NASA Contractor Report 198326

Materials Research for High Speed Civil Transport and Generic Hypersonics - Metals Durability

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Contract NAS1-20013, Task 9

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National Aeronautics and
Space Administration
Langley Research Center
Hampton, Virginia 23681-0001

FOREWORD

Thermomechanical Fatigue of Titanium Alloys (Contract NAS1-20013, Task 9) was performed by The Boeing Company, Commercial Airplane Group, Seattle, Washington, for NASA Langley Research Center (LaRC), Hampton, Virginia. Mr. Dennis Dicus, Metallic Materials Branch, Materials Division, was the research task manager.

The authors wish to acknowledge the valuable technical assistance of Mr. Edward P. Phillips, of the Mechanics of Materials Branch, Materials Division.

Boeing personnel involved in this task included:

Dan Hoffman (task integrator and coordinator)
Eric Gay (static testing)
Mark Parsons (fatigue testing)
Paul Schulz (task leader)

This report covers the period from October 1993 to June 1995.

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GLOSSARY

21S	abbreviated designation for Titanium Metals Corporation's Timetal® Beta 21S
ASTM	American Society for Testing and Materials
BMS	Boeing Material Specification
CAA	chromic acid anodize
DITS	Design Integration Trade Study
HSCT	High-Speed Civil Transport
IR&D	internal research and development
ksi	thousand pounds force per square inch
msi	million pounds force per square inch
OHT	open-hole tension
PMC	polymer matrix composite
RMI	Reactive Metals Inc.
RT	room temperature
SPF	superplastically formed
ST	solution treated
STA 1000	solution treated and vacuum aged at 1,000°F for 8 hr
TMF	thermomechanical fatigue

1.0 SUMMARY

New titanium alloys with improved static and dynamic properties have the potential for applications on a Mach 2.4 High-Speed Civil Transport (HSCT). In addition, some of these alloys may offer reduced processing costs due primarily to the ability to form at lower temperatures. The objective of this effort was to begin to generate a physical and mechanical property database on two representative or model alloys. Titanium Metals Corporation's Timetal® Beta 21S (21S) was selected as being representative of the metastable beta alloy family, and RMI's Ti-6-2-2-2-2 was selected as being representative of newer alpha-beta alloys.

An analytical and experimental program, involving NASA, Lockheed Martin Aeronautical Systems, McDonnell Douglas Aerospace, and Boeing, was designed to provide static properties, notched and unnotched fatigue life, crack growth rate data in both the threshold and Paris regimes, residual strength following thermomechanical fatigue, and toughness data. The program also included crack growth rate modeling efforts. In all cases, testing was done at room and elevated temperatures representative of the HSCT operating environment. The Boeing portion of this overall plan included tests to determine static properties, fatigue life, and residual strength following thermomechanical fatigue (TMF). The residual strength portion of the program was dropped after initial static strength open hole tension properties were obtained. This test series was indicated to be unnecessary since past titanium alloys have not shown significant changes in residual strength following aging under load at temperatures in the range up to 450°F.

In order to ensure data compatibility, Boeing procured sufficient 21S to supply NASA and Lockheed test needs as well as their own. Likewise, Lockheed procured sufficient Ti-6-2-2-2-2 to supply NASA and Boeing.

This report covers baseline static testing of 21S and Ti-6-2-2-2-2, and includes the static test database (see Appendix D) on which this report is based. Fatigue tests have been initiated on both alloys and are continuing as planned. These tests will continue under Task 15 (Materials Durability) of NASA Contract NAS1-20220. Raw data obtained to date on these tests is reported in Appendix E; complete results will be reported under the new contract when they are available.

The original test plan called for both alloys to be evaluated following forming operations. Boeing had planned to stretch-form the 21S, and Lockheed's intent was to procure the Ti-6-2-2-2-2 after it had been superplastically formed (SPF'd). Problems obtaining acceptable amounts of either alloy in a formed state necessitated a switch to an unformed material baseline with limited testing conducted on formed material. These and other processing problems point out the risk that is endemic to working with newer materials.

Static test results for stretch formed 21S (1.8% forming level) showed typical yield stress ranging from 174 ksi at room temperature to 151 ksi at 350°F. Ultimate strength ranged from 201 ksi to 184 ksi, at these temperatures. The unformed 21S exhibited yield stess from 191 to 161 ksi, and ultimate strength from 202 to 178 ksi, at room temperature and 350°F respectively. The unformed 6-2-2-2-2 material showed yield stresses from 176 to 144 ksi, and ultimate strengths

from 187 to 168 ksi, at room and 350°F temperatures, respectively. In this temperature range, modulus for unformed 21S ranged from 15.7 to 14.9 Msi, formed 21S showed 15.9 to 14.7 Msi, and modulus for 6-2-2-2-2 ranged from 17.6 to 17.2 Msi.

2.0 INTRODUCTION

The HSCT program is currently looking at two families of materials for use in building a Mach 2.4 cruise speed airplane: titanium and polymer matrix composites (PMC). Any material that will be selected for use must be able to survive a 60,000-hr life at elevated temperatures up to 350°F. Figure 2.0-1 shows proposed vehicle design requirements for the HSCT, including those concerned with the durability issue (ref. 1). Figure 2.0-2 shows the latest thermal profiles for a Mach 2.4 version of the airplane. These profiles are generated by purely aerodynamic heating of the entire airframe at Mach 2.4; the local effect of higher temperatures in the vicinity of the engines is not included.

Design Element	Requirement	Design Element	Requirement
Mach number	2.0 to 2.4	Range, nmi	5,000 to 6,500
Flight length, hr	4.5	Altitude, ft	60,000 to 70,000
Engine fuel type	Conventional	Noise	FAR 36, Stage 3
Number of flights	30,000	Lifetime, hr	72,000
Time at cruise, hr	60,000	Temperature limit, °F	<350 (400 dive)

Figure 2.0-1. Vehicle Design Requirements

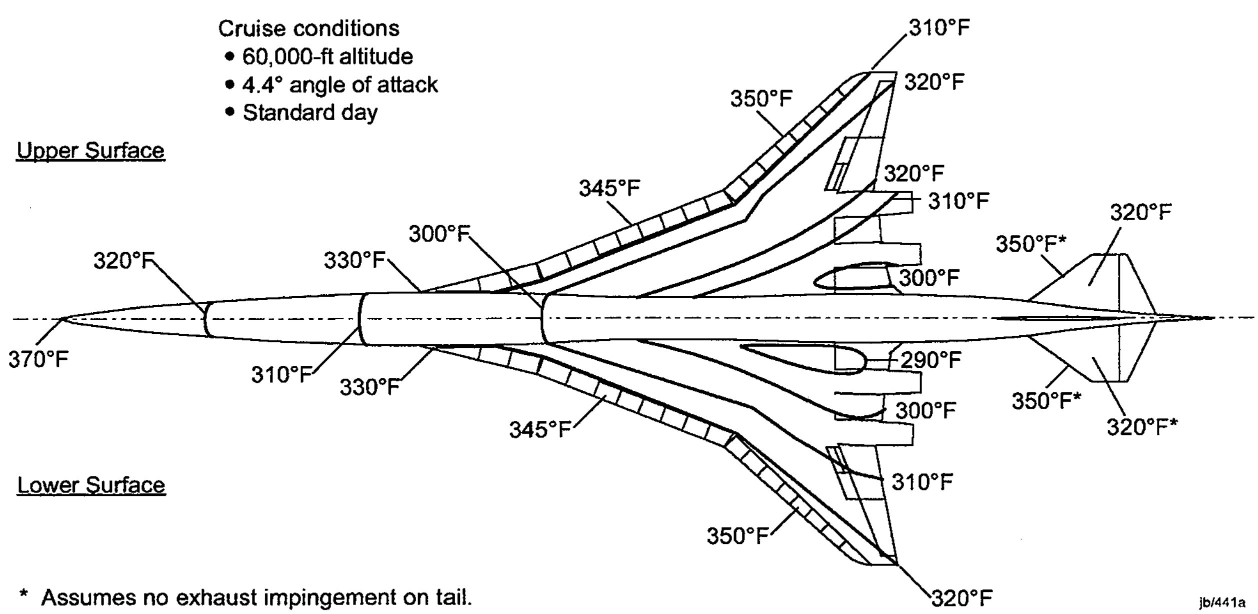


Figure 2.0-2. Study Vehicle Configuration and Thermal Profiles

An extensive program to provide environmental durability test data and life-prediction methods has been established to ensure that any material (metal or PMC) is viable for the HSCT. To date, no PMC has been validated for long-term use at the maximum temperatures expected for a Mach 2.4 aircraft. Even if PMCs are selected for the majority of the structure that does not encounter maximum temperatures, design studies show that upwards of 50% of the structure will still be titanium. Although the investigation to date has centered on sheet and strip forms, much of the weight will be composed of other forms, such as plate, forgings, and extrusions. Even though the new titanium alloys offer attractive properties, a considerable durability and damage tolerance database will have to be generated to provide the confidence necessary to commit them to an airplane.

3.0 TECHNICAL APPROACH

3.1 Materials and Processes

Alloy development is an ongoing activity for the HSCT. It is possible that the alloys eventually selected for production are not yet widely available. Because long-term durability validation involves some real-time testing, it is necessary to select representative or model alloys for long-term durability testing. These alloys will become part of a test program designed to validate both the alloy families and a variety of analytical methodologies being developed to predict long-term behavior in terms of material response, residual strength, and life. Figure 3.0-1 shows the evolution of titanium properties over the last 25 years. Included on this chart are the high strength (Titanium Metals Corporation's Timetal ® Beta 21S) and high toughness (RMI's Ti-6-2-2-2-2) alloys selected as models for use on this program (ref. 2).

