5	46	163.5	146.9	10.2	26.2
			66.4					
			71.5					
		T	76.8					
			69.0					
			73.5					
	STOA	L	74.9	60	154.4	139.4	12.0	28.7
			75.7					
			82.8					
		T	81.2					
			80.0					
			82.3					
Angle (P-241-3)	Annealed	L	83.5	73	141.8	128.9	14.5	31.2
			84.3					
			82.2					
	STA	L	72.2	51	160.0	145.7	10.2	22.2
			68.3					
			61.2					
	STOA	L	74.8	70	151.1	140.3	12.2	28.5
			69.8					
			70.1					

*Average longitudinal properties (4 tests)

6.3 FATIGUE CHARACTERISTICS

The notched fatigue characteristics of Ti-6Al-4V extrusions heat treated to various strength levels are shown in figures 13 and 14. The data for the three strength levels of each extrusion are plotted as log averages to allow a comparison between heat treatments. No major differences in fatigue characteristics were demonstrated. Differences in strength level or extrusion heat-lot did not appear to influence notched fatigue life. These fatigue data are comparable to those generated for beta forged and alpha-beta forged Ti-6Al-4V bar (ref. 7).

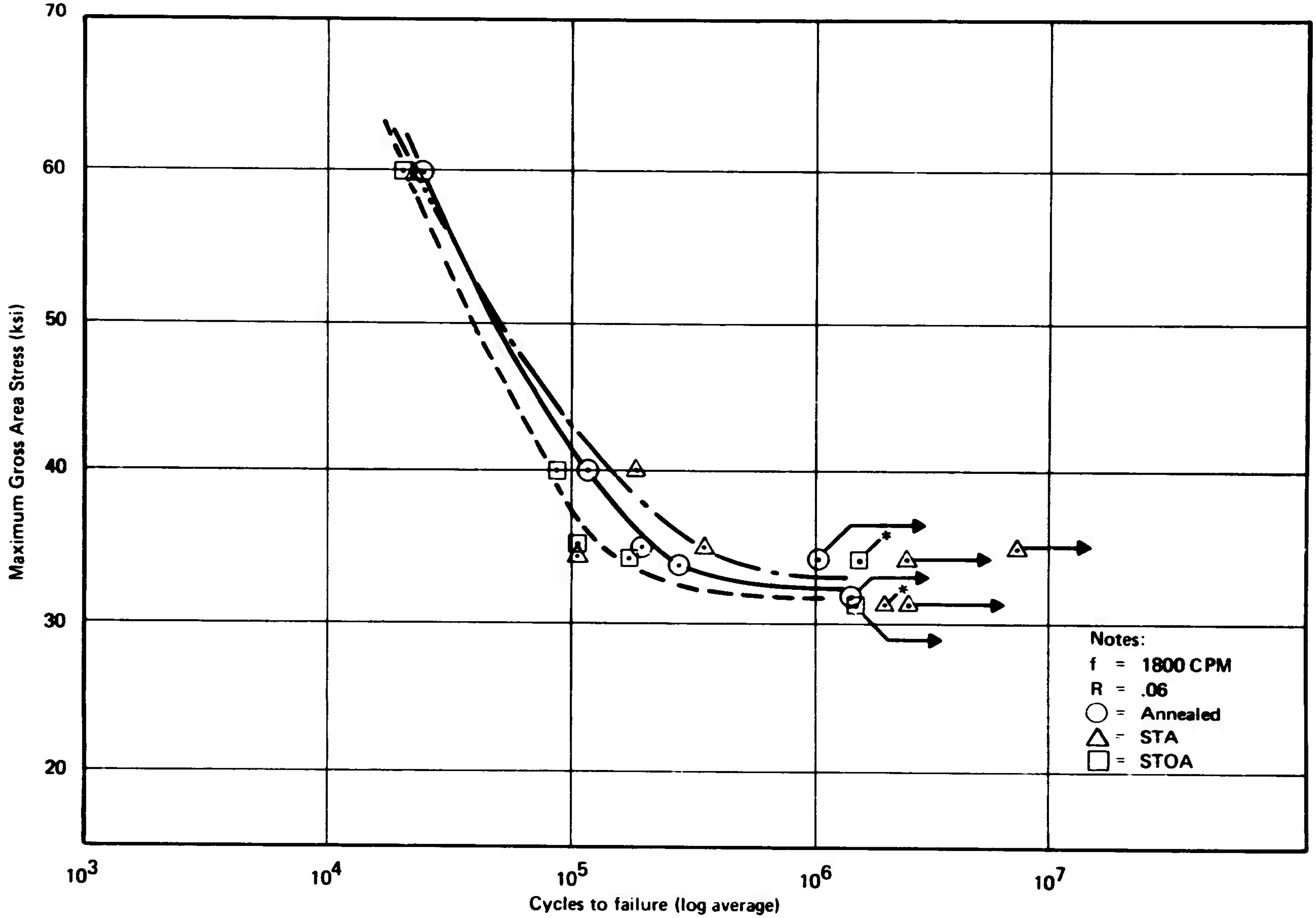


FIGURE 13.—NOTCH FATIGUE CHARACTERISTICS (K_T = 2.58) OF Ti-6Al-4V TEE EXTRUSIONS

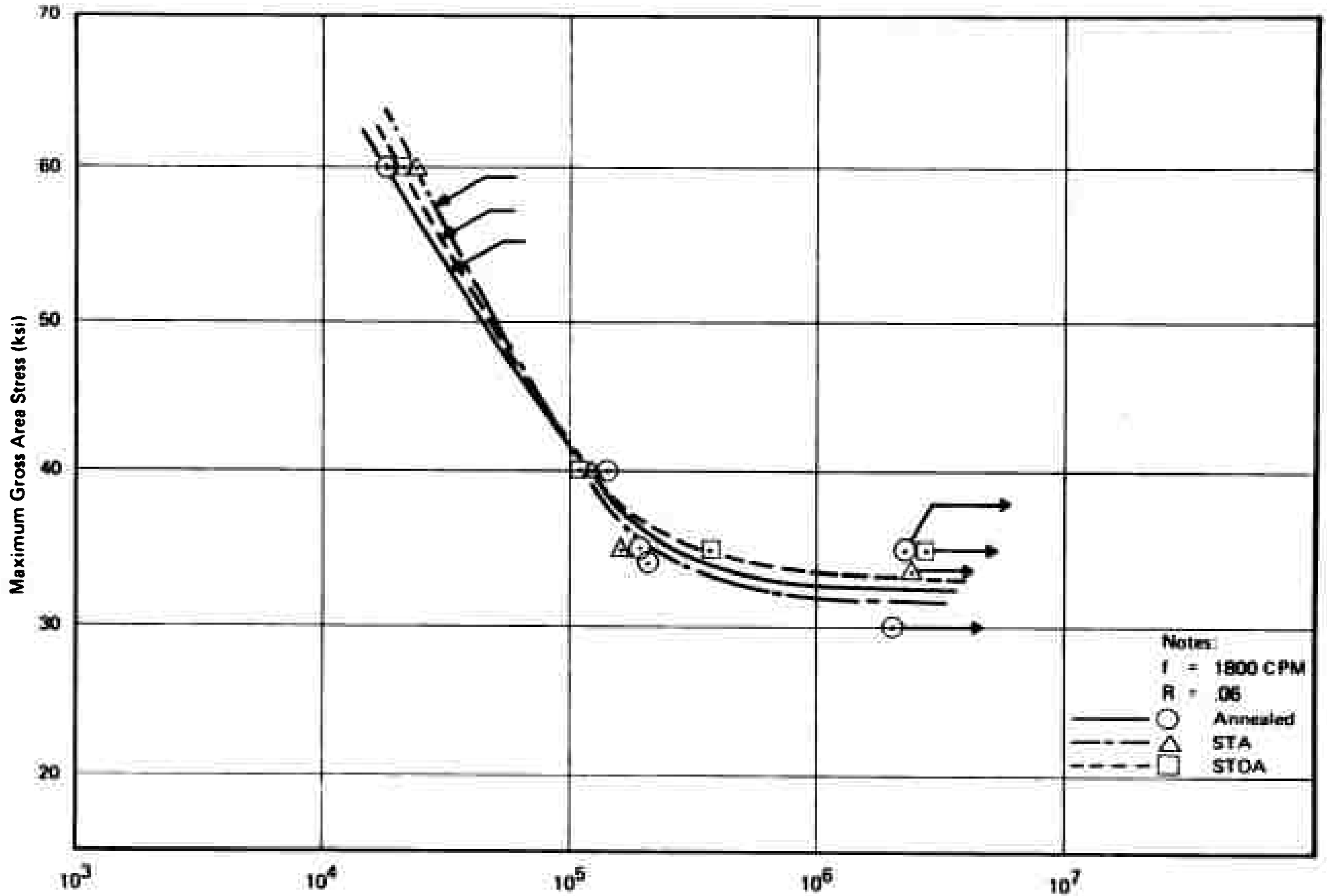


FIGURE 14.--NOTCH FATIGUE CHARACTERISTICS OF Ti-6Al-4V ANGLE EXTRUSIONS

7.0 CONCLUSIONS

The characterization of SST prototype Ti-6Al-4V extrusions has led to the following general conclusions:

- Ti-6Al-4V extrusions procured for the SST prototype are characterized by wide variations in chemical composition, microstructure, crystallographic texture, and mechanical and fracture properties. Stress corrosion resistance as measured by K_{ISCC} values is the property most affected by variations in microstructure, texture and oxygen content.

- The average tension and compression moduli of annealed SST Ti-6Al-4V extrusions are higher than those reported by state-of-the-art handbooks for Ti-6Al-4V mill products.

- The notched fatigue characteristics ($K_t = 2.58$) for extruded Ti-6Al-4V heat treated to various strengths are nearly identical to those of SST beta processed Ti-6Al-4V bar and forging.

- The design properties of Ti-6Al-4V extrusions, particularly fracture toughness and K_{ISCC}, can be greatly improved by more stringent controls on composition, microstructure and crystallographic texture.

8.0 RECOMMENDATIONS

The extrusion technology developed by the SST prototype program leads to additional technical questions to be answered by further work. Some answers can be found in the greater developed technologies of Ti-6Al-4V sheet, plate or bar and forgings. Additional extrusion data was generated concurrently by further testing also covered by Phase I of the SST Follow-On Program. This further work, reported in the associated DOT report, FAA-SS-72-13 (ref. 8), was conducted to supplement the data described in this report such that a more quantitative analysis could be implemented. The tests on additional extrusions included mechanical, fracture toughness, stress corrosion, metallurgical characterization and regression analyses. The Phase II effort consists of incorporating the advanced extrusion technology generated in Phase I into a new extrusion specification and the verification testing of extrusions procured to the new specification. The following areas of future work are recommended:

