27
12-12-77
256 NT 15
SAND-77-1202

Unlimited Release

MASTER

A DESIGNER'S GUIDE TO THE MECHANICAL PROPERTIES AND FRACTURE TOUGHNESS OF TITANIUM 6Al-6V-2Sn

James P. Hickerson

Prepared by Sandia Laboratories, Albuquerque, New Mexico 87115
and Livermore, California 94550 for the United States Energy Research
and Development Administration under Contract AT (29-1)-789

Printed November 1977

Sandia Laboratories

SF 2900 Q(7-73)

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Issued by Sandia Laboratories, operated for the United States Energy Research & Development Administration by Sandia Corporation.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research & Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Printed in the United States of America
Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price: Printed Copy \$4.50; Microfiche \$3.00

SAND-77-1202
Unlimited Release
Printed November 1977

A DESIGNER'S GUIDE TO THE MECHANICAL PROPERTIES
AND FRACTURE TOUGHNESS OF TITANIUM 6Al-6V-2Sn

James P. Hickerson
Physical Metallurgy Division II - 5835
Sandia Laboratories, Albuquerque, New Mexico 87115

ABSTRACT

During the Phase 3 design of the B77 laydown bomb, titanium 6Al-6V-2Sn was chosen for certain structural components. Comprehensive mechanical property and fracture toughness information for this alloy were lacking, necessitating a test program keyed to the anticipated weapon environment and stockpile-to-target sequence. This report covers the mechanical tests of strength, notch sensitivity, and fracture toughness that were conducted. The information is presented in the form of a designer's guide to properties that can be expected from three heat treatments of the alloy (in order of increasing strength):

1. duplex anneal
2. solution treat, quench, age at 578°C
3. solution treat, quench, age at 478°C

Test temperatures spanned -60°C to 180°C, and test times ranged from 10 ms to several hours in duration. The results showed the duplex annealed condition to be most tough and least notch sensitive. It was found that any change in heat treatment, test temperature, or loading rate that boosted strength did so at the expense of fracture toughness and notch sensitivity.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

1-2
[Signature]

CONTENTS

	<u>Page</u>
ACKNOWLEDGEMENT	5
I. INTRODUCTION.	7
II. METALLURGICAL BACKGROUND.	9
III. TENSILE PROPERTIES.	11
A. Modulus of Elasticity	11
B. Poisson's Ratio	11
C. Strength and Elongation	11
1. Duplex Annealed Specimens	12
2. Solution Treated and Aged Specimens	12
IV. FRACTURE TOUGHNESS.	13
A. Duplex Annealed Specimens	14
B. Solution Treated and Aged Specimens	15
V. NOTCH SENSITIVITY	16
VI. SOME GENERAL OBSERVATIONS AND PRECAUTIONS	18
A. Chemistry	18
B. Metallurgy.	19
C. Environmental Behavior.	20
D. Mechanical Behavior	21
REFERENCES.	22
TABLES.	25
FIGURES	35
APPENDIX I: Important Figures with English Units . . .	53
APPENDIX II: Engineering Stress-Strain Curves.	57

ACKNOWLEDGEMENT

Special equipment for this project was prepared by Rick Blose (5835). Rick also conducted many of the mechanical tests. John Lewis (3715) gave special attention to procurement of materials and services. Don Clarin (8157) and Charlie Maak (5832) reviewed the manuscript. The B77 Materials Evaluation Program that produced these data was authorized by Gary Beeler, Henry Hanser, and Don Clarin (all 8157), and coordinated with Gary Ulitchny (Bendix Corporation, Kansas City Division), Dan Dawson (8314), Henry Rack (5832), Jon Munford (5832) and Steve Pohlman (5831). Dick Rohde (5832) served as the SLA coordinator.

I. INTRODUCTION

The purpose of this report is to provide designers, stress analysts, and metallurgists with detailed mechanical property information on titanium alloy 6Al-6V-2Sn. It is not intended as a research document, but rather as a guide to be used in predicting how hardware made from this alloy would respond to typical nuclear weapon stockpile and delivery environments. Included are information on tensile behavior, fracture toughness, and notch sensitivity as affected by heat treatment, temperature, and loading rate. A concluding section gives recommendations and precautions regarding the general use of the alloy.

Titanium 6Al-6V-2Sn is a heat treatable alloy that can be processed to provide a variety of properties. Because of this, the data presented in this report may not relate directly to the parts being considered by others. Also, being responsive to thermal treatment is a mixed blessing in the sense that improperly controlled processing can produce unforeseen and undesirable properties. Metallurgical assistance from Metallurgy Department 5830 and Materials Department 8310 is strongly recommended during all stages of design.