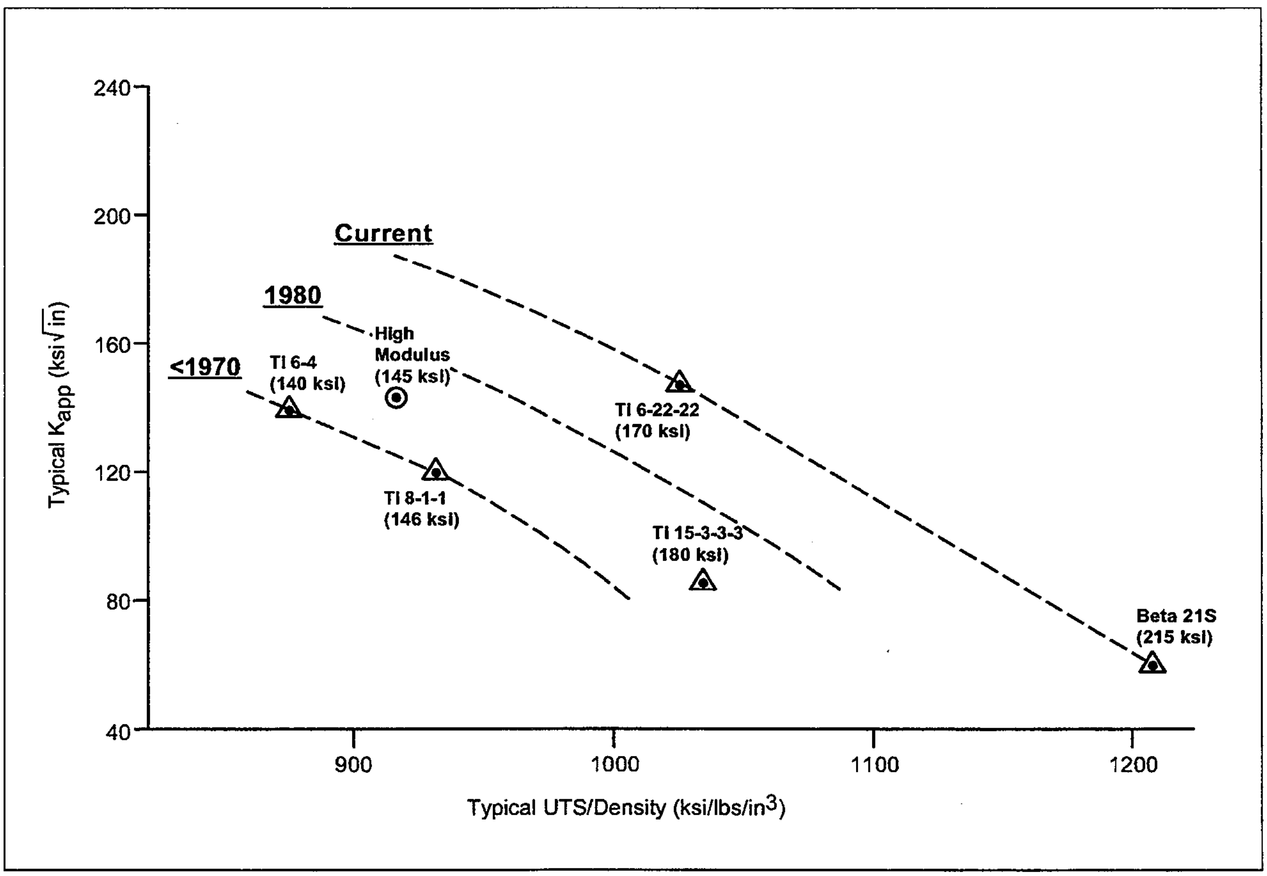


Figure 2.0-3. Titanium Alloy Development

3.1.1 Timetal Beta 21S

The model beta alloy selected for evaluation was 21S. This recently developed alloy was specifically designed for improved oxidation and chemical resistance, elevated temperature strength, creep resistance, and thermal stability. Although this alloy is also available in sheet, plate, bar, and billet, the main interest is in strip form, where it is available in continuous lengths, reasonable widths, and a variety of thicknesses.

21S is normally purchased in the solution-treated (ST) condition, formed in the "as-received" condition, then aged to develop the desired strength characteristics. This procedure is followed because material elongation drops significantly following aging.

A 30-ft-long by 36-in-wide piece of strip was purchased in the ST condition. The nominal thickness was 0.060 in. The 21S strip procured for this task was purchased to and met the requirements of Boeing Material Specification (BMS) 7-334. Figure 3.1.1-1 shows the BMS requirements and applicable certification values. Complete vendor certifications are shown in appendix A.

	0.2% Offset yield stress, ksi	Ultimate strength, ksi	Elongation, %
BMS 7-334 requirement	115 to 140	120 to 145	8
Task material (Heat G9604)	127	131	15

Figure 3.1.1-1. Vendor Certifications for 21S Condition ST Material

The plan called for forming (stretching) this material to 2% permanent set and then converting it to condition STA 1000 by vacuum-aging for 8 hr at 1,000°F. Two separate problems occurred during the fabrication process. These involved the stretch-forming operation and staining experienced during chemical cleaning operations.

Although one piece was successfully stretch-formed to 1.9% permanent set, three other pieces failed during the forming operation at lower strain levels. Subsequent tests conducted on the as-received, condition ST material showed that it did not work harden as most metals (including 21S in the STA condition) do. This indicated that the initial successful stretch-forming operation was probably the exception rather than the rule. Even if it were possible to stretch additional pieces of this material, it was obvious that considerable expense would be required to create a "formed" baseline. Based on this, a decision was made, with NASA concurrence, to switch to unformed stock as the baseline and to conduct limited testing with formed material.

The second problem that occurred while fabricating 21S specimens concerned staining of the alloy during chemical cleaning. The particular pieces of material affected by this problem were not converted to specimens and therefore did not affect the task results, but this problem does raise concerns about the material's desirability for use on the HSCT.

Details of these fabrication anomalies can be found in appendix B.

3.1.2 Titanium-6-2-2-2-2

The model alpha-beta alloy selected for this evaluation is Ti-6-2-2-2-2, developed by RMI Titanium Co. This alloy was initially developed in the early 1970s. It was intended to provide high strength in heavy sections with good fracture toughness (ref. 3). It is reported to possess excellent SPF characteristics. More recent efforts have centered on refining thermomechanical processing procedures to optimize strength, toughness, and crack growth rate properties. This alloy is produced in standard wrought product forms such as sheet, plate, bar, and forgings. The material tested on this task was obtained from Lockheed and machined into specimens in the as-received condition. Lockheed-furnished vendor certification values are shown in appendix C. No fabrication anomalies were noted with this alloy.

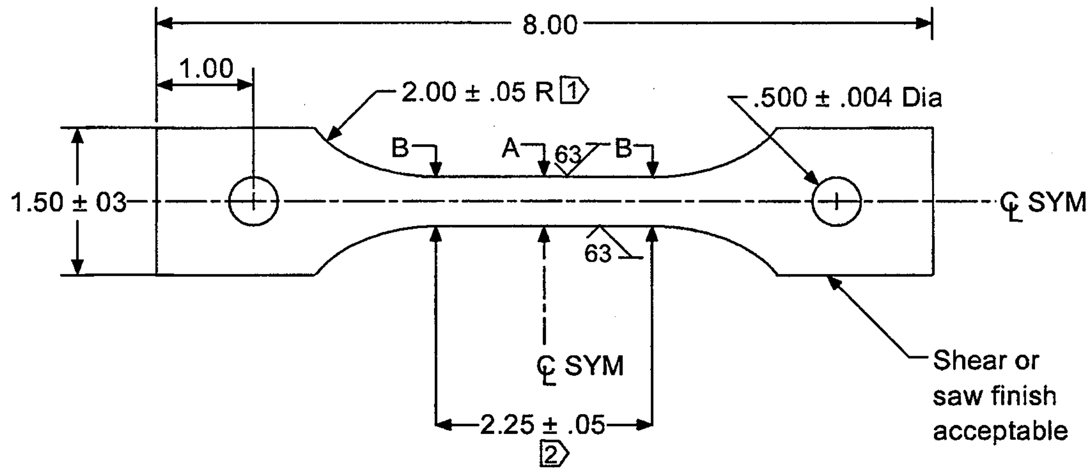
3.2 Mechanical Test Program

3.2.1 Baseline Static Testing

Static tests were planned to verify initial material quality and determine baseline unexposed stress-strain behavior. Figure 3.2.1-1 shows the static test plan for each alloy. The plan used both dogbone specimens and notched (open-hole) tension tests. The dogbone specimen used for unnotched tension is shown in figure 3.2.1-2. The specimen used for open-hole tension (OHT) is shown in figure 3.2.1-3.

Specimen Series Number	Specimen Drawing Number	Test Temperature	Replicates
T-1	D6-4671-877	RT	3
T-2	D6-4671-877	250°F	3
T-3	D6-4671-877	350°F	3
T-4	D6-4671-877	400°F	3
OHT-1	SP00046	RT	3
OHT-2	SP00046	250°F	3
OHT-3	SP00046	350°F	3

Figure 3.2.1-1. Baseline Test Plan for Each Alloy



Tolerances:
X.XX ± .03
X.XXX ± .003
X.XXXX ± .0005
Except as noted

A	.505 max .495 min
B	A + .003 to A + .005

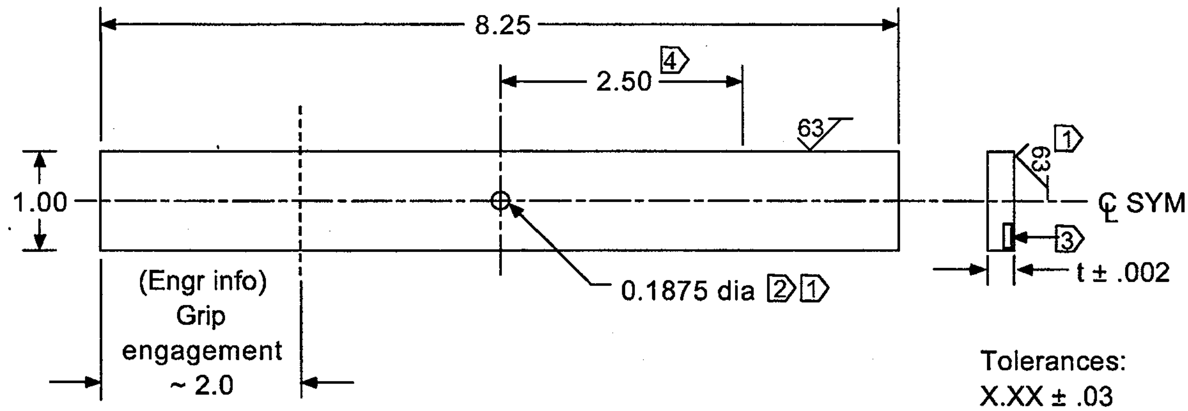
1 Fillet radii must fair smoothly into the reduced section.

2 The reduced section must be symmetrical about the ℄ of the holes to within ± .01. The "B" width must decrease uniformly and smoothly into the "A" width the center.

Notes:
1. Do not alter the natural finish of the material.
2. Rubber stamp part no. per instructions on shop order.
3. Directions of grain per EWR release.

jb/78€

Figure 3.2.1-2. Unnotched Tension Specimen



Tolerances:
X.XX ± .03
X.XXX ± .003
X.XXXX ± .0005
Except as noted

1. The surface roughness shall exhibit a finish of rhr 63 or better.

2. Drill pilot hole approximately .01 diameter less than reamer size with an aluminum backing plate to reduce burrs. Use a speed of approximately 1750 RPM and a feed rate of 2 5/8 in per min. Ream the center hole with a .187 diameter reamer with an aluminum backing plate. The hole wall finish is to be rhr 63 or better. Drill and ream each specimen individually.

3. Steel stamp or electro etch specimen ID at this location on both ends per fabrication release.

4. Edge radii in test section should be .02 to .04 radius.

Notes:
1. Tolerances shall be as noted
2. Break all edges
3. Machine specimens from center of plate thickness

jb/787

Figure 3.2.1-3. OHT Specimen

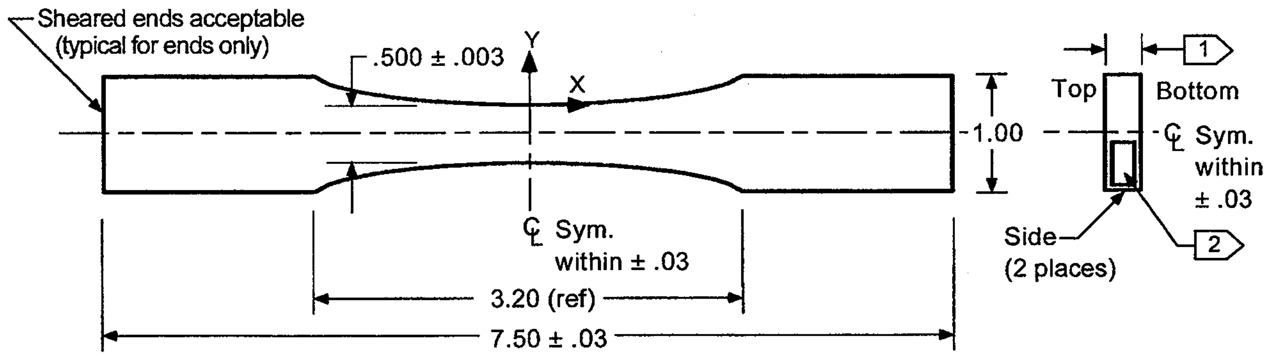
3.2.2 Unnotched Fatigue Life Testing

Fatigue life testing to evaluate the effects of stress, temperature, and frequency was planned using unnotched ($K_t = 1.0$) specimens. The test plan for each alloy is shown in figure 3.2.2-1. The specimen used for unnotched fatigue testing is shown in figure 3.2.2-2.