- The data summarized by this report should be combined with other similar data and further computer analyses be conducted such that the effects of variations material composition and mill processing are further delineated. The effects of the accuracy of chemical analysis on the regression analysis should be included in the evaluation.

- A greater quantity of extrusions should be evaluated for plane stress fracture toughness to better characterize extrusions and to determine the major factors governing K_{IC} variations.

- Practical controls on microstructure, composition and texture in conjunction with consistant mill processing should be developed and incorporated into an industry material specification. These specification controls would minimize property variations and markedly improve extrusion fracture characteristics.

APPENDIX A

BOEING MATERIAL SPECIFICATION
BMS 7-44C

TITANIUM 6Al-4V EXTRUDED AND ROLLED STRUCTURAL SHAPES

[redacted]

1. SCOPE

This specification covers Titanium -6 Aluminum -4 Vanadium alloy extruded and hot rolled structural shapes.

This specification requires qualified products.

2. REFERENCES

Except where a specific issue is indicated, the issue of the following references 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-146, Hot Extraction of Hydrogen

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

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

f. BAC 5439, Ultrasonic Inspection

3. CLASSES AND CONDITIONS

Condition I	-	Mill Annealed
Condition III	-	Solution Treated and Aged at 1000F
Condition IV	-	Solution Treated and Aged at 1250F

4. FORMS

Extruded or rolled structural shapes.

5. MATERIAL REQUIREMENTS

5.1 FABRICATION PRACTICES

Material shall be produced by multiple melting technique using consumable electrode practice. At least one melting stage shall be conducted in vacuum. One stage may be melted in an inert gas atmosphere.

R

5.2 **CHEMICAL COMPOSITION**

For method of determination and limits, see Section 8.1.

Element	Composition (Weight Percent)	
	Minimum	Maximum
Aluminum	5.5	6.75
Vanadium	3.5	4.5
Iron	---	0.30
Carbon	---	0.10
Nitrogen	---	0.03
Hydrogen	---	0.0125 [2]
Oxygen	---	0.20
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.

5.3 **HEAT TREAT CONDITION**

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

Condition	Heat Treatment	Time and Temperature
I	Mill Anneal	1300 ± 25F for two (2) hours and air cool.
III	Solution Treatment and age at 1000F	1725F ± 25F* for nominally 1 hour and water quench, 1000F ± 25F for four (4) hours and air cool.
IV	Solution Treatment and age at 1250F	1725 ± 25F* for nominally 1 hour and water quench, 1250F ± 25F for four (4) hours and air cool.