The collection of these data was made possible by funding from the B77 laydown bomb development program. During the course of design of this weapon it was determined that a high strength-to-weight ratio titanium alloy was needed for the aft case and parachute afterbody components. Titanium 6Al-6V-2Sn offered the best combination of strength, toughness, heat treatment response, and well-developed industrial fabrication practices. Complementary studies of material properties were carried on at Sandia Laboratories and Bendix Corporation, Kansas City. Although the

report deals only with mechanical properties and fracture behavior, a much more extensive array of information on the corrosion, stress corrosion, sustained load cracking, heat treatment, and fabrication of this alloy can be obtained through metallurgy departments of Sandia (8310, 5830) and Process Engineering and Materials Testing Divisions at Bendix.

II. METALLURGICAL BACKGROUND

The specimens tested in this study were machined from large-diameter extrusions that provided the stock for fabricating full scale B77 hardware. Starting material for the extrusions was ingots of 2000 kg or greater supplied to Cameron Iron Works, Houston, by Reactive Metals Inc. Cameron trimmed, upset, pierced, and forward extruded these ingots as large diameter tubes typically 5 m long. The extrusion temperature was 980°C, which is in the lower region of beta phase stability. The rough machined extrusions were nominally 47 cm (18.5 in.) outside diameter and possessed either a 3.5 cm (1.38 in.) or 5.7 cm (2.25 in.) wall depending on whether they were intended for aft case or afterbody fabrication. The tube ends were trimmed and then test rings 14 cm (5.5 in.) long were cut from the tubes for laboratory testing. The remainder of the tubes were used by Bendix Corporation for manufacturing hardware. The test data reported herein were taken from specimens machined from 3.5 cm thick test rings. The chemistry of these rings is given in Table 1.

Heat treatments for laboratory tests were chosen to provide three different levels of strength and fracture toughness. Table 2 lists the heat treatment schedules and the tensile yield strengths sought. All B77 metallurgists examined these or similar heat treatments. Table 3 presents the actual heat treatments given test rings in this study. Aging temperatures were somewhat below the intended values due to a furnace calibration error. Midway through the program the duplex annealed condition was recognized as providing sufficient strength with superior toughness and data gathering thereafter concentrated on it.

Duplex annealing and solution treatment were carried out on full section test rings in order to simulate the thermal heating and cooling rates seen by full scale hardware. Aging of solution treated material was performed in high vacuum on finish machined specimens. Furnace pressures were consistently less than 10^{-6} torr, and subsequent oxygen and hydrogen analysis indicated no significant changes in these embrittling species.

Particular attention was paid to the orientation of specimens cut from the extrusions, since it was believed that this might significantly affect the results. Measurements made later showed that there was very little effect of orientation on properties in these extrusions, although this may not be generally true. Tensile and fracture toughness specimens were cut from the test rings such that the loads would be applied parallel to the tube axis and the fracture plane would be perpendicular to it. The direction of crack propagation in toughness specimens was parallel to the circumferential direction in the tube wall. Notch bend specimens were oriented with their long axis parallel to the tube axis. Notches were located so that fracture would simulate the growth a crack from the outer tube wall radially inward.

III. TENSILE PROPERTIES

A. Modulus of Elasticity

No specific measurements of Young's modulus were made; however, initial slopes of stress strain curves were compared with published data of the Titanium Metals Corporation of America [1]. A curve fit through their data for modulus versus test temperature is given in Fig. 1.

No strain rate effects on elastic modulus were detected in the tensile tests. It also appeared as though heat treatment had little effect on the modulus. The data in the figure are probably accurate to within five percent of actual values for a wide range of heat treatments and loading rates.

B. Poisson's Ratio

No direct measurements of Poisson's ratio were made. Reference 1 lists Poisson's ratio as 0.32.

C. Strength and Elongation

Tensile tests were conducted at a variety of temperatures and strain rates on specimens shown in Fig. 2. Dual opposing strain gages (bending compensated) with high elongation characteristics were bonded to specimens when tests were to last less than 10 seconds. Tests of longer duration were instrumented with standard ASTM Class B1 extensometers. Load, time, and strain data were stored on a digital recording oscilloscope and later reduced to stress, strain, and strain rate.

Test temperatures were controlled by an Instron Environmental Chamber to $\pm 1^{\circ}\text{C}$. Soak times at temperature were a minimum of 20 minutes prior to testing.

Various strain rates were achieved by controlling the displacement rate of the actuator of the MTS test machine. This method produced a strain versus time plot such as that shown in Fig. 3. The linear portion of the curve after yielding was used to calculate a plastic strain rate, $\dot{\epsilon}_p$, and is hereafter used in correlating data.

1. Duplex Annealed Specimens. The effects of temperature and strain rate on mechanical behavior of duplex annealed material are shown in Figs. 4 and 5. Appendix I contains the data of Fig. 4 in English units. Table 4 provides the engineering values taken from individual stress-strain curves found in Appendix II.