Specimen Series Number	Target Life, cycles	Test Temperature, °F	Frequency, Hz	Replicates
LIFE-1	100,000	RT	5	5
LIFE-2	100,000	250	5	5
LIFE-3	100,000	350	5	5
LIFE-4	100,000	400	5	3
LIFE-5	300,000	RT	5	5
LIFE-6	300,000	250	5	5
LIFE-7	300,000	350	5	5
LIFE-8	300,000	400	5	3
LIFE-9	100,000	RT	0.5	5
LIFE-10	100,000	250	0.5	5
LIFE-11	100,000	350	0.5	5

Figure 3.2.2-1. Unnotched Fatigue Test Plan for Each Alloy

Fatigue tests have been initiated on both alloys and are continuing as planned. These tests will continue under Task 15 (Materials Durability) of NASA Contract NAS1-20220. Raw data obtained to date on these tests is reported in Appendix E; complete results will be reported under the new contract when they are available.



X ± .003	Y ± .003
.10	.0006
.20	.0023
.30	.0052
.40	.0093
.50	.0146
.60	.0213
.70	.0293
.80	.0390
.90	.0504
1.00	.0637
1.10	.0795
1.20	.0981
1.30	.1205
1.40	.1483
1.50	.1856
1.60	.2500

[1] Thickness per EWR.
[2] Specimen ID stamped per EWR. Both ends.

Notes:

1. 63 or better - all surfaces.
2. Hand-finish test section sides with dowel and 320 grit sandpaper in longitudinal direction of specimen. Flat deburr top and bottom surfaces In longitudinal direction of specimen (non-clad surfaces only).
3. Tolerances: .xx ±0.03 .xxx ±.005 (except as noted).
4. All machining per BAC 5492. Class I. Titanium Only.

jb/903

Figure 3.2.2-2. Unnotched Fatigue Test Specimen

3.2.3 Notched Fatigue Life Testing

Limited fatigue life testing was planned for the OHT specimens shown previously (fig. 3.2.1-3). This was done to establish an initial notched specimen fatigue life database. No attempt was made to fully characterize the fatigue life. All testing was planned at 5.0 Hz.

Fatigue tests have been initiated on both alloys and are continuing as planned. These tests will continue under Task 15 (Materials Durability) of NASA Contract NAS1-20220. Raw data obtained to date on these tests is reported in Appendix E; complete results will be reported under the new contract when they are available.

4.0 RESULTS AND DISCUSSION

4.1 Beta 21S Baseline Static Testing

Static test results for the 21S strip material are summarized in figure 4.1.1-1a for unnotched tension. The same results are presented in graphical form in figure 4.1.1-1b. Open hole tension test results are summarized in figure 4.1.1-2. The open hole results were planned to be used for comparison with residual strength test results. The residual strength tests were subsequently determined to be unnecessary since past titanium alloys have not shown significant changes in residual strength following aging under load at temperatures in the range up to 450°F. The results for individual specimens are listed in appendix C. Typical stress-strain curves for the formed material are shown in figure 4.1.1-3. Typical stress-strain curves for the unformed material are shown in figure 4.1.1-4. Figure 4.1.1-5 shows the room temperature test setup. Figure 4.1.1-6 shows the elevated temperature test setup used for the 250° and 350°F testing. Testing at 400°F was conducted in an oven (fig. 4.1.1-7). Typical failed specimens are shown in figure 4.1.1-8.

Beta 21S, nominal 0.060 strip, STA 1000, tension, longitudinal

Forming level %	Test temp., °F	Elastic modulus, msi	0.2% offset yield stress, ksi	Ultimate strength, ksi	Elongation %	Replicates
1.8	70	15.9	174	201	5	8
1.8	350	14.7	151	184	11	2
0	70	15.7	191	202	8	3
0	250	15.2	170	184	9	3
0	350	14.9	161	178	10	3
0	400	(1)	160	173	10	3
BMS 7-334 Requirement for STA 1000: (2)			165	180	4(unformed)	

(1) Modulus not reported due to unresolved test measurement discrepancy.

(2) Room temperature requirement.

Figure 4.1.1-1a. Beta 21S STA 1000 Unnotched Tension Static Test Summary

These results show that the material exceeds the requirements of BMS 7-334 for the STA1000 condition. Validity of the 400°F modulus test data is in question. The 400°F tests used high-temperature strain gages, unlike the lower temperature tests that used extensometers. Although individual stress-strain curves looked reasonable and scatter for replicate specimens was low, the modulus indicated by measurements at 400°F was 18% higher than that reported at 350°F. An attempt was made to resolve this discrepancy by testing excess formed specimens with both strain gage and extensometer instrumentation. These tests were, however, unable to resolve the discrepancy. It was concluded that a data acquisition error occurred. No attempt was made to fabricate new specimens and retest since interest in this alloy had declined.

Beta 21S, nominal 0.060 strip, STA 1000, tension, longitudinal

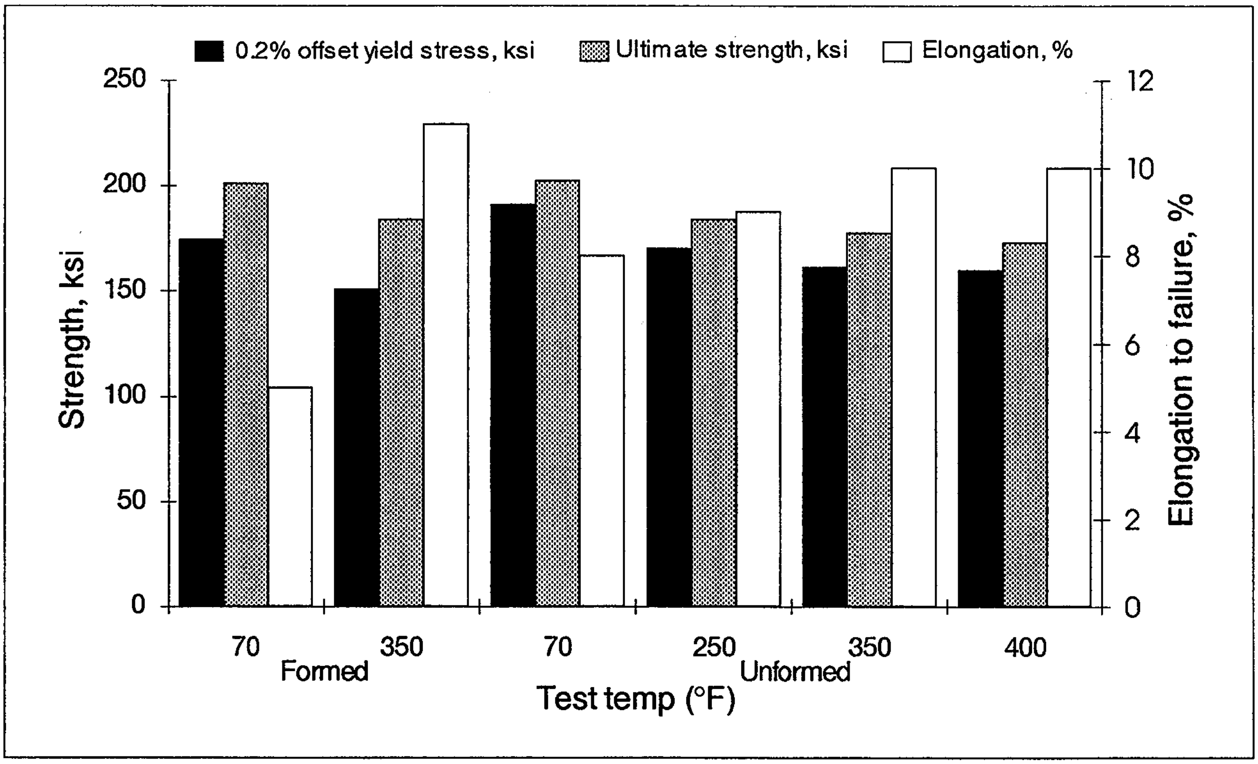


Figure 4.1.1-1b. Beta 21S STA 1000 Unnotched Tension Static Test Summary

Beta 21S, 0.060 strip, open hole tension, nominal 1" width, nominal 3/16" hole, longitudinal direction

Forming level %	Test temp., °F	Ultimate gross stress, ksi	Ultimate net stress, ksi	Ultimate load, lbs	Elongation, %	Replicates
1.8	70	147	181	8683	(1)	3
1.8	250	147	181	8540	3	3
1.8	350	145	178	8397	4	3
0	70	166	204	9957	4	3
0	250	152	186	9097	6	3
0	350	146	179	8701	7	3

(1) Specimen elongation not taken.