*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 (smallest dimension). Define section 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.

b. Mechanical deformation or straightening after final heat treatment is not allowed unless one of the following conditions is met:

(1) The straightening is done at 1100F to 1450F for Condition I material, or at the designated aging temperature for Condition III or Condition IV material.

(2) Partial aging, straightening at the designated aging temperature for Condition III or Condition IV material, and completion of aging cycle. Completion of the aging cycle may be done during hot stretching.

(3) Straightening at a temperature below the annealing temperature for Condition I material, or below the designated aging temperature for Condition III or Condition IV material, followed by a stress relief at 1000F for one hour following the straightening operation.

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.

5.4 **MECHANICAL PROPERTIES**

The room temperature mechanical properties, as determined by the methods in Section 8.2.1, shall meet the requirements in Table I.

TABLE I

MECHANICAL PROPERTIES

CONDITION	THICKNESSES (INCHES)	F_{tu} Minimum (psi)	F_{ty} Minimum 0.2% Offset (psi)	Elongation, Minimum (Percent) [2]	F_{cy} Minimum 0.2% Offset (psi) [3]
I [1]	.188	135,000	125,000	10.0	128,000
III	0.188 - 0.500 0.501 - 0.750 0.751 - 1.000 1.001 - 2.000 Over 2.000	160,000 155,000 150,000 140,000 130,000	145,000 140,000 135,000 130,000 120,000	7.0 7.0 6.0 6.0 6.0	160,000 155,000 150,000 140,000 130,000
IV	0.188 - 0.750 0.751 - 1.000 Over 1.000	144,000 130,000 130,000	130,000 120,000 120,000	10.0 9.0 9.0	140,000 130,000 128,000

[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 5.3. For circumscribing circles larger than 9" minimum F_{tu} is 130,000 psi and minimum F_{ty} is 120,000 psi.

[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 a one inch gage length.

5.5 SURFACE CONDITION

The surfaces shall be descaled or pickled. 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.

5.6 QUALITY AND UNIFORMITY

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.

All extrusions thicker than 0.250 inch shall be capable of meeting Class A ultrasonic inspection requirements of BAC 5439 (Type II inspection).

5.7 DIMENSIONAL TOLERANCES

Unless otherwise specified, the following tolerances apply.

5.7.1 CROSS SECTIONAL DIMENSIONS

TOLERANCE (inch)

ORDERED DIMENSION	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

5.7.2 LENGTH

TOLERANCE (inch)

LENGTH	OVER	UNDER
Up to 12 feet Inclusive	0.25	0
Lengths over 12 feet	0.50	0

5.7.3 CORNER AND FILLER RADII

TOLERANCE (inch)

RADII	Cross-Section Area 5 Sq. In.	Cross-Section Area 5 Sq. In.
Fillet	± .062	± .375
Corner	± .050	± .125

5.7.4 ANGLES

Angles shall be ± 2 degrees.

5.7.5 STRAIGHTNESS

Deviation of any edge from a flat surface shall not exceed 0.125 inch in any 5-foot length when the weight of the part is used to minimize the bow.

5.7.6 TWIST

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

5.7.7 TRANSVERSE FLATNESS

Deviation from flat shall not exceed 0.010 inch per inch of width.

6. QUALIFICATION

a. All requests for qualification shall be directed to a Materiel Department of The Boeing Company, which will request data and samples when desired for qualification purposes.

b. Data shall be submitted by a supplier desiring qualification, indicating compliance with the requirements of this specification for the following categories:

(1) Condition I

(2) Condition III

(3) Condition IV

c. Test data must show conformance with Section 5.4 specifically. In addition, it will be necessary to demonstrate that the supplier can supply extrusions sufficiently free of residual stresses that extrusions will not warp during machining to greater than the raw material tolerances given in Section 5.7.4., 5.7.5., 5.7.6., and 5.7.7. When this is demonstrated for extrusions supplied in Condition III, the supplier will be qualified for extrusions in all conditions up to the cross section of the extrusion supplied for qualification. When this is demonstrated for extrusions supplied in Condition IV, the supplier will be qualified for extrusions in Conditions IV and I only, up to the cross section of the extrusion supplied for qualification. When this is demonstrated for extrusions supplied in Condition I, the supplier will be qualified for extrusions in Condition I only, up to the cross section of the extrusion supplied for qualification.

d. After review of supplier data or Boeing tests, the supplier will be advised as to whether product approval has been granted. Products which qualify will be listed in BMS 7-44.

e. No changes in raw material or methods of manufacturing shall be made without notification and prior written approval. Requalification of the revised material may be required, and a revised supplier designation may be requested. Qualified products will be listed in the BMS Qualified Products List.

7. QUALITY CONTROL

7.1 SUPPLIER QUALITY CONTROL

The supplier shall maintain an internal quality control system verifying product integrity and maintaining records of the test reports required by Section 7.1. These records shall be made available to authorized representatives of The Boeing Company upon request. Unless otherwise specified, the supplier shall furnish to The Boeing Company three copies of actual test data showing conformance to Sections 5.2 and 5.4, with each lot* of material. The report shall include:

a. Purchase order number.

b. Drawing number.

c. Material specification number.

d. Lot number

e. Heat number of material

f. Quantity

g. Mechanical properties

h. Chemical analysis

* 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.

7.2 **PURCHASER QUALITY CONTROL**

The purchaser's quality control organization shall perform tests and inspections as needed to verify conformance to the requirements of this specification. Complete records shall be maintained by the Quality Control Department.

8. MATERIAL TEST METHODS

8.1 **CHEMICAL 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. Limits for check analysis shall be according to AMS 2249. 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 Boeing Quality Control Department. Analysis for oxygen content conducted at The Boeing Company shall be performed by the Neutron Activation Analysis technique.

8.2 MECHANICAL TESTING

8.2.1 TENSILE TESTING

a. The following tensile specimens per ASTM E8 shall be used.

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

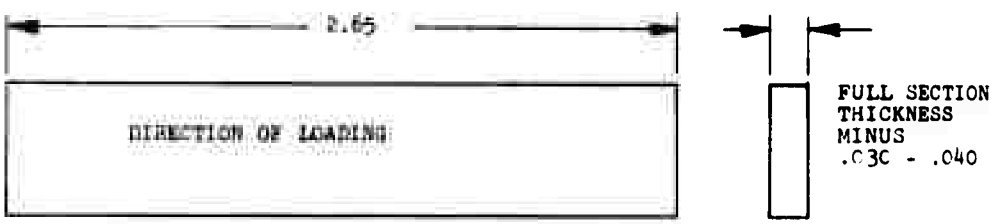
   (2) Material thickness greater than .375 inch - Figure 9, .250 inch diameter.