In general, it is observed that as strain rate increases tensile yield and tensile ultimate strength increase. Simultaneously, uniform elongation (the strain at the ultimate tensile stress) declines. Strength declines as temperature rises; however, elongation increases. A definite ductility minimum is found at low temperatures and high loading rates (Fig. 5). The stress-strain curves show that little strain hardening occurs at any combination of temperature and strain rate.

2. Solution Treated and Aged Specimens. The tensile properties of the two solution treated and aged conditions are given in Figs. 6 and 7 and Tables 5 and 6. The individual stress-strain curves appear in Appendix II.

The general observations concerning the effects of temperature and loading rate on these two heat treatments parallel those made for duplex annealed material. Strength levels are, of course, higher but ductility is correspondingly lower.

IV. FRACTURE TOUGHNESS

Fracture toughness tests were performed on the compact specimen illustrated in Fig. 8. Displacements of the knife edges in the machined notch were measured during each test by a clip-on displacement gage of the type recommended by ASTM Designation E399 [2]. The gages used had a resonant frequency of 700 Hz, which results in a period that is less than 1/7 that represented by the most rapid toughness test.

Testing procedures for solution treated and aged specimens were similar to those recommended by E399, with the exception that loading rates were often higher and cracks extended across 0.65 the gage width. Shapes of load-displacement curves and specimen dimensions were otherwise in conformance with requirements for valid K_{IC} testing.

Specimens of duplex annealed material usually exhibited too much yielding prior to fracture to meet E399 requirements for valid K_{IC} testing. These test results were evaluated by a J integral technique first proposed by Rice, Paris, and Merkle [3] for deeply cracked compact specimens. Merkle and Corten [4] and the author [5] have since shown that the equation suggested by Reference 3 slightly underestimates values of J and accordingly it was slightly modified to give

$$J_{IC} = \frac{2.2 A}{B b}$$

A = area under the load-displacement curve up to the point where crack extension occurs

B = specimen thickness

b = remaining unbroken ligament

After calculating J_{IC} from the test data values of K_{IC} were obtained by assuming the familiar relation between stress intensity and the crack extension force [6]

$$K_{IC} = \sqrt{\frac{EJ_{IC}}{1 - \nu^2}}$$

E = Young's modulus

ν = Poisson's ratio

Determining the onset of crack extension in J Integral tests of duplex annealed specimens also required special attention. Tests lasting longer than 10 seconds were instrumented for resonant frequency detection of crack growth [7,8]. Tests of shorter duration could not be instrumented with resonant frequency equipment. If load-displacement curves from these specimens did not meet ASTM E399 standards for valid K_{IC} measurement, then the onset of crack extension was assumed to lie between the intercept of a 5 percent secant line [2] and maximum load or a discontinuity signifying unstable crack extension. This then placed upper and lower bounds on the value of fracture toughness even though the absolute value could not be obtained.

The loading rate during a test was represented by the rate of change of the stress intensity factor, $\dot{K}$. This was approximately constant during the last third of the test and was used for correlating data.

A. Duplex Annealed Specimens

The toughness behavior of duplex annealed material is illustrated in Fig. 9. Table 7 presents the data for individual specimens and Appendix I provides graphical results in English units.

Because the precision of the toughness data is lower than that of tensile data, one must question the absolute shape of the failure surface in Figure 9. The general behavioral trends are, however, most probably correct. As loading rate and temperature increase, K_{IC} tends to increase. For the conditions tested the minimum value of K_{IC} obtained was 57.3 MPa $\sqrt{m}$ at a loading rate of 0.0087 MPa $\sqrt{m}/s$ and a temperature 24°C. This agrees favorably with the threshold value of stress intensity required for sustained load cracking at room temperature [9].

B. Solution Treated and Aged Specimens

The behavior of solution treated and aged material is given in Figs. 10 and 11 and Tables 8 and 9. The general behavior patterns attributed earlier to duplex annealed material also apply here. In addition, heat treatment is seen to have a marked effect on fracture toughness. The high strength STA 478C material is considerably less tough than the STA 578C material which, in turn, is less tough than duplex annealed material.

V. NOTCH SENSITIVITY

Notch sensitivity was measured by testing bend specimens with notch radii varying from .05 mm to 1.5 mm. The specimen dimensions are given in Fig. 12. Specimens were tested in a three-point bending fixture that had a span of 40 mm between the two end supports. Constant deflection rates were maintained during tests that were classified as

1. low rate: total elapsed time of 80-200 s.
2. high rate: total elapsed time of 8-30 ms.

Total test time was governed by the deflection required to reach maximum load.

The data obtained from the tests were correlated with the notch radius of the test specimens. The maximum load reached and the value of the notch tip J integral at maximum load were both measured. The former quantity represents a measure of notch strength and the latter a measure of the work required to fracture the specimen. Values of J were calculated from [3]

$$J = \frac{2A}{Bb}$$

A = area under the load displacement curve up to maximum load

B = specimen thickness

b = unbroken ligament between the notch root and back edge of the specimen

The room temperature notch strengths of the three heat treatments are shown in Figs. 13 and 14. The inherent superiority of the duplex annealed material is apparent. At notch radii greater than .5 mm there is very little effect of radii on notch strength for this heat treatment.