Figure 4.1.1-2. Beta 21S STA 1000 Open Hole Tension Static Test Summary

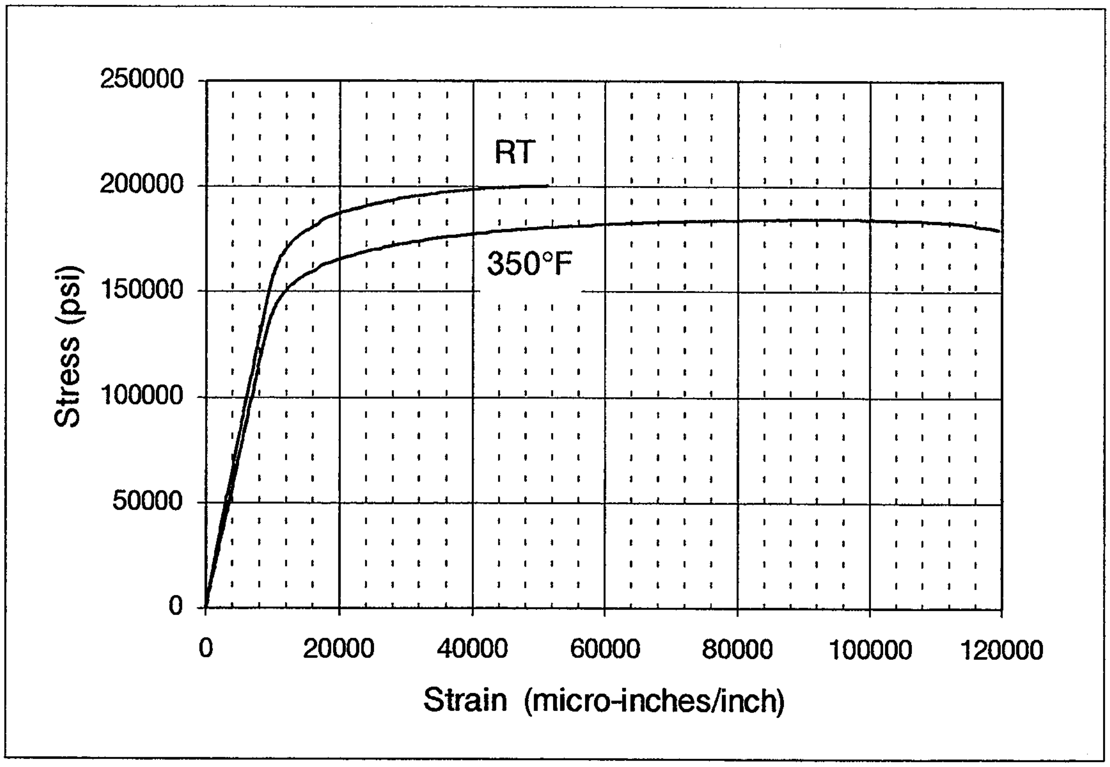


Figure 4.1.1-3. Typical Stress-Strain Curves for Formed 21S

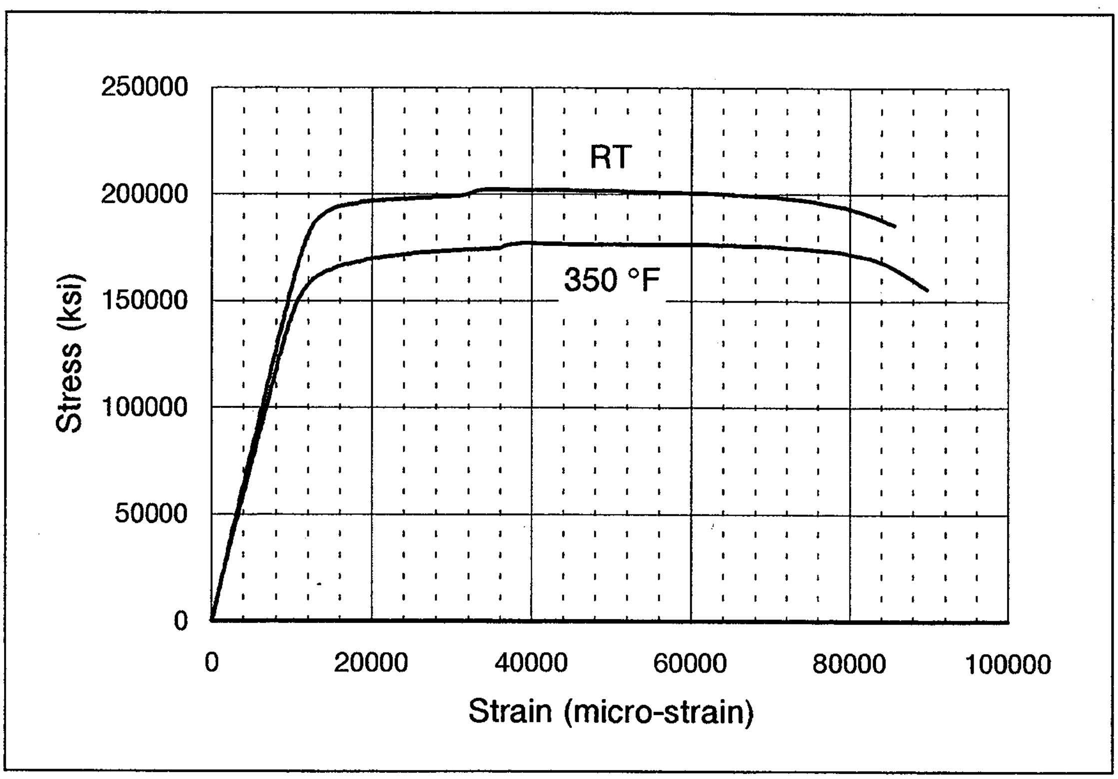


Figure 4.1.1-4. Typical Stress-Strain Curves for Unformed 21S

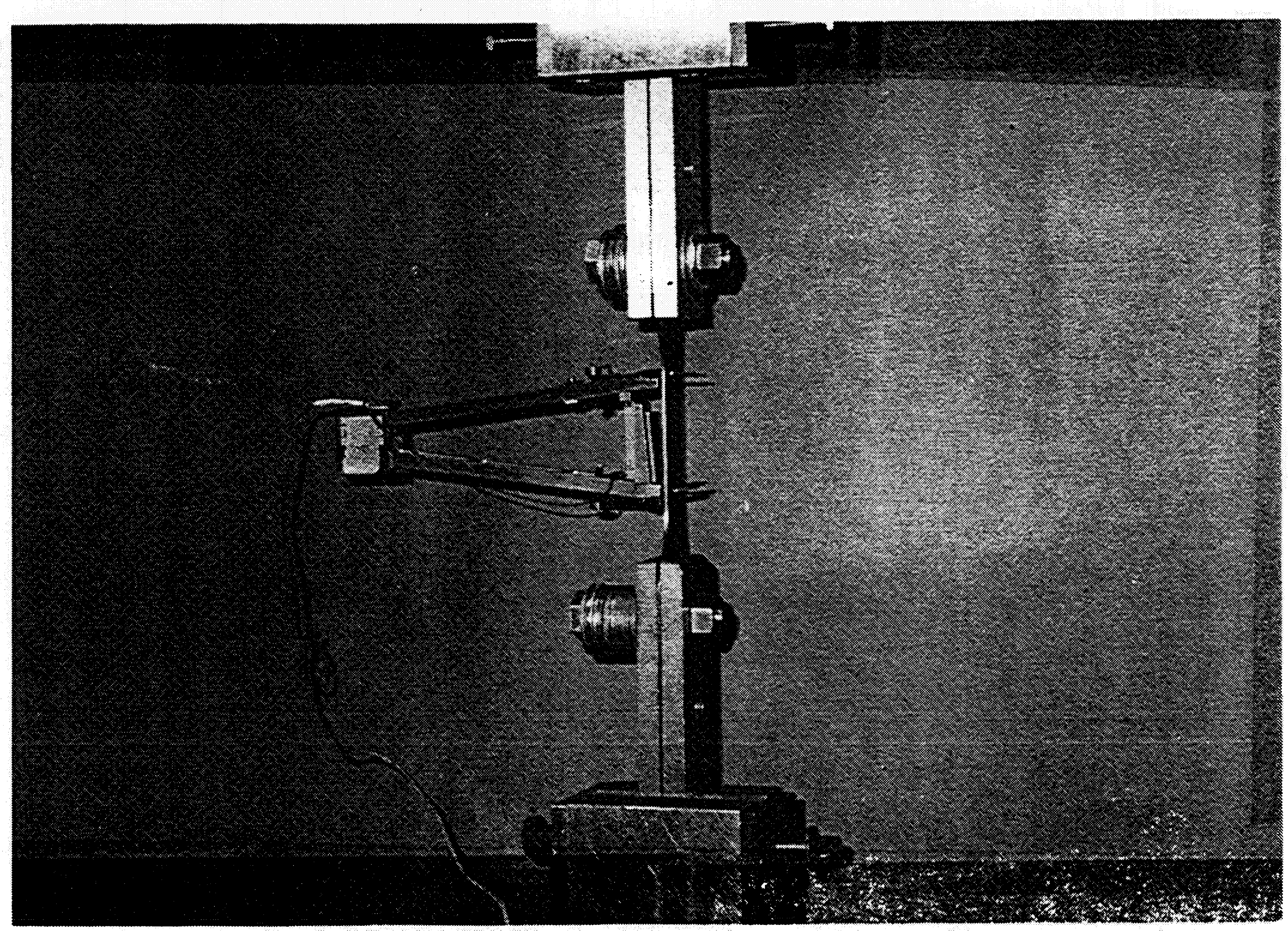


Figure 4.1.1-5. Room Temperature Test Setup

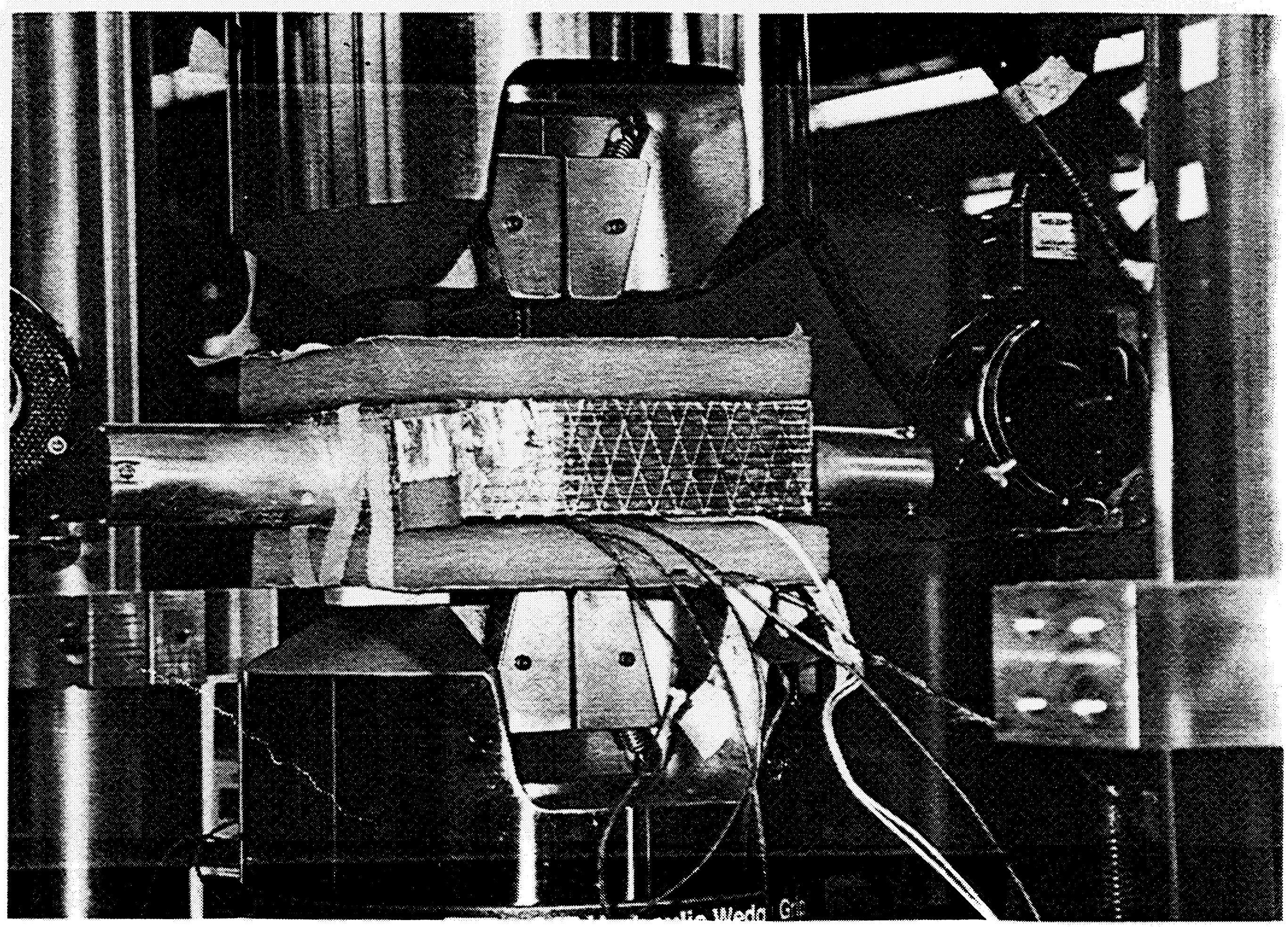


Figure 4.1.1-6. 250° and 350°F Test Setup

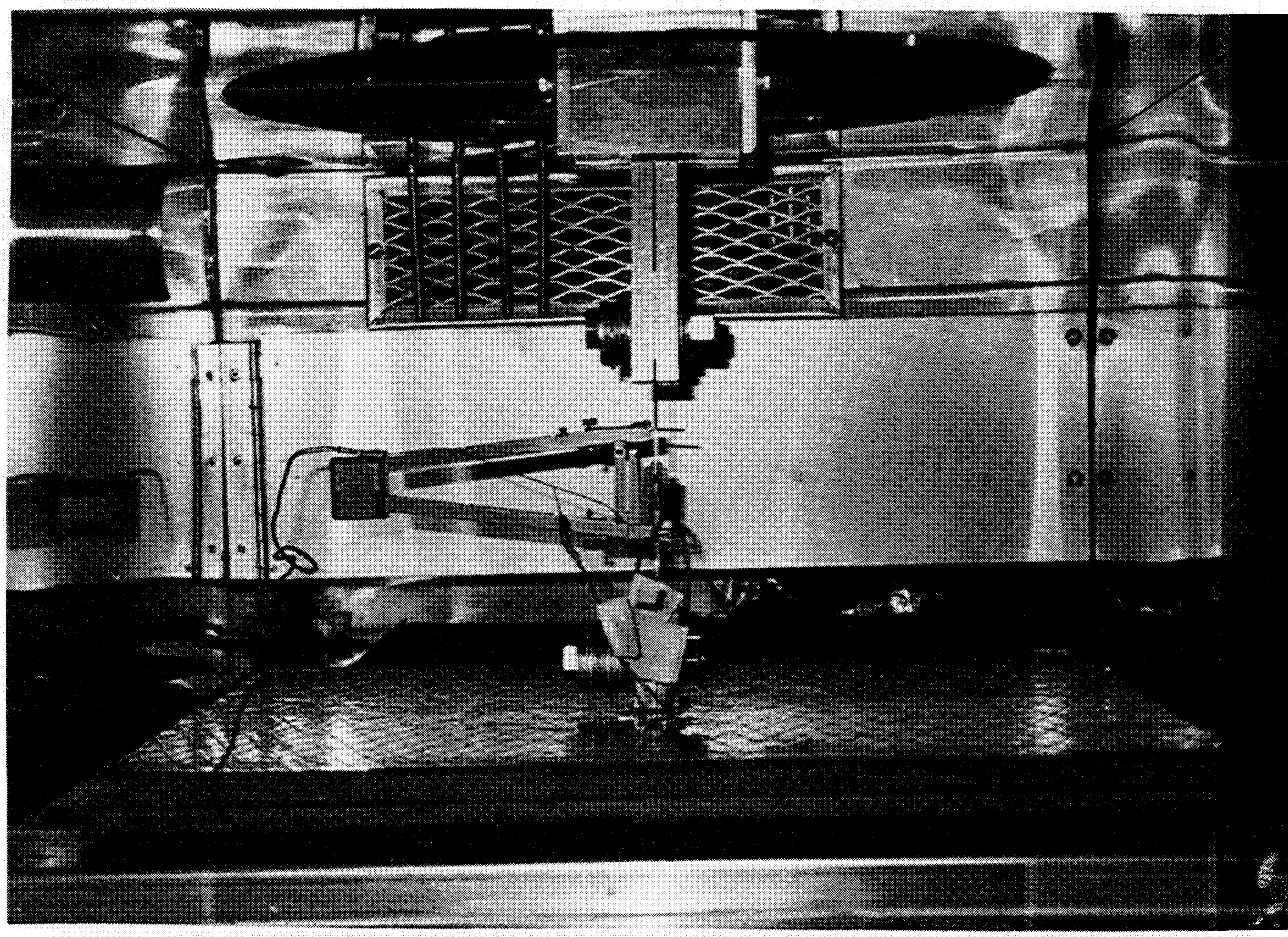


Figure 4.1.1-7. 400°F Test Setup

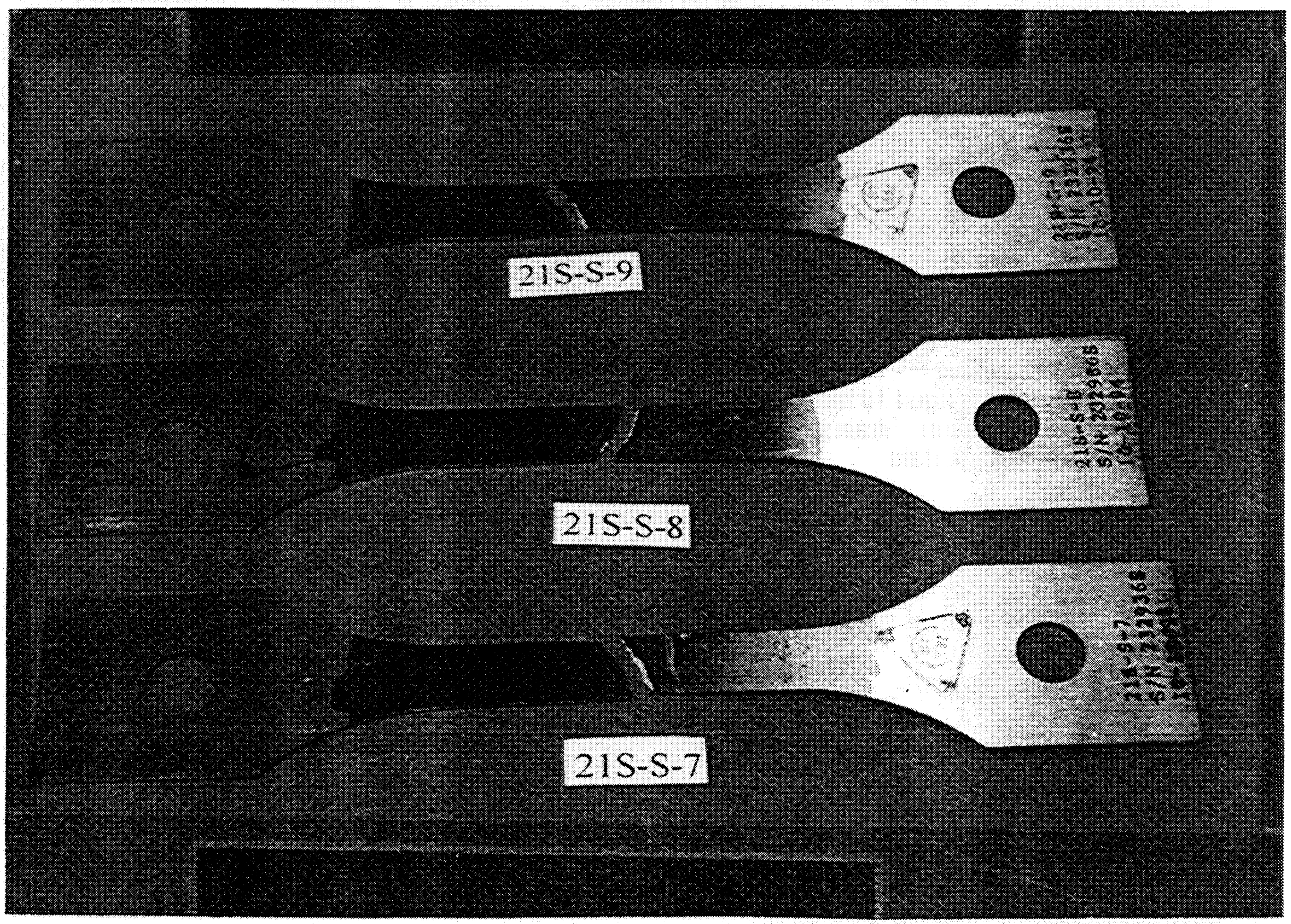


Figure 4.1.1-8. Failed 21S Static Test Specimens

4.2 Ti-6-2-2-2-2 Baseline Static Testing

Static test results for the unformed 6-2-2-2-2 sheet material are summarized in figure 4.2.1-1a for unnotched tension. The same results are presented in graphical form in figure 4.2.1-1b. Open hole tension test results are summarized in figure 4.2.1-2. The open hole results were planned to be used for comparison with residual strength test results. For the reasons noted in section 4.1 the residual