   (3) When thickness permits, Figure 9,.500 inch diameter may be used.

b. 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. 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 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 will be prepared from each of three lengths selected at random.

8.2.2 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 1. 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 1

R

9. IDENTIFICATION

Unless otherwise specified, each shape shall be continuously marked with the material specification number, revision letter, the condition, heat number, lot number, the supplier's identification, and drawing number. The characters shall be not less than 3/8 inch in height, shall be applied using a suitable marking fluid, having a color which contrasts with the color of the surface of the shape and is easily legible. The identification shall be capable of being removed in hot alkaline cleaning solution without rubbing. The markings shall have no deleterious effect on the material or its performance. The characters shall be sufficiently durable to withstand normal handling. Esterbrook (Cado) Flo-Master Ink or an equivalent halogen-free marking ink is recommended. Metal stamping may be used on one end.

10. PACKAGING AND MARKING

a. When packaged, the packaging shall be adequate to assure safe delivery.

b. When packaged, each container shall be durably and legibly marked with drawing number, specification number, purchase order number, lot number, quantity, and supplier's identification.

APPENDIX B
DETAILED TEST PROCEDURES

B.1 FRACTURE TOUGHNESS

Notched bend specimens of the configurations shown in figures B-1 and B-2 were used to determine fracture toughness, K_{IC}. The specimen thickness was usually limited to the thickness of 0.480 inches since the majority of the Ti-6Al-4V plate data was generated at this gage in the past years. This thickness was also very convenient since 0.500 inch material was usually used as a standard for evaluating affects of preferred orientation, heat treatment and compositional variables. Also 0.500 inch maximum thick material was close to covering most of the thick section applications on the SST. It is realized that 0.480 inch does not satisfy the ASTM requirements of $t > 2.5(K_{IC})^2/TYS$ but it is useful to distinguish between near K_{IC} conditions (i.e., 0.480 inch) and clearly mixed mode conditions (K_C) for gages such as 0.050 inch. Hence, fracture toughness values obtained using this test have previously been called K_{IC} internally at Boeing. However, to avoid confusion over validity this property will not be called K_{IC} in this report but will arbitrarily be called K_{IE}.

Figure B-3 shows the standard four-point loaded notched bend specimen and related formulae and figure B-4 shows the notch orientation code. The specimens were precracked by fatigue cycling in either a Sonntag SF-10-U fatigue machine with a cantelever bending fixture or in a Vibraphor resonant cycling fatigue machine with tensile loading. The fracture testing was conducted in tensile testing machines at room temperature in air. The gross area bending stress rate applied to the specimen was 1000 psi/sec. Load deflection curves were taken for each specimen with the load P_5 (5% secant load) used for the calculation of the fracture toughness value K_{IE}.

B.2 STRESS CORROSION RESISTANCE, K_{ISCC}

Stress corrosion tests were conducted using the same specimen configurations used for fracture toughness and a sustained loading technique in the environment of 3½% NaCl aqueous solution. In general two approaches were developed involving either a series of specimens or only one or two specimens.

B.3 MULTI SPECIMEN APPROACH

Here several specimens, usually three to five were loaded to various K levels until failure or until a predetermined length of time whichever is shorter. The stress intensity level is plotted vs. time to failure and a curve is drawn to determine the threshold value at which no failure occurs. This value is defined as K_{ISCC} for relatively thick sections. The primary interest was to determine the threshold K level that a material will sustain in 3½% NaCl. Figure B-5 shows a plot of sustain load K vs. time and the resulting threshold value.