The two solution treated conditions exhibit more notch sensitivity as well as lower notch strengths although their tensile yield and ultimate strengths are significantly higher than the duplex annealed condition.

The effect of notch radius on the energy (maximum value of J) required for fracture of duplex annealed material is shown in Fig. 15. The energy required to fracture the test specimens is seen to continually increase with radius, due to the greater deflections required to cause fracture. This behavior of test specimens is illustrated in Fig. 16.

The preceding figures clearly show that notch strength and fracture energy increase with increasing loading rate. This appears to be due to two causes:

1. Tensile yield and ultimate strengths are both elevated by higher loading rates. This reduces notch tip plasticity and perhaps forestalls crack initiation.
2. Fracture toughness (resistance to crack propagation) was found to increase as loading rate increased.

It is also clear from the preceding figures that the higher strength heat treatments are more sensitive to notch acuity. In spite of their higher strengths, the solution treated and aged materials have lower notched strengths than the duplex annealed material and also show greater losses in notched strength at small radii.

VI. SOME GENERAL OBSERVATIONS AND PRECAUTIONS

Titanium alloys offer some distinct advantages to the design engineer. They possess high strength-to-weight ratios, good corrosion resistance, are often heat treatable, retain their strength at moderately high temperatures, and are readily fabricated by most techniques commonly applied to other structural metals. They do, however, present some unique problems to the user that should be taken into account in the design stage. This section discusses several of these areas that might not be obvious to someone having little prior experience with titanium alloys. For more information the reader is strongly encouraged to consult specialists in Metallurgy Department 5830, Materials Department 8310, industrial firms experienced in producing hardware, and the references found in this report.

A. Chemistry

Minor impurity elements such as iron, carbon, hydrogen, oxygen, and nitrogen can significantly impair properties if they are present in more than minute amounts. Iron and carbon are primarily controlled in the initial melting operations, and for that reason the user can protect himself by obtaining starting material that meets an appropriate chemistry specification.

Oxygen, hydrogen, and nitrogen can be introduced very easily during the course of hardware fabrication if proper precautions are not taken during heat treating, joining, and cleaning. All three species can severely embrittle the alloy, and may also alter its response to heat treatment [10,11,12]. Vacuum heat treating, protective coatings, removal of contaminated surfaces, and special pickling and cleaning practices

have all been employed to minimize these problems. Sound industrial methods exist but they may affect design or fabrication steps and should be considered prior to committing hardware to production.

B. Metallurgy

Without detailing all the metallurgical transformations and responses of this alloy, let it be said that the possibilities for heat treatment and the changes that can result are as extensive with titanium 6Al-6V-2Sn as they are with any modern quenched and tempered steel. This means that strength, ductility, toughness, corrosion behavior, resistance to environmental cracking, and microstructure can be dramatically altered by changes in

1. Alloy chemistry and contamination level
2. Processing temperatures and times
3. Cooling rates from heat treating or hot working temperatures
4. Section size, geometry, and thickness
5. Welding or brazing or metallurgical bonding practice.

For the user this means that unwanted properties or variations in properties may be obtained in the final part unless a skillful manipulation of design and processing variables is accomplished. It also means that there may be limitations in section size or shape that restrict or prevent the use of the alloy in certain situations.

It is also true that minor changes in processing that affect, one of the properties listed above, may not be evidenced by changes in another. For example, large differences in toughness or stress corrosion resistance might occur in two pieces of hardware made by two different methods that

produce the same tensile properties. If one were to rank properties in terms of increasing sensitivity to processing changes, the list would be approximately as follows.

1. tensile yield and ultimate strength
2. tensile elongation
3. fracture toughness
4. resistance to environmental cracking

C. Environmental Behavior

Although general corrosion or galvanic corrosion is not usually a serious problem for titanium hardware in the nuclear weapon stockpile, certain constituents in the environment can create environmental cracking [10]. If stresses (applied or residual) exist, then the presence of salt water or aqueous chloride solutions can cause cracks to initiate and grow from sharp notches or defects. The presence of methyl alcohol, perhaps remaining from an earlier cleaning step, has been the cause of similar failures. Special machining fluids and cleaning solvents are generally employed when structural titanium parts are to be made.

It has also been observed that contact with cadmium can lead to a cracking failure similar to the liquid metal embrittlement of aluminum by mercury [13]. At temperatures above 300°C silver and gold can create the same types of failure [14]. Cadmium plated steel parts should never be used in contact with titanium. A similar caution must be applied to silver and gold, perhaps present in electrical contacts or conductive seals if temperatures above 300°C are to be reached. Other low-melting point metals or metalloids might also be a problem.