strength tests were subsequently determined to be unnecessary. The results for individual specimens are listed in appendix C. Typical stress-strain curves are shown in figure 4.2.1-3. Test setup and equipment is the same as used for Beta21S testing (ref Figures 4.1.1-5 thru 4.1.1-7).

Ti-6-2-2-2-2, 0.17% Si, .068 (nominal) sheet, STA (1), tension

Forming level %	Test temp., °F	Elastic mod (msi)	Fty (ksi)	Ftu (ksi)	Elongation, %	Replicates
0	70	17.6	176	187	8	3
0	250	17.0	151	173	8	3
0	350	17.2	144	168	9	3
0	400	17.1 (3)	138	165	(2)	3

(1) ST 30 min @ 1650°F, aged 10 hrs @ 950°F.
(2) Elongation was not taken. Strain gage installation obscured elongation gage marks.
(3) E based on strain gage data.

Figure 4.2.1-1a. Ti-6-2-2-2-2 STA Unnotched Tension Static Test Summary

Ti-6-2-2-2-2, 0.17% Si, .068 (nominal) sheet, STA (1), tension

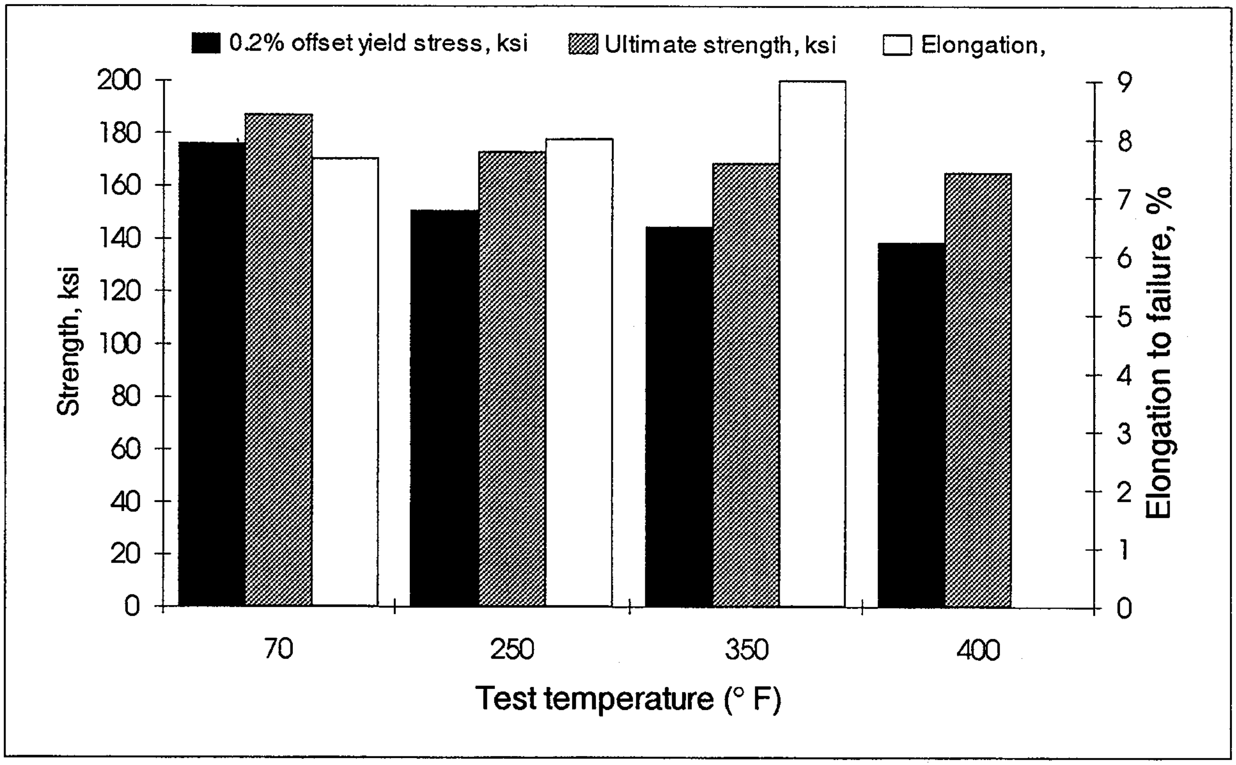


Figure 4.2.1-1b. Ti-6-2-2-2-2 STA Unnotched Tension Static Test Summary

Ti-6-2-2-2-2, 0.17% Si, .068 (nominal) sheet, STA(1), open hole tension nominal 1" width 3/16" hole