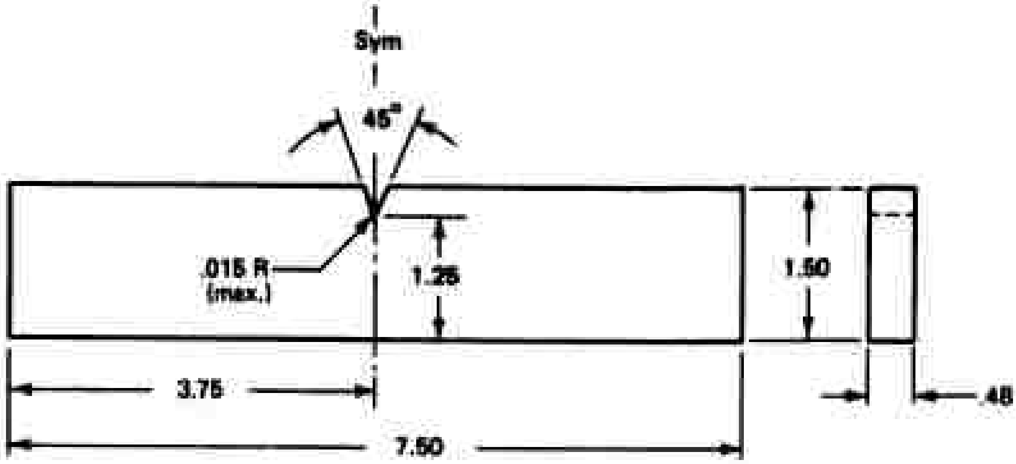


FIGURE B-1.—NOTCH BEND SPECIMEN

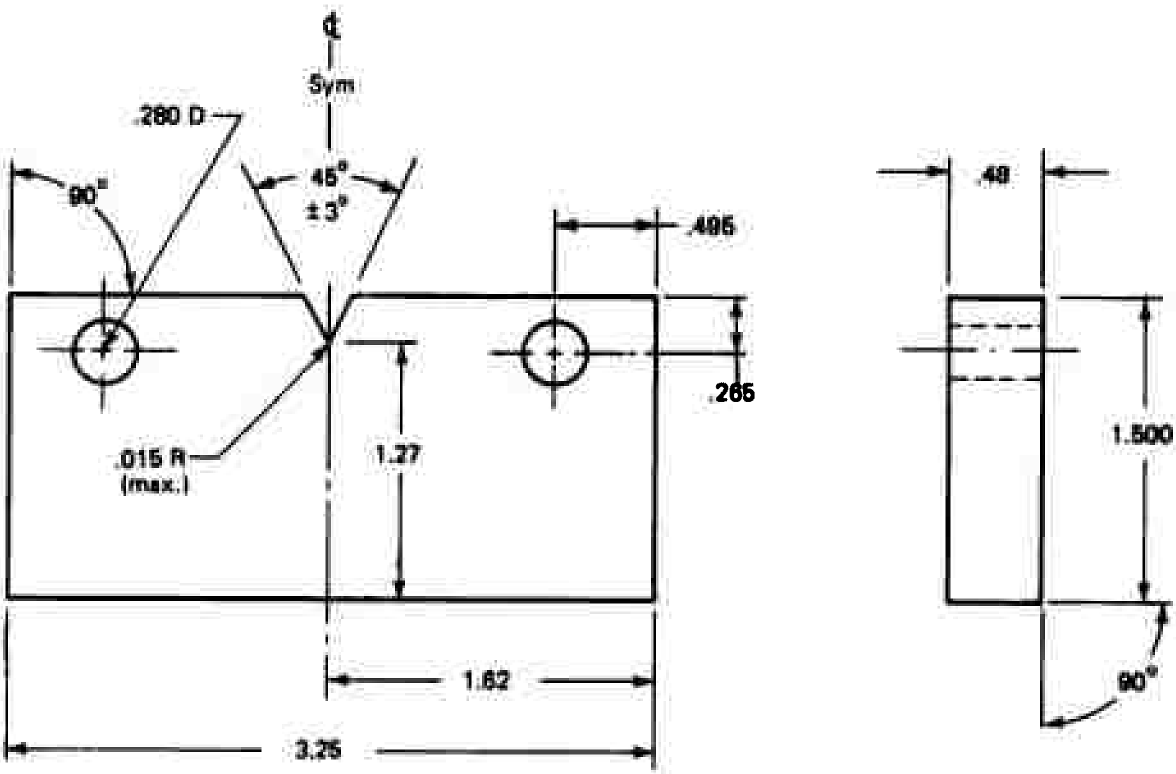


FIGURE B-2.—SHORT NOTCHED BEND SPECIMEN

FORMULAE

K_{IE}	=	$P_5 \alpha$ stress intensity factory (critical)
$K_I i$	=	$P\alpha$ stress intensity level (environmental)
α	=	$\frac{L}{BW^{3/2}} \left(\frac{1}{1-\mu^2}\right) \quad 34.7\frac{a}{W} - 55.2\left(\frac{a}{w}\right)^2 \; E \; 196\left(\frac{a}{w}\right)^3 \quad ^{1/2}$
P_5	=	Intersection of load-deflection curve and line drawn from origin with slope offset 5% from linear portion of load-deflection curve
P_{max}	=	Ultimate load
E	=	Modulus of elasticity (assumed = 16.0×10^3 ksi)
μ	=	Peisson's ratio (assumed = .33)
σN	=	Net area stress = $\frac{Mc}{I}$ where $M = L\frac{P_5}{2}$ and $I = \frac{B(W-a)^3}{12}$

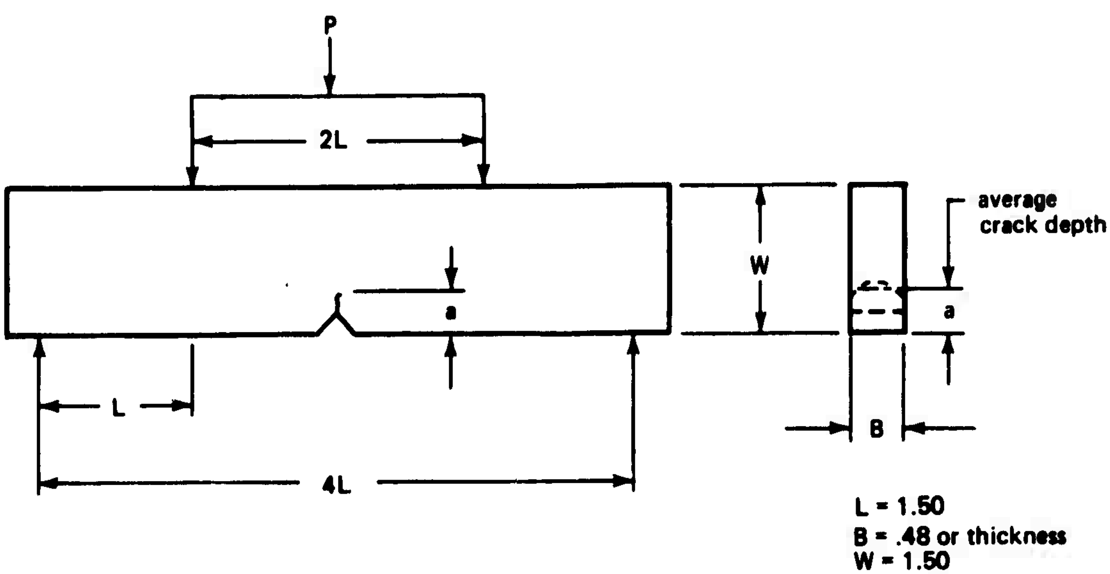
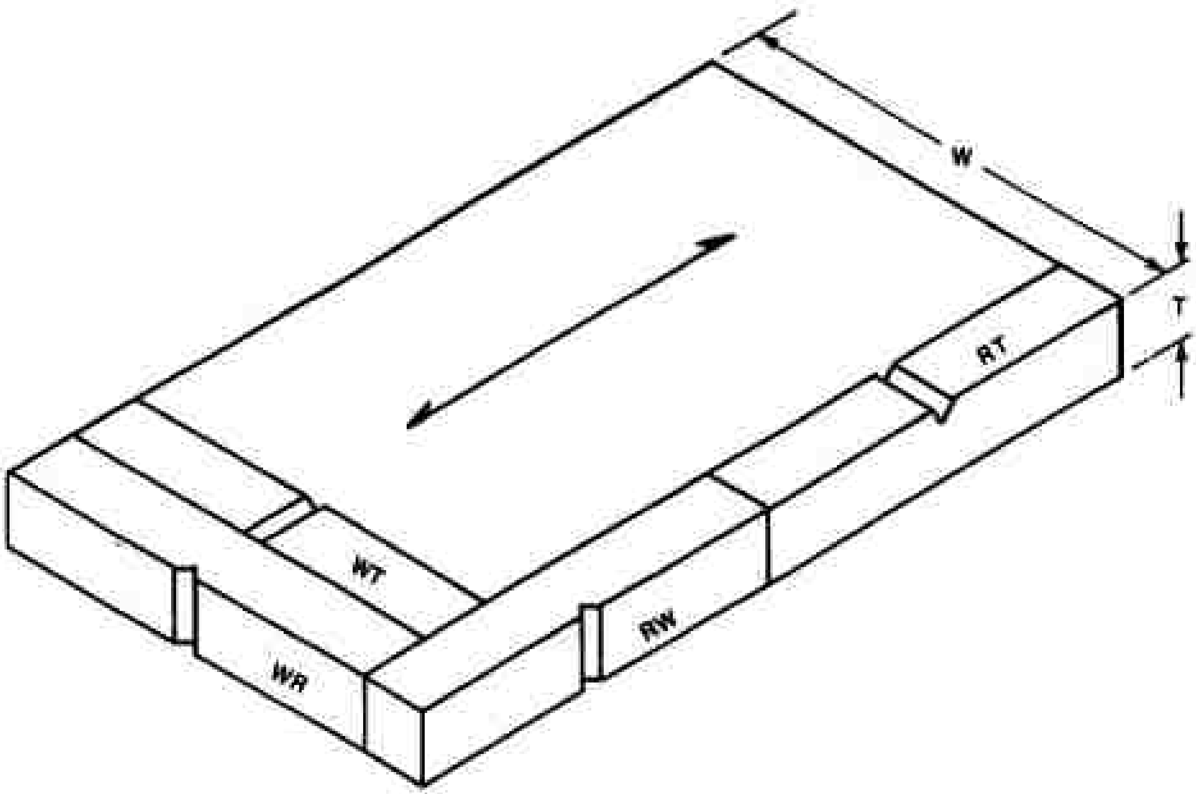