D. Mechanical Behavior

Titanium 6Al-2V-2Sn is usually heat treated for the purpose of achieving some specified level of strength or fracture toughness. As with most alloy systems, it is observed that strengthening occurs at the sacrifice of toughness. Figure 17 shows the general relationship observed in the data collected at moderately low rates. Variations in strength and toughness were achieved by changing heat treatment and test temperature. A similar trend is portrayed in Reference 1.

Titanium alloys also respond to sustained loads in ways not ordinarily encountered in other structural materials. At high stresses titanium 6Al-6V-2Sn is known to creep at room temperature [1,15] and also may fail in vacuum or uncontaminated air by a mechanism known as sustained load cracking [16]. With proper precautions these problems can be dealt with. Professional assistance of materials experts is strongly recommended if high stresses are encountered or long service lives are anticipated.

REFERENCES

1. TIMET Titanium Engineering Bulletin No. 10, Titanium Metals Corporation of America, 233 Broadway, New York, NY, 10007.
2. Designation E399-75, "Standard Method of Test for Plane-Strain Fracture Toughness of Metallic Materials," Annual Book of ASTM Standards, Part 10 (1975).
3. J. R. Rice, P. C. Paris, and J. G. Merkle, "Some Further Results of J Integral Analysis and Estimates," ASTM STP 536 (1973), p. 231.
4. J. G. Merkle and H. T. Corten, "A J Integral Analysis for the Compact Specimen, Considering Axial Force as Well as Bending Effects," Journal of Pressure Vessel Technology, 96 (1974), p. 286.
5. James P. Hickerson, Jr., "Comparison of Compliance and Estimation Procedures for Calculating J Integral Values," to be published in a forthcoming ASTM Special Technical Publication of Papers Presented at the 10th National Symposium on Fracture Mechanics, 1976, Philadelphia.
6. J. A. Begley and J. D. Landes, "The J Integral as a Fracture Criterion," Fracture Toughness, ASTM STP 514, (1972), p. 1.
7. Unpublished work by the author and R. E. Blose (5835) in developing resonant frequency measurement practices for detecting crack extension during toughness testing.
8. E. D. Scussel, "Fracture Toughness Tester," Sandia Internal Memorandum, RS 2326/0006, January 1977.
9. J. W. Munford and H. J. Rack, unpublished research within Metallurgy Department 5830 in support of B77 development.

10. R. A. Wood and R. J. Favor, Titanium Alloys Handbook, Metals and Ceramics Information Center, Battelle Columbus Laboratories, 1972.
11. J. M. Furguson, "The Oxidation and Contamination of Titanium and Its Alloys," DMIC Memorandum 238, Metals and Ceramics Information Center, Battelle Columbus Laboratories, July 1, 1968.
12. D. N. Williams and R. A. Wood, "Effects of Surface Condition on the Mechanical Properties of Titanium and Its Alloys," MCIC Report 71-01, Metals and Ceramics Information Center, Battelle Columbus Laboratories, August 1971.
13. D. N. Fager and W. F. Spurr, "Solid Cadmium Embrittlement: Titanium Alloys," Corrosion, 24 (1969), p. 409.
14. Unpublished research by R. E. Stolz, Sandia Laboratories Division 8314.
15. H. P. Chu, "Room Temperature Creep and Stress Relaxation of a Titanium Alloy," Journal of Materials, 5 (1970), p. 633.
16. H. J. Rack and J. W. Munford (Sandia Laboratories Division 5832), "Environmental Cracking of the Alpha-Beta Alloy: Ti 6-6-2," to be presented at the Symposium on Environment-Sensitive Fracture of Engineering Materials, Chicago, October 24-27, 1977.

TABLE 1. Chemical Compositions of the Three Heats of Titanium 6Al-6V-2Sn
Used for Specimen Fabrication*

RMI Heat Number	ELEMENT									
	C	N	Fe	Al	V	Cu	Sn	Y	H	O
P-8072	.02	.011	.75	5.7	5.7	.77	2.1	< .005	28 ppm	.155
P-8073	.02	.011	.73	5.8	5.8	.74	2.1	< .005	25 ppm	.149
P-8074	.03	.009	.78	5.8	5.8	.79	2.1	< .005	25 ppm	.156

*All heats purchased to Military Specification MIL-T-9047.