Forming level %	Test temp., °F	Ultimate gross stress, ksi	Ultimate net stress, ksi	Ultimate load, lbs	Elongation, %	Replicates
0	70	150	184	10090	(2)	3
0	250	135	167	9230	(2)	3
0	350	132	162	8940	(2)	3

(1) ST 30 min @ 1650°F, aged 10 hrs @ 950°F
(2) Elongation not taken
(3) Data from this test series not yet available

Figure 4.2.1-2. Ti-6-2-2-2-2 STA Open Hole Tension Static Test Summary

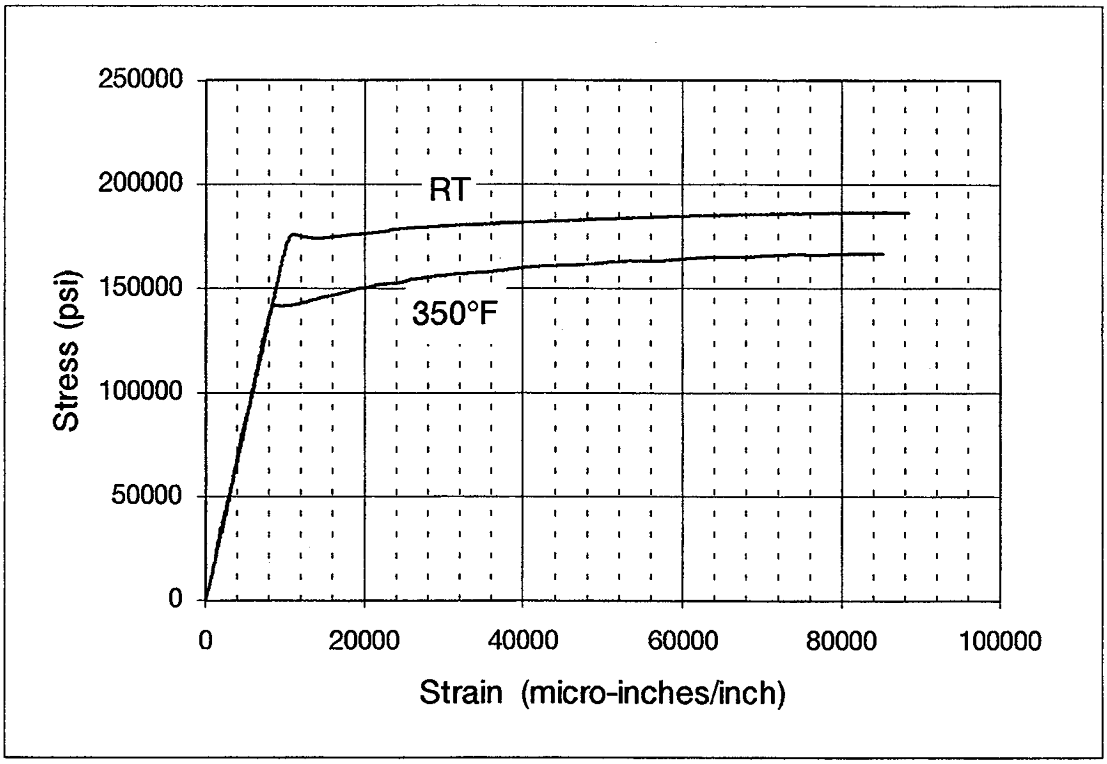


Figure 4.2.1-3. Typical Stress-Strain Curves for Unformed 6-2-2-2-2

5.0 CONCLUSIONS

Mechanical properties for Beta21S met material specifications; however, stretch forming was demonstrated to be very difficult. The majority of the material on which stretch forming was attempted was damaged and not used for test. This problem with the alloy contributed to it's being dropped as a candidate material.

Ti-6-2-2-2-2 testing produced strength properties at expected levels.

6.0 RECOMMENDATIONS

Unformed, as received materials, should be used for baseline testing. Limited testing of formed materials can be attempted to explore forming effects on properties.

After the initial Beta21S static and fatigue test matrices are completed, the material should be dropped from the durability test program. Testing on Ti-6-2-2-2-2 sheet material should continue.

7.0 REFERENCES

1. Bhatia, Kumar G. et. al.: NASA Materials and Structures Design Integration Trade Study, First Year Written Report, NAS1-19349, Task Assignment No. 8, NASA CR, January 1995.

2. Curtis, Gene: MDOC Titanium Alloy Development, NAS1-20013, Task Assignment No. 1, Task Review, October 19, 1994.

3. Boyer, Rod; Welsch, Gerhard; Collings, E.W.: Materials Properties Handbook: Titanium Alloys, ASM International, c. 1994, p. 713.

APPENDIX A - BETA 21S SUPPLIER CERTIFICATIONS

Supplier certifications for 21S are contained on the following pages.

ATTACHMENT TO PRODUCT CERTIFICATION

TIMET

Titanium Metals Corporation
TIMET Central Distribution Center
100 South Air Park Blvd., Morristown, TN 37813
Telephone (615) 587-1888 FAX (615) 586-4228

Mill Order	INVOICE	CUSTOMER	Purchase Order
89552	113443	BOEING COMPANY	HX1982

Heat	TEST	Grade	Product Description
G9604	W8186	TIMETAL * 21S	.060 X 36 X 360

SPECIFICATIONS

BMS7-334A

Results are from TIMET Quality Control Records on file. The undersigned has verified that the information on the attached mill product certification meets the requirements of the above referenced order.

5-2-94
Date

TIMET
43
JAMES A. TAYLOR
CDC Manager

Authorized Signature

First In Titanium Worldwide

CERTATT.DOC

ATTACHMENT TO
PRODUCT CERTIFICATION

TIMET®

Titanium Metals Corporation

TIMET Central Distribution Center
100 South Air Park Blvd., Morristown, TN 37813
Telephone (615) 587-1888 FAX (615) 586-4228

MILL ORDER 11652	INVOICE 115627	CUSTOMER BOEING COMPANY	PURCHASE ORDER HY7426
HEAT G9604	TEST W8186	GRADE TIMETAL * 21S	PRODUCT DESCRIPTION .060 X 36 X 360

SPECIFICATIONS

BMS 7-334

Results are from TIMET Quality Control Records on file. The undersigned has verified that the information on the attached mill product certification meets the requirements of the above referenced order.

TIMET 43 JAMES A. TAYLOR CDC Manager

6-28-94
Date

Authorized Signature

First in Titanium Worldwide

CERTATT.CDC

Titanium Metals Corporation
100 Titanium Way, Toronto, Ohio 43964
Telephone (614) 537-5695, FAX (614) 537-5759

APPROVED CERTIFICATE

MILL ORDER	CUSTOMER	PURCHASE ORDER
20-86976-21	TSC-CDC, Morristown, TN	CDC 400-1 REL 268
HEAT	GRADE	PRODUCT DESCRIPTION
G9604	TIMETAL®21S	.060 X 36 X COIL

SPECIFICATIONS

BMS 7-334_; TRE 2335_

CHEMICAL ANALYSIS
(Weight Percent)

	C	Fe	N	Al	Mo	O	Si
Max	0.050	0.400	0.040	3.500	16.000	0.150	0.250
Min		0.200		2.500	14.000	0.110	0.150
G9604-AVG	**0.013**	**0.340**	**0.009**	**3.000**	**14.950**	**0.145**	**0.195**

	Nb
Max	3.200
Min	2.400
G9604-AVG	2.615

	H2 (ppm)	LOCATION
Max	150	
G9604-W8186-AF	**27**	**FRONT**
G9604-W8186-AB	**29**	**BACK**

	OXYGEN	NITROGEN	LOCATION
Max	0.15	0.040	
Min	0.11		
G9604-W8186-AF	**0.14**	**0.005**	**FRONT**
G9604-W8186-AB	**0.14**	**0.004**	**BACK**

Balance titanium.

MECHANICAL PROPERTIES

Percent Recrystalization

IDENTITY	SECTION ID	RECRYSTAL IZATON %
G9604-W8186-F	**-**	**75**
G9604-W8186-B	**-**	**90**

Grain Size result

IDENTITY	GRAIN SIZE
Min	6
G9604-W8186-AF	**7.5**
G9604-W8186-AB	**7**

ANNEALED 2-5 MIN @ 1550F AC
Room Temperature Tensile Results

IDENTITY	TENSILE DIR	TS KSI	YS KSI	4D, % EL
Max		145	140	
Min		120	115	8
G9604-W8186-AF	**L**	**131**	**127**	**15**
G9604-W8186-AF	**T**	**134**	**131**	**15**

TIMET®
Titanium Metals Corporation
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APPROVED CERTIFICATE

MILL ORDER	**CUSTOMER**	**PURCHASE ORDER**
20-86976--21	TSC-CDC, Morristown, TN	CDC 400-1 REL 268
HEAT	**GRADE**	**PRODUCT DESCRIPTION**
G9604	TIMETAL®21S	.060 X 36 X COIL

MECHANICAL PROPERTIES

ANNEALED 2-5 MIN @ 1550F AC
Room Temperature Tensile Results

IDENTITY	TENSILE DIR	TS KSI	YS KSI	4D, % EL
Max		145	140	
Min		120	115	8
G9604-W8186-AB	**L**	**127**	**125**	**20**
G9604-W8186-AB	**T**	**130**	**129**	**19**

ANNEALED 2-5 MIN @ 1550F AC + 8 HRS @ 1000F AC
Room Temperature Tensile Results (YS @ .2% offset)

IDENTITY	TENSILE DIR	TS KSI	YS KSI	4D, % EL
Min		180	165	4
G9604-W8186-BF	**L**	**190**	**173**	**10**
G9604-W8186-BF	**T**	**196**	**182**	**7**
G9604-W8186-BB	**L**	**187**	**174**	**10**
G9604-W8186-BB	**T**	**193**	**178**	**10**

ANNEALED 2-5 MIN @ 1550F + 8 HRS @ 1100F
Room Temperature Tensile Results (YS @ .2% offset)

IDENTITY	TENSILE DIR	TS KSI	YS KSI	4D, % EL
Min		150	140	5
G9604-W8186-CF	**L**	**170**	**157**	**12**
G9604-W8186-CF	**T**	**173**	**160**	**11**
G9604-W8186-CB	**L**	**165**	**149**	**11**
G9604-W8186-CB	**T**	**166**	**153**	**12**

ANNEALED 2-5 MIN @ 1550F + 8 HRS @ 1275F AC + 8 HRS @ 1200F AC
Room Temperature Tensile Results (YS @ .2% offset)

IDENTITY	TENSILE DIR	TS KSI	YS KSI	4D, % EL
Min		125	115	10
G9604-W8186-EF	**L**	**140**	**127**	**15**
G9604-W8186-EF	**T**	**142**	**129**	**15**
G9604-W8186-EB	**L**	**133**	**120**	**17**
G9604-W8186-EB	**T**	**135**	**124**	**17**

COMPLIANCE STATEMENTS

1 105 degree bend test performed and is acceptable. Bend factor R/T 3.0 examined at 20X.
2 Surface free from contamination.