FIGURE B-3.—FOUR POINT LOADED NOTCHED BEND SPECIMEN FORMULAE



R = ROLLING DIRECTION
W = WIDTH
T = THICKNESS

FIGURE B-4.—GRAIN DIRECTION TEST CODES FOR NOTCHED BEND SPECIMENS

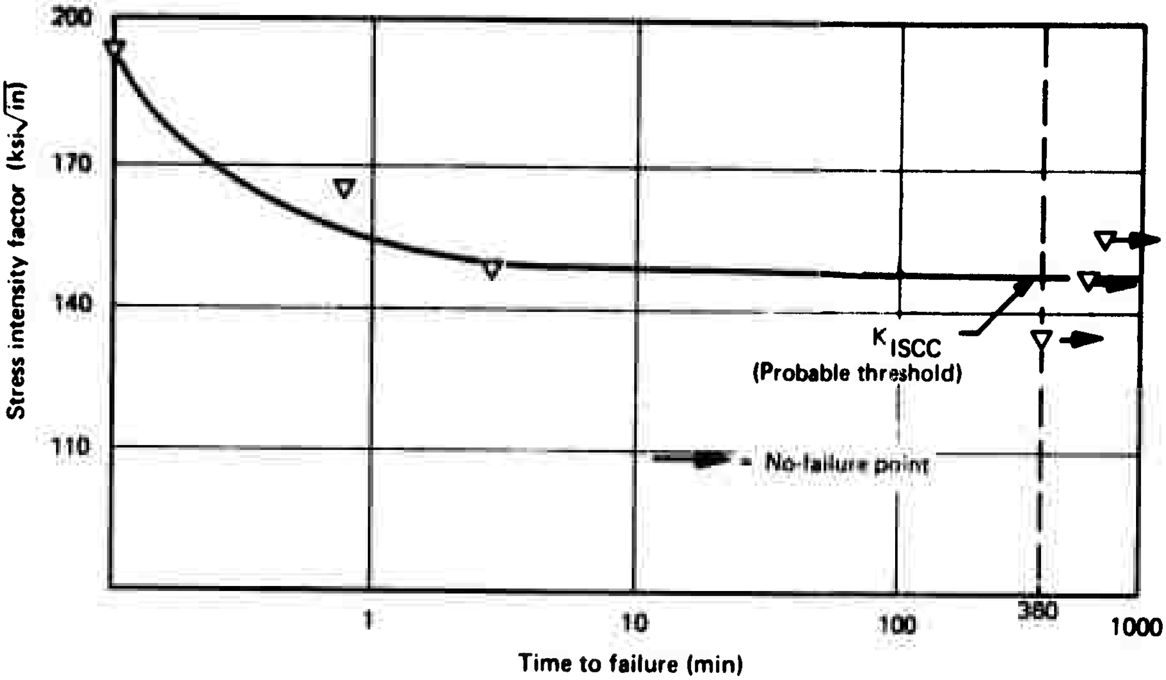


FIGURE B-5.—TYPICAL SUSTAINED-LOADING CHARACTERISTICS OF TITANIUM ALLOY Ti-6Al-4V IN SALT WATER

B.4 SINGLE SPECIMEN APPROACH

In order to conserve material or where material quantity was limited, single specimen procedure was used in many cases. Here one specimen is fatigue cracked and sustained loaded for a given length of time at a fairly low level. The level is pre-selected based on what the anticipated threshold K will be. After this first no failure, the specimen is re-fatigue cracked and reloaded at a higher K level. This process is repeated until failure occurs. The more accurately the threshold is known before the test, the smaller the spread will be between the highest no failure K and the failure K. This results in a more accurate estimation of the actual threshold.

The maximum number of tests conductable on a single specimen are related to the length the fatigue crack is grown between sustained loadings, the width of the specimen used and the specimen validity requirements. The specimens were refatigue cracked between sustained loadings to eliminate any chemical or electrochemical passivation effects at the crack tip as well as to eliminate plastic yield zone affects on the stress corrosion mechanism. Here the K level during fatigue cracking was kept at a lower level than the next sustained load. This prevented a large plastic yield zone which in some cases has inhibited stress corrosion cracking. Past experience has shown that when the fatigue K level is higher than the level used in the subsequent sustain load test, the "threshold" can be erroneously tested to be much higher than its true value. In order to insure no plastic zone affects the length of the fatigue crack was usually kept at a minimum of $1/2\pi \times [(K_{FATIGUE})^2/TYS]$ which is twice the amount generally accepted as the radius of the plastic yield zone. The number of refatigue cracking steps and hence the number of subsequent sustained loadings were restricted to keep the ratio of crack length to specimen width at generally approximately 0.33 for the notch bend specimens.

B.5 TIME TO FAILURE

For both the multi-specimen and single specimen procedures the standard time at which the specimens were held was 60 minutes. This was a departure from the procedures used in 1965 where 360 minutes was used as the no failure time cut-off limit. This was justified since 96% of the failed specimens failed before 60 minutes.

B.6 CALCULATION OF K_{SCC} OR K_{ISCC}

As mentioned previously the determination of the threshold K was accomplished by plotting time to failure vs. K level and drawing a smooth curve through the data just above or at the highest no failure K level. This curve is useful in showing the length of time to failure at K levels between K_{ISCC} and K_{IC} but this region is generally of little interest in evaluation materials for other than short term (0.1 min.) properties.

Most of the threshold values reported herein was determined using the highest no failure and lowest failure loads. Using the one specimen recracking approach there would be, of course, only one failure level. For example, if a specimen did not fail at a K of 40 but failed at a K of 50 an approach would be to simply call the threshold value 45 keeping in mind the accuracy would be ± 5 ksi√in. A refinement of this approach was used which considered the time the specimen took to fail at the failure level. If for example a specimen did not fail at 40 but failed at 50 in 59 minutes the actual threshold would be closer to 50 than 40. By analyzing the shape of many curves like that shown in figure B-5 a series of factors were developed to permit a refinement.