TABLE 2. Aim Heat Treatments and Anticipated Yield Strengths

Name	Annealing Temp./Time	Solution Treatment Temp./Time	Quench Media	Aging Temp./Time	R.T. Yield Strength (MPa/ksi)
Duplex Anneal	900°C/2 hr. Air Cool				896/130
	785°C/2 hr. Air Cool				
STA-600°C		350°C/2 hr.	Water	600°C/8 hr.	1068/155
STA-500°C		850°C/2 hr.	Water	500°C/8 hr.	1172/170

TABLE 3. Actual Heat Treatments and Resulting Yield Strengths

Name	Annealing Temp./Time	Solution Treatment Temp./Time	Quench Media	Aging Temp./Time	R.T. Yield Strength (MPa/ksi)
Duplex Anneal	903 $\pm$ 3°C/2 hr. Air Cool				883/128
	786 $\pm$ 3°C/2 hr. Air Cool				
STA-578°C		852 $\pm$ 5°C/2 hr.	Water	578°C/8 hr.	1165/169
STA-478°C		852 $\pm$ 5°C/2 hr.	Water	478°C/8 hrs.	1206/175

TABLE 4. Tensile Properties of Duplex Annealed 6Al-6V-2Sn

Specimen	Test Temp. (°C/°F)	Plastic Strain Rate (1/s)	Yield Strength (MPa/ksi)	Ultimate Strength (MPa/ksi)	Uniform Strain (%)	Total Elongation in 25 mm* (%)
T205	-60/-76	2.0×10^{-5}	1041/151	1103/160	7.0	9.1
T19	-60/-76	2.1×10^{-3}	1117/162	1144/166	3.0	10.4
T196	-60/-76	2.8×10^{-2}	1133/164	1169/170	1.5	5.0
T28	-66/-87	7.5×10^{-2}	1207/174	1227/178	2.4	
T188	-59/-74	1.0	1151/167	1214/176	2.8	
T26	-66/-87	2.0	1234/179	1268/184	2.2	
T197	-20/-4	2.8×10^{-3}	1000/145	1041/151	8.5	19.4
T186	-19/-2	5.9	1083/157	1151/167	3.1	
T31	25/77	1.8×10^{-5}	848/123	945/137	11.0	13.8
T17	24/75	1.9×10^{-3}	910/132	965/140	12.7	14.7
T18	24/75	2.1×10^{-3}	882/128	945/137	11.0	16.0
T189	21/70	1.7×10^{-2}	945/137	987/143	7.2	19.0
T24	25/77	9.0×10^{-2}	903/131	972/141	~ 6.2	
T185	22/72	7.0×10^{-1}	1000/145	1055/153	3.1	
T23	24/75	4.5	1027/149	1083/157	3.8	
T199	60/140	2.6×10^{-3}	862/125	938/136	11.2	17.0
T191	60/140	5.4	979/142	1014/147	4.1	
T204	100/212	1.9×10^{-5}	738/107	855/124	8.8	12.6
T20	100/212	1.9×10^{-3}	814/118	924/134	11.0	14.3
T202	99/210	1.2×10^{-2}	821/119	895/130	7.2	12.5
T22	101/214	1.0×10^{-1}	834/121	924/134	8.6	
T187	99/210	9.0×10^{-1}	862/125	917/133	~ 10.2	
T25	100/212	5.4	972/141	979/142	6.8	
T201	141/286	1.8×10^{-3}	717/104	834/121	9.6	14.2
T195	141/286	5.0	848/123	917/133	~ 11.6	
T203	179/354	1.8×10^{-5}	659/95.6	800/116	10.8	14.6
T21	181/358	1.9×10^{-3}	710/103	841/122	11.0	14.6
T200	179/354	1.2×10^{-2}	731/106	827/120	9.2	14.0
T30	179/354	8.9×10^{-2}	724/105	855/124	12.8	
T194	179/354	7.0×10^{-1}	738/107	841/122	13.5	
T27	180/356	5.5	841/122	896/130	13.3	

* These data could not be obtained from specimens on which only strain gages were mounted and necking preceded fracture.

TABLE 5. Tensile Properties of STA-578°C Titanium 6Al-6V-2Sn

Specimen	Test Temp. (°C/°F)	Plastic Strain Rate (1/s)	Yield Strength (MPa/ksi)	Ultimate Strength (MPa/ksi)	Uniform Strain (%)	Total Elongation in 25 mm* (%)
T78	-66/-87	1.9×10^{-3}	1331/193	1379/200	3.0	5.2
T75	-66/-87	1.5×10^{-1}	1344/195	1393/202	3.7	
T67	-66/-87	4.0	1400/203	1448/210	2.1	
T77	25/77	1.9×10^{-5}	1103/160	1193/173	7.8	7.9
T74	24/75	1.9×10^{-3}	1165/169	1214/176	5.8	7.8
T66	24/75	8.4×10^{-2}	1206/175	1269/184	4.4	
T65	24/75	5.8	1241/180	1282/186	4.0	
T80	100/212	1.8×10^{-3}	1041/151	1138/165	7.7	11.3
T70	101/214	9.3×10^{-2}	1062/154	1124/163	5.5	
T69	101/214	4.1	1172/170	1207/175	4.9	
T79	180/356	2.0×10^{-3}	958/139	1062/154	9.0	11.7
T72	180/356	5.4×10^{-2}	1007/146	1075/156	~ 8.3	
T73	180/356	4.3	1089/158	1138/165	6.7	

* These data could not be obtained from specimens on which only strain gages were mounted and necking preceded fracture.