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100 Titanium Way, Toronto, Ohio 43964
Telephone (614) 537-5695, FAX (614) 537-5759

APPROVED CERTIFICATE

MILL ORDER	**CUSTOMER**	**PURCHASE ORDER**
20-86976-21	TSC-CDC, Morristown, TN	CDC 400-1 REL 268
HEAT	**GRADE**	**PRODUCT DESCRIPTION**
G9604	TIMETAL®21S	.060 X 36 X COIL

COMPLIANCE STATEMENTS

HEAT CODE = HACLA

105 degree bend test performed and is acceptable. Bend factor R/T 3.0 examined at 1X.

Results are from TIMET Quality Control Records on file.
Cert Master used: STR39

Date : 20-JAN-1994
Time : 10:52

8

Authorized Signature

This certification package contains the following checked items :

MANIFEST	✓
CERTIFICATION	✓
BILLET MAP	
CUSTOMER WAIVER FORM	

BRENT E. KING
QUALITY ASSURANCE AUDITOR

APPENDIX B - BETA 21S FABRICATION ANOMALIES

This appendix provides additional details on the 21S fabrication anomalies noted in section 3.1. The material was received as a 30-ft-long coil. It was then sheared into two pieces to fit the current setup on the stretch-form machine at Boeing's Emergent Manufacturing facility. Actual lengths were based on material needs of the various participants. The first piece, originally 163.5 in long, was successfully stretched to approximately 1.85% permanent set. This is based on an average of four measurements, including one set of scribe lines, two sliding forming strain indicators, and the overall length. Because it was the first piece, the total stretch was accomplished in two stages. The first load application provided 1.2% elongation.

The other half of the coil, originally 196.5 in long, failed at a grip edge at approximately 1.6% strain. The torn end was removed and the remainder stretched again to approximately 2.4% total strain. Both strain values were based on overall length measurement only.

A second coil of material was ordered, received, and sheared to the same lengths as had been used on the first coil. This material came from the same heat as the original order. The 163.5-in-long piece failed at the edge of the jaw during the stretch. Residual strain was estimated using width measurements and a Poisson ratio of 0.5 to account for the plastic regime. The center 100 in of the sheet (approximately station 30 to station 130) showed less than 0.4% elongation. Strain was higher near the ends, but only in the 0.8% to 1.0% range. This is substantially below the 17% to 20% elongation range reported on the material certifications for this heat.

Examination of the six ends obtained to this time showed a relatively sharp notch at the edge of the jaw (fig. B-1). Several corners showed through the thickness necking, and it appeared that failure was imminent. It was apparent that the initial successful stretch was the exception rather than the rule, and no attempt was made to stretch the 196.5-in segment of the second coil.

Static test specimens were then machined from the as-received, condition ST material. This was done to ensure that the material met specification and to examine how changes in strain rate or other parameters might help in stretch-forming this alloy. The one successful and two unsuccessful forming attempts had been conducted at a strain rate of approximately 0.03 in/in/min. It was estimated that the machine could stretch at approximately 0.003 in/in/min, but the beneficial effects of this, if any, were unknown.

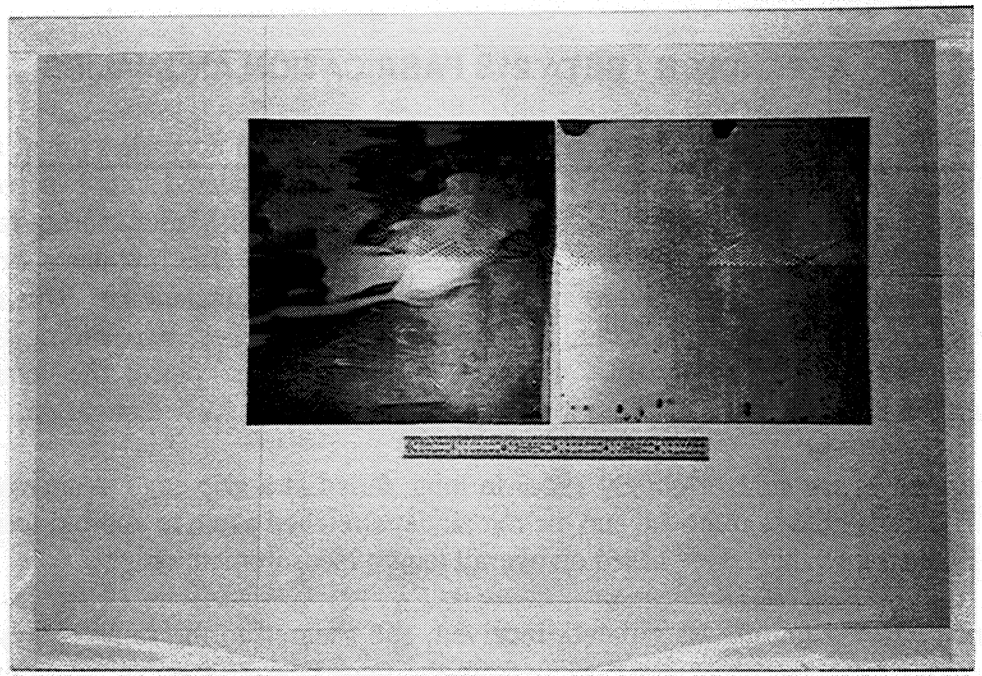

Figure B-1. *Typical Notch at End of Stretch Form Grip*

A total of eight specimens were tested. Typical results for three different strain rates are shown in figures B-2 through B-4. Figure B-2 shows a specimen loaded at 0.005 in/in/min through yield and then 0.01 in/in/min to failure. This loading scenario is in accordance with ASTM E8, so that the results can be used to verify that the material did meet the strength requirements of BMS 7-334. Figure B-3 shows a specimen loaded at 0.003 in/in/min to failure. This is equivalent to the slowest rate at which the production stretch-form facility could operate with sheets similar in length to those used on this task. Figure B-4 shows a specimen loaded at 0.03 in/in/min, simulating the rate at which the large sheets of material had been stretched. Although slower rates produced greater elongation, the most striking feature of all three curves is the lack of any work hardening. Based on these curves and the ends that were examined previously, it was felt that stretch-forming this material would be difficult at best, and a decision was made to switch to an unformed baseline for this task.