This approach is slightly non-conservative but it was considered more desirable to obtain the best possible estimate of the actual threshold in order to study the inter-relationship of such material parameters such as composision, heat treatment, texture, etc., rather than a conservatively biased approach using the highest no failure K level.

APPENDIX C
DETAILED FRACTURE TEST DATA

TABLE C-1.—DETAILED ANNEALED Ti-6Al-4V EXTRUSION DATA

Specimen Code	Vendor	Heat	Lot	BAC No.	Grain Direction	K_{ISCC} (ksi√in)	Mech Properties* UTS (ksi)	TYS (ksi)	Elong (%)	CYS (ksi)	O_2 (wt %)	Al (wt %)	V (wt %)	Fe (wt %)	K_{ADJ} (O_2=.2 wt %)
FM 959-1	HARVEY	BC 21	3113-3	1671-60	T	44	139.5	129.3	11	138.4	.17	6.58	4.07	.25	34
-2	HARVEY	BC 21	3113-3	1671-50	T	43	139.5	129.3	11	138.4	.17	6.58	4.07	.25	
-3	HARVEY	BC 39	3111-2	1671-62	T	48	143.5	132.8	10.3	136.4	.16	6.4	4.0	.23	35
-4	HARVEY	BC 39	3111-2	1671-62	L	46	143.5	132.8	10.3	136.4	.16	6.4	4.0	.23	
-5	HARVEY	BC 39	3111-2	1671-62	L	49	143.5	132.8	10.3	136.4	.16	6.4	4.0	.23	
-6	TMCA	K6363	E1332	1670-46	L	35	145.6	129.4	16	142.9	.19	6.40	4.1	.22	33
1M-1	TMCA	K4886	E1296	1670-48	T	41	140.4	126.5	16	134.5	.18	6.1	4.2	.16	32
-2	TMCA	K4886	E1296	1670-48	T	35	140.4	126.5	16	134.5	.18	6.1	4.2	.16	
-3	TMCA	K4886	E1296	1670-48	L	37	140.4	126.5	16	134.5	.18	6.1	4.2	.16	
-4	TMCA	K4886	E1296	1670-48	L	38	140.4	126.5	16	134.5	.18	6.1	4.2	.16	
2M-1	TMCA	K6417	E1324	1670-50	T	41	142.1	129.7	16	140.3	.19	6.3	4.0	.15	36
-2	TMCA	K6417	E1324	1670-50	T	34	142.1	129.7	16	140.3	.19	6.3	4.0	.15	
-3	TMCA	K6417	E1324	1670-50	L	35	142.1	129.7	16	140.3	.19	6.3	4.0	.15	
-4	TMCA	K6417	E1324	1670-50	L	35	142.1	129.7	16	140.3	.19	6.3	4.0	.15	
3M-1	HARVEY	BC 39	3111-2	1671-62	T	44	143.5	132.8	10.7	136.4	.16	6.4	4.0	.23	32
-2	HARVEY	BC 39	3111-2	1671-62	T	46	143.5	132.8	10.7	136.4	.16	6.4	4.0	.23	
-3	HARVEY	BC 39	3111-2	1671-62	L	59	143.5	132.8	10.7	136.4	.16	6.4	4.0	.23	
-4	HARVEY	BC 39	3111-2	1671-62	L	44	143.5	132.8	10.7	136.4	.16	6.4	4.0	.23	
4M-1	TMCA	K6417	E1324	1670-50	T	44	142.1	129.7	16	140.3	.19	6.3	4.0	.15	41
-2	TMCA	K6417	E1324	1670-50	T	43	142.1	129.7	16	140.3	.19	6.3	4.0	.15	
-3	TMCA	K6417	E1324	1670-50	L	35	142.1	129.7	16	140.3	.19	6.3	4.0	.15	
-4	TMCA	K6417	E1324	1670-50	L	35	142.1	129.7	16	140.3	.19	6.3	4.0	.15	

*Average Longitudinal Properties From Material Certifications

TABLE C-1.—DETAILED ANNEALED Ti-6Al-4V EXTRUSION DATA (continued)

Specimen Code	Vendor	Heat	Lot	BAC No.	Grain Direction	K_{ISCC} (ksi√in)	Mech Properties* UTS (ksi)	TYS (ksi)	Elong (%)	CYS (ksi)	O_2 (wt %)	Al (wt %)	V (wt %)	Fe (wt %)	K_{ADJ} (O_2=.2) wt %
5M-1	C-W	K6676	2141	1671-51	T	33	143.6	129.8	14.3	137.8	.17	6.3	4.1	.14	23
-2	C-W	K6676	2141	1671-51	T	32	143.6	129.8	14.3	137.8	.17	6.3	4.1	.14	
6M-1	C-W	K6642	2157	1671-51	T	21	145.1	132.5	14.0	137.5	.18	6.2	4.1	.16	15
-2	C-W	K6642	2157	1671-51	T	21	145.1	132.5	14.0	137.5	.18	6.2	4.1	.16	
7M-1	TMCA	K6328	E1317	1673-22	T	34	144.2	132.8	16.2	138.5	.190	6.3	4.1	.16	31
-2	TMCA	K6328	E1317	1673-22	T	35	144.2	132.8	16.2	138.5	.190	6.3	4.1	.16	
-3	TMCA	K6328	E1317	1673-22	T	34	144.2	132.8	16.2	138.5	.190	6.3	4.1	.16	
-4	TMCA	K6328	E1317	1673-22	T	34	144.2	132.8	16.2	138.5	.190	6.3	4.1	.16	
8M-1	C-W	A1537	2117	1671-26	T	44	137.2	125.4	14.7	131.7	.161	6.12	4.10	.19	32
-2	C-W	A1537	2117	1671-26	T	44	137.2	125.4	14.7	131.7	.161	6.12	4.10	.19	
-3	C-W	A1537	2117	1671-26	L	59	137.2	125.4	14.7	131.7	.161	6.12	4.10	.19	
-4	C-W	A1537	2117	1671-26	L	45	137.2	125.4	14.7	131.7	.161	6.12	4.10	.19	
9M-1	C-W	K6641	2142	1671-51	T	22	146.4	132.9	13.7	145.6	.190	6.2	4.2	.18	18
-2	C-W	K6641	2142	1671-51	T	21	146.4	132.9	13.7	145.6	.190	6.2	4.2	.18	
10M-1	C-W	K6643	2135	1671-51	T	22	142.6	132.0	14.8	135.7	.180	6.3	4.3	.17	16
-2	C-W	K6643	2135	1671-51	T	22	142.6	132.0	14.8	135.7	.180	6.3	4.3	.17	
11M-1	C-W	K6583	2141	1671-51	T	21	145.5	130.8	13.8	135.5	.200	6.2	4.3	.18	21
-2	C-W	K6583	2141	1671-51	T	21	145.5	130.8	13.8	135.5	.200	6.2	4.3	.18	
12M-1	C-W	K6669	2141	1671-51	T	33	145.4	134.1	14.8	134.1	.190	6.2	4.1	.18	26
-2	C-W	K6669	2141	1671-51	T	21	145.4	134.1	14.8	134.1	.190	6.2	4.1	.18	
13M-1	C-W	K3502	2141	1671-51	T	34	149.3	138.0	14.2	145.1	.200	6.3	4.3	.20	27
-2	C-W	K3502	2141	1671-51	T	20	149.3	138.0	14.2	145.1	.200	6.3	4.3	.20	