TABLE 6. Tensile Properties of STA-478°C Titanium 6Al-6V-2Sn

Specimen	Test Temp. (°C/°F)	Plastic Strain Rate (1/s)	Yield Strength (MPa/ksi)	Ultimate Strength (MPa/ksi)	Uniform Strain (%)	Total Elongation in 25 mm* (%)
T92	-66/-87	1.8×10^{-3}	1393/202	1517/220	3.6	3.6
T86	-66/-87	8.0×10^{-2}	1496/217	1613/234	3.0	3.0
T83	-66/-87	3.2	1551/225	1676/243	2.6	2.6
T96	25/77	1.7×10^{-5}	1152/173	1351/196	3.1	3.1
T91	24/75	1.7×10^{-3}	1207/175	1331/193	4.5	5.2
T81	24/75	8.0×10^{-2}	1338/194	1462/212	3.1	3.1
T90	24/75	3.5	1379/200	1517/220	3.2	3.2
T94	100/212	1.6×10^{-3}	1138/165	1282/186	4.3	4.8
T84	100/212	8.8×10^{-2}	1172/170	1282/186	~ 5.0	
T85	101/214	3.5	1276/185	1373/199	4.5	6.2
T82	179/354	2.1×10^{-3}	933/136	1069/155	8.5	11.6
T89	180/356	6.7×10^{-2}	1145/166	1269/184	3.1	3.4
T87	180/356	4.0	1124/163	1234/179	4.9	

*These data could not be obtained from specimens on which only strain gages were mounted and necking preceded fracture.

TABLE 7. Fracture Toughness of Duplex Annealed Titanium 6Al-6V-2Sn

Specimen	Test Temp. (°C/°F)	Fracture Toughness, K_{IC} (MPa $\sqrt{m}$ /ksi $\sqrt{in}$)	Loading Rate, $\dot{K}$ (MPa $\sqrt{m}$ /s)
T205	-60/-76	73.3/66.7	.010
T4	-62/-80	63.9/58.1	1.0
T212	-59/-74	77.2/70.2	14.
T8	-60/-76	91.2/83.0	180.
T226	-60/-76	79.5/72.3	1200.
T16	-60/-76	82.8/75.3	6000.
T230	-20/-4	63.9/58.1	.96
T210	-20/-4	104/94.8	7000.
T145	24/75	57.3/52.1	.0087
T14	25/77	72.9/66.3	1.2
T12	25/77	72.5/66.0	1.2
T228	24/75	82-88/75-80	5.2
T9	23/73	83-93/76-85	200.
T221	22/72	91-108/83-98	1200.
T147	25/77	112/102	6000.
T234	60/140	86.7/78.9	.88
T214	62/144	109-134/100-122	7000.
T215	100/212	64.2/58.4	.0081
T5	102/216	84.3/76.7	1.1
T211	101/214	82-108/74-99	12.
T2	100/212	84-107/77-98	160.
T213	99/210	101-113/92-103	1000.
T7	99/210	120/109	9800.
T233	140/284	83.3/75.8	.81
T220	139/282	104-120/95-109	6700.
T224	180/356	92.3/84.0	.0085
T10	180/356	112/102	.67
T225	182/360	82-98/75-89	16.
T1	181/358	85-121/78-110	180.
T231	180/356	78-125/71-114	1000.
T11	182/360	107-157/98-143	6400.

TABLE 8. Fracture Toughness of STA-578°C Titanium 6Al-2V-2Sn

Specimen	Test Temp. (°C/°F)	Fracture Toughness, K_{IC} (MPa $\sqrt{m}$ /ksi $\sqrt{in}$)	Loading Rate, K (MPa $\sqrt{m}/s$)
T50	-60/-76	39.1/35.6	0.66
T61	-60/-76	46.6/42.4	178.
T62	-65/-85	52.9/48.1	7180.
T52	24/75	38.7/35.2	.0095
T49	24/75	43.5/39.6	.78
T55	24/75	55.9/50.9	159.
T56	24/75	59.9/54.5	5760.
T54	100/212	56.6/51.5	.63
T64	100/212	63.4/57.7	169.
T57	100/212	72.9/66.3	6020.
T53	180/356	68.1/62.0	.79
T59	180/356	84.8/77.2	196.
T60	180/356	84.6/77.0	6570.

TABLE 9. Fracture Toughness of STA-478°C Titanium 6Al-6V-2Sn

Specimen	Test Temp. (°C/°F)	Fracture Toughness, K_{IC} (MPa $\sqrt{m}$ /ksi $\sqrt{in}$)	Loading Rate, $\dot{K}$ (MPa $\sqrt{m}/s$)
T34	-60/-76	28.2/25.7	.57
T47	-60/-76	29.9/27.2	160.
T46	-66/-87	37.9/34.5	7400.
T33	24/75	27.7/25.2	.0087
T37	24/75	33.4/30.4	.78
T38	24/75	37.4/34.0	154.
T39	24/75	43.0/39.1	5240.
T36	100/212	38.5/35.0	.84
T40	101/214	45.9/41.8	178.
T44	100/212	50.9/46.3	6220.
T35	180/356	47.8/43.5	.78
T45	181/358	56.2/51.1	176.
T41	179/354	45.9/41.8	170.
T42	180/356	64.4/58.6	6440.