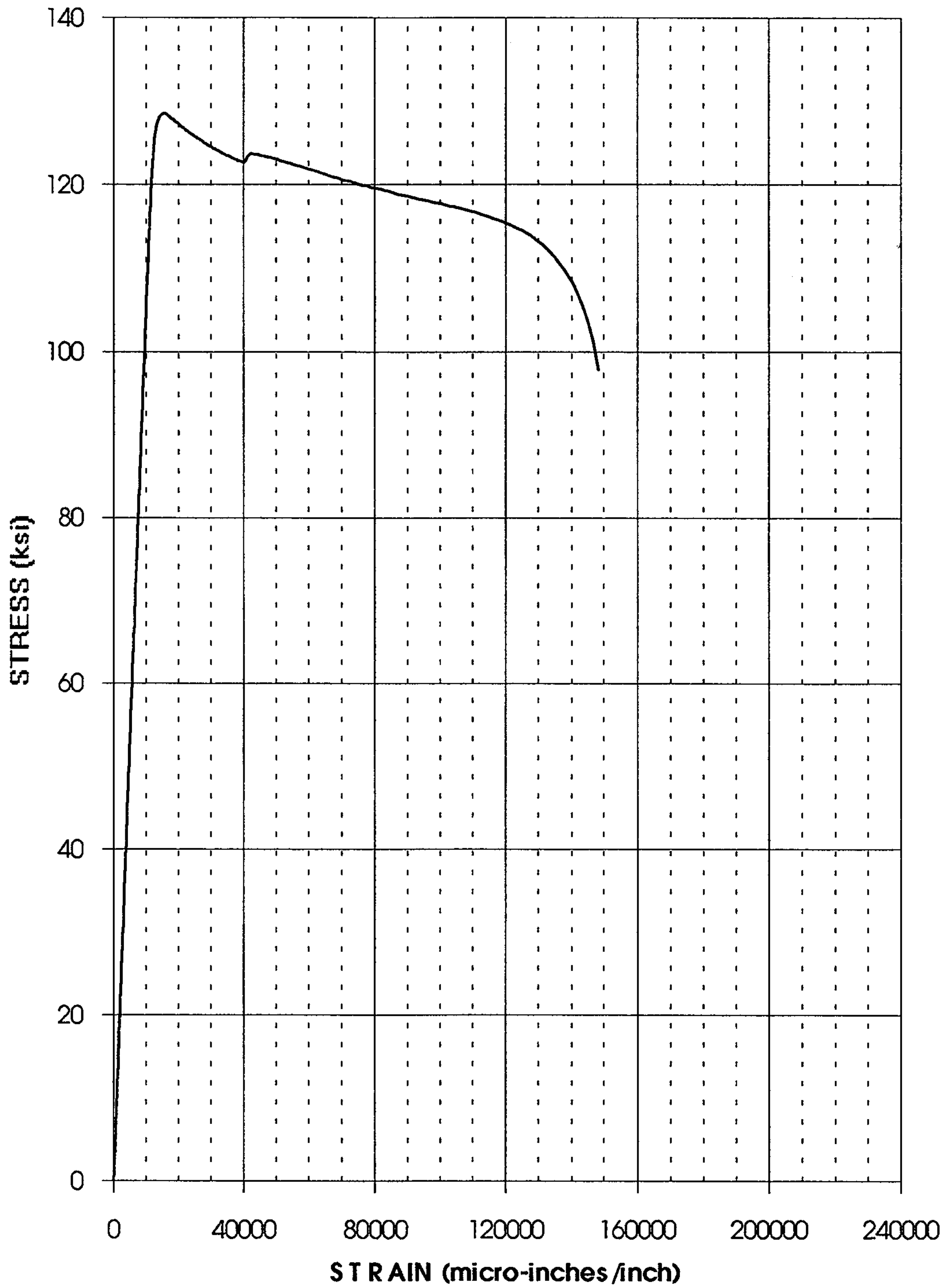

Figure B-2. *Beta 21S Loaded in Accordance With ASTM E8*

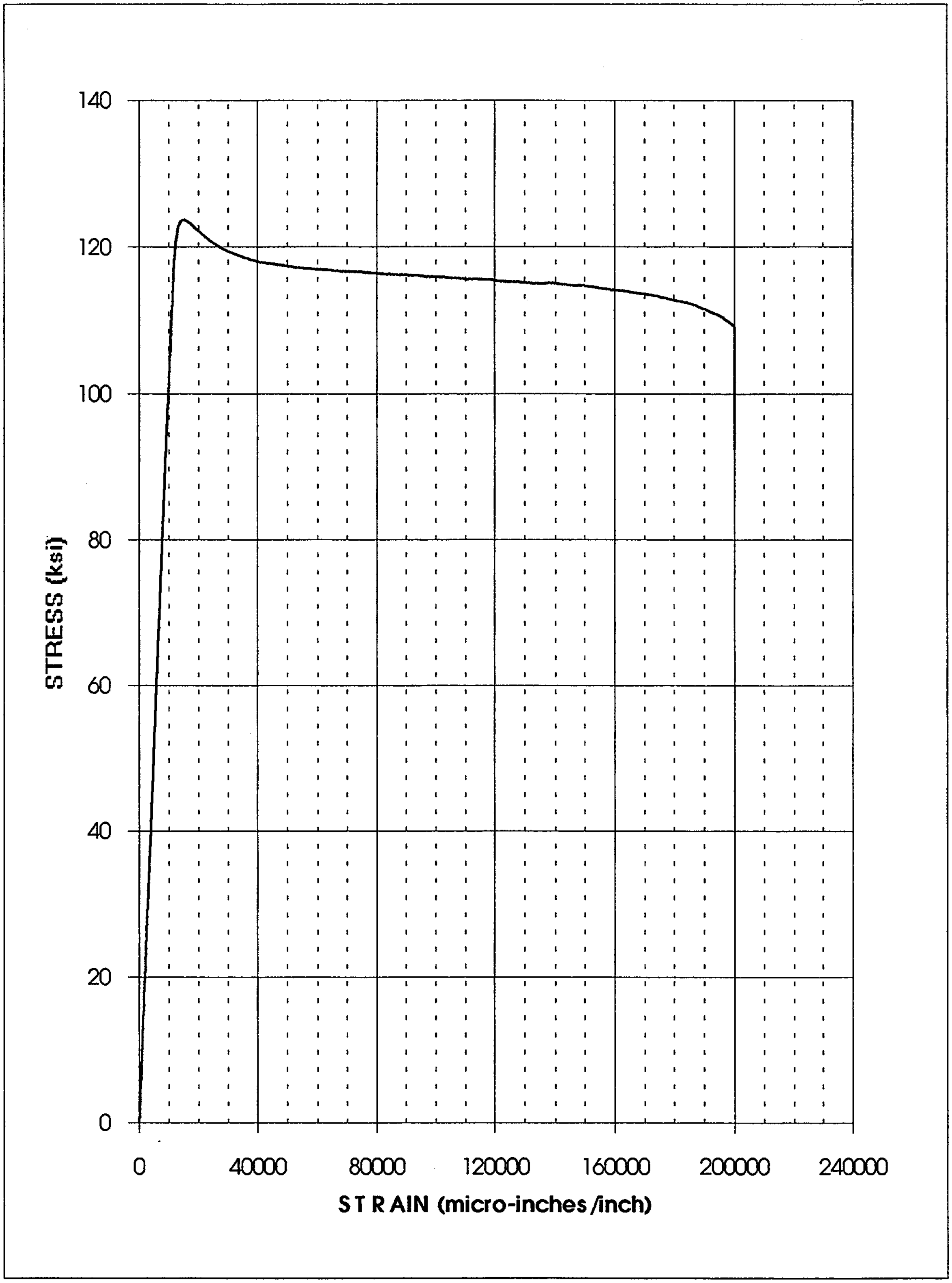

Figure B-3. Beta 21S Loaded at 0.003 in/in/min

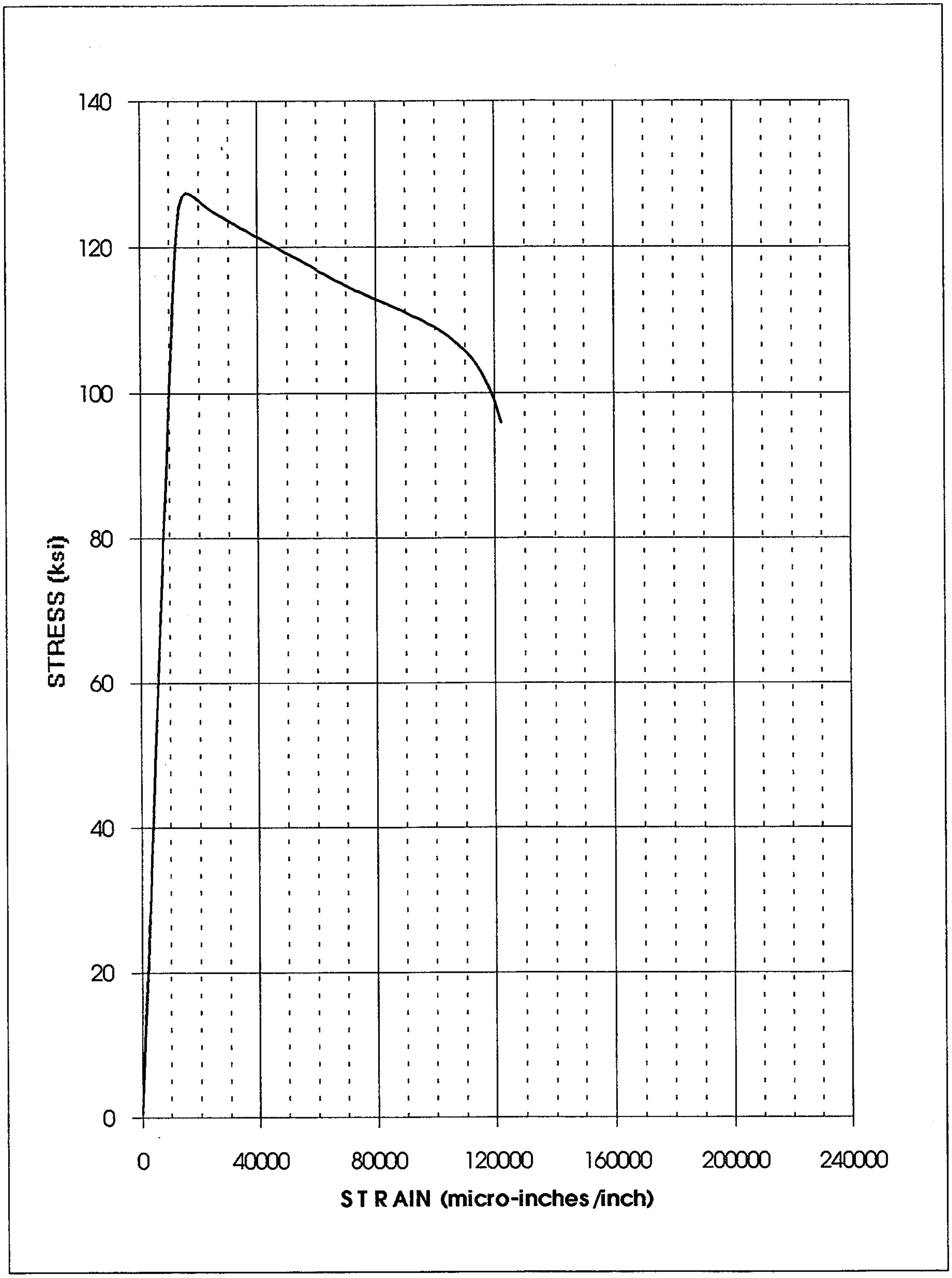

Figure B-4 *Beta 21S Loaded at 0.03 in/in/min*

The other fabrication anomaly concerned staining. A 54-in-long segment of the one piece that had been successfully stretched was vacuum-aged at 1,000°F. This was a trial run to ensure that no diffusion bonding would occur. The trial was successful and the segment had good visual appearance following age. There was minor stress relief pillowing in one area, but the piece was generally flat and uniform in color.

The vacuum-age facility was closed for significant repairs before the remaining pieces could be aged. BMS 7-334 refers to MIL-H-81200 for aging procedures. Both the BMS and the MIL specification allow aging in air at temperatures up to 1,000°F, and a decision was made to proceed in that manner. All remaining pieces were coated with Everlube and aged in air. Following air age, the parts were uniformly darkened. This was assumed to be due to the Everlube. The parts were then cleaned in accordance with Boeing Process Specification BAC 5753, method 2.

The initial step in this process is immersion in Isoprep 58, followed by air-water blast. The Isoprep 58 is used as a scale conditioner but also used to remove Everlube before additional cleaning. All pieces still contained significant darkened (stained) areas following the Everlube removal. This voided the initial assumption that the stain was Everlube.

Continuing the cleaning process, the parts then underwent a seven-step immersion clean process that includes alkaline clean (Isoprep 58), a nitric hydrofluoric etch, nitric acid immerse, three intermediate rinse operations, and air dry. The pieces were cleaned as follows:

1. Alkaline Clean. Immerse in Isoprep 58 for 10 to 20 min. (Specification allows full range of time. Parts with significant stain allowed to stay in for near maximum amount.) Solution temperature is 185°F.

2. Two-Stage Immersion Rinse. First tank held at 100°F and second tank at ambient temperature. Parts are in each tank less than 1 min.

3. Nitric Hydrofluoric Etch. Immerse in BAC 5753 solution 2B for 3 min; solution at room temperature.

4. Two-Stage Immersion Rinse. Both tanks are at ambient temperature. Parts are in each tank less than 1 min.

5. Nitric Acid Immerse. Immerse for 30 sec in BAC 5753 solution 14. Solution held at 120°F. Hose rinse as parts are removed from tank. BAC 5753 solution 14 equivalent to BAC 5625 solution 22.

6. Two-Stage Immersion Rinse. Both tanks are at ambient temperature. Parts are in each tank for 60 sec.

7. Air Dry. Parts held in 175°F lightly circulating air for 20 min.

An initial cleaning operation using these seven steps removed approximately 50% of the darkened area. In order to determine if a second cleaning cycle would remove the remaining stain, one piece was reprocessed through the seven steps listed above. Before initiating the actual cleaning steps, portions of the stain were removed with a jitterbug sander using 180 or finer grit. Also, the actual part was photocopied before and after sanding in an attempt to determine the effectivity of the second run to remove the remaining stain. A comparison of the part following cleaning with the photocopies indicated the following:

1. Stain was removed from areas that had been sanded and areas that had not been sanded.

2. New stains, equally dark, appeared in areas that were <u>not</u> stained prior to cleaning.

In light of this, a third cleaning operation was conducted The overall appearance of the sheet was recorded along with specific stain locations. No change in appearance was observed following the Isoprep and subsequent rinse. However, as the sheet was lifted from the nitric hydrofluoric etch, the appearance had changed dramatically. Side "south," previously heavily stained was now largely clean. Side "north," largely clean going into the tank, was now heavily stained, as shown in figure B-5. The remaining steps produced no discernible change in the location, amount, or shade of the stain.