*Average Longitudinal Properties From Material Certifications

TABLE C-1.—DETAILED ANNEALED Ti-6Al-4V EXTRUSION DATA (continued)

Specimen Code	Vendor	Heat	Lot	BAC No.	Grain Direction	K_{ISCC} (ksi√in)	Mech Properties* UTS (ksi)	TYS (ksi)	Elong (%)	CYS (ksi)	O_2 (wt %)	Al (wt %)	V (wt %)	Fe (wt %)	K_{ADJ} (O_2=.2 wt %)
14M-1	TMCA	K5616	E1297	1670-48	T	35	142.2	127.6	17.4	135.0	.18	6.3	4.1	.17	29
-3	TMCA	K5616	E1297	1670-48	L	42	142.2	127.6	17.4	135.0	.18	6.3	4.1	.17	
-4	TMCA	K5616	E1297	1670-48	L	36	142.2	127.6	17.4	135.0	.18	6.3	4.1	.17	
15M-1	TMCA	K5616	E1297	1670-48	T	34	142.2	127.6	17.4	135.0	.18	6.3	4.1	.17	28
-2	TMCA	K5616	E1297	1670-48	T	34	142.2	127.6	17.4	135.0	.18	6.3	4.1	.17	
-3	TMCA	K5616	E1297	1670-48	L	~35	142.2	127.6	17.4	135.0	.18	6.3	4.1	.17	
-4	TMCA	K5616	E1297	1670-48	L	36	142.2	127.6	17.4	135.0	.18	6.3	4.1	.17	
FM 962-1	C-W	A1717	2075	1671-26	T	34	137.6	127.1	13.5	131.4	.149	6.23	4.22	.18	18
-2	C-W	A1690	2117	1671-26	T	35	147.7	135.6	13.7	142.7	.172	6.20	4.18	.17	26
-3	C-W	A1701	2106	1671-26	T	34	138.3	127.9	13.5	133.8	.150	6.40	3.90	.19	18
-4	C-W	A1717	2075	1671-26	T	34	137.6	127.1	13.5	131.4	.149	6.23	4.22	.18	18
-5	C-W	A1701	2106	1671-26	T	34	138.3	127.9	13.5	133.8	.15	6.40	3.90	.19	18
-6	C-W	A1537	2117	1671-26	T	42	137.2	125.4	14.7	131.7	.161	6.12	4.10	.19	30
-7	C-W	303876	2075	1671-26	T	31	144.3	134.3	13.5	136.4	.191	6.5	4.3	.19	28
-8	C-W	A1757	2106	1671-26	T	32	137.5	125.5	13.8	132.7	.142	5.98	4.0	.18	14
-9	C-W	A1690	2117	1671-26	T	20	147.7	135.6	13.7	142.7	.172	6.20	4.18	.17	11
-10	C-W	A1757	2106	1671-26	T	21	137.5	125.5	13.8	132.7	.142	5.98	4.0	.18	2
-11	C-W	A1690	2117	1671-26	T	35	147.7	135.6	13.7	142.7	.172	6.20	4.18	.17	26
-12	C-W	A1757	2106	1671-26	T	33	137.5	125.5	13.8	132.7	.145	5.98	4.0	.18	14
FM 974-1	HARVEY	BD-86	3215-2	1671-90	T	44	136.5	129.5	12.7	134.6	.140	6.4	4.7	.26	30
-2	HARVEY	BD-86	3215-2	1671-90	T	53	136.5	129.5	12.7	134.6	.140	6.4	4.7	.26	
-3	HARVEY	BE-43	3223-4	1671-93	T	44	141.5	131.5	12.7	134.7	.150	6.4	4.1	.24	19
-4	HARVEY	BE-43	3223-4	1671-93	T	35	141.5	131.5	12.7	134.7	.150	6.4	4.1	.24	

*Average Longitudinal Properties From Material Certifications

TABLE C-1.—DETAILED ANNEALED Ti-6Al-4V EXTRUSION DATA (continued)

Specimen Code	Vendor	Heat	Lot	BAC No.	Grain Direction	K_{ISCC} (ksi$\sqrt{in}$)	Mech Properties*				O_2 (wt %)	Al (wt %)	V (wt %)	Fe (wt %)	K_{ADJ} (O_2=.2 wt %)
							UTS (ksi)	TYS (ksi)	Elong (%)	CYS (ksi)					
FM 974-5	HARVEY	B6-06	3168-1	1671-100	T	55	136.7	125.3	11.7	138.1	.120	6.4	4.2	.21	23
-6	HARVEY	B6-06	3168-1	1671-100	T	43	136.7	125.3	11 7	138.1	.120	6.4	4.2	.21	
-7	HARVEY	B8-57	3223-2	1671-93	T	34	139.0	131.0	13.3	141.5	.150	6.2	4.0	.21	18
-8	HARVEY	B8-57	3223-2	1671-93	T	34	139.0	131.0	13.3	141.5	.150	6.2	4.0	.21	
FM 967A-1	C-W	A1537	2117	1671-26	T	44	137.2	125.4	14.7	131.7	.161	6.12	4.10	.19	38
-2	C-W	A1537	2117	1671-26	T	~51	137.2	125.4	14.7	131.7	.161	6.12	4.10	.19	
-3	C-W	A1537	2117	1671-26	T	44	137.2	125.4	14.7	131.7	.161	6.12	4.10	.19	
-4	C-W	A1537	2117	1671-26	T	~66	137.2	125.4	14.7	131.7	.161	6.12	4.10	.19	
-5	C-W	A1537	2117	1671-26	T	50	137.2	125.4	14.7	131.7	.161	6.12	4.10	.19	
-6	C-W	A1537	2117	1671-26	T	59	137.2	125.4	14.7	131.7	.161	6.12	4.10	.19	

*Average Longitudinal Properties From Material Certifications

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