Fig. 1. Young's Modulus versus Temperature for Titanium 6Al-6V-2Sn.

Fig. 2. Tensile Specimen Dimensions.

DUPLEX ANNEALED
SPECIMEN T18
24C

Fig. 3. Typical Data of Stress and Strain versus Time.

Fig. 4. Yield Stress (0.2% offset) Data for Duplex Annealed Specimens.

Fig. 5. Uniform Strain Data for Duplex Annealed Specimens.

Fig. 6. Tensile Properties of STA-578C Specimens.

Fig. 7. Tensile Properties of STA-478C Specimens.

Fig. 8. Fracture Toughness Specimen Dimensions.

Fig. 9. Fracture Toughness of Duplex Annealed Titanium 6Al-6V-2Sn.

Fig. 10. Fracture Toughness of STA-578C Material.

Fig. 11. Fracture Toughness of STA-478C Material.

PART NO.	DIM "R"
RB0088-000	0.002
RB0088-001	0.005
RB0088-002	0.010
RBC088-003	0.015
RBC088-004	0.020
RB0088-005	0.025
RB0088-006	0.040
RB0088-007	0.060

Fig. 12. Dimensions of the Notch Bend Specimen.

Fig. 13. Fracture Loads at Low Loading Rates and Room Temperature.

Fig. 14. Fracture Loads at High Loading Rates and Room Temperature.

Fig. 15. Breaking Energy of Duplex Annealed Specimens at Room Temperature.

Fig. 16. Representative Load-Displacement Curves of Notch Bend Specimens.

Fig. 17. Strength versus Toughness Data for Titanium 6Al-6V-2Sn.

APPENDIX I

Important Figures with English Units

Yield Stress of Duplex Annealed Material.

Fracture Toughness of Duplex Annealed Material.

APPENDIX II
Engineering Stress-Strain Curves

UNLIMITED RELEASE

Distribution:

1281 S. W. Key
 1282 T. G. Priddy
 1282 J. T. Black
 1284 R. T. Othmer
 1320 M. L. Kramm
 Attn: 1321 C. E. Dalton
 1322 R. D. Andreas
 1323 D. J. Rigali
 1324 E. C. Rightley
 1710 V. E. Blake, Jr.
 Attn: 1712 J. W. Kane
 1713 J. T. Risse
 1714 E. I. Bruce
 4311 C. C. Burks
 4314 T. L. Workman
 4336 S. L. Jeffers
 4337 B. E. Bader
 4341 P. A. Longmire
 4342 W. R. Reynolds
 4361 W. C. Hines
 4363 J. P. Hickerson (5)
 5000 A. Narath
 Attn: 5100 J. K. Galt
 5200 E. H. Beckner
 5300 O. E. Jones
 5400 A. W. Snyder
 5700 J. H. Scott
 5800 R. S. Claassen
 Attn: 5810 R. G. Kepler
 5820 R. L. Schwoebel
 5840 H. J. Saxton
 5830 M. J. Davis
 5831 N. J. Magnani
 5831 S. J. Pohlman
 5832 R. W. Rohde
 Attn: K. H. Eckelmeyer
 5832 J. W. Munford
 5832 C. H. Maak
 5832 H. J. Rack
 5833 J. L. Ledman
 Attn: J. L. Jellison
 G. Knorovsky
 T. V. Nordstrom
 F. J. Zanner
 5834 D. M. Mattox
 Attn: F. Randich
 5835 C. H. Karnes
 Attn: J. A. Van Den Avyle
 W. B. Jones
 M. Soo Hoo
 5835 R. E. Blöse (3)

5844 F. P. Gerstle, Jr.
 8120 W. E. Alzheimer
 8121 A. T. Jones
 8122 C. S. Hoyle
 8123 W. D. Zinke
 8141 H. Hanser
 8150 D. E. Gregson
 8157 G. N. Beeler
 8157 J. L. Bolen
 8157 D. A. Clarin
 8158 A. S. Rivenes
 8312 D. R. Adolphson
 8312 M. W. Mote
 8314 W. R. Hoover
 Attn: J. A. Brooks
 B. C. Adegard
 A. J. West
 8314 D. B. Dawson
 8366 J. D. Gilson
 8266 Tech. Library
 3141 Tech. Library (5)
 3151 Tech. Writing (3)
 For DOE/TIC (Unlimited
 Release)
 DOE/TIC (25)
 (R. P. Campbell 3172-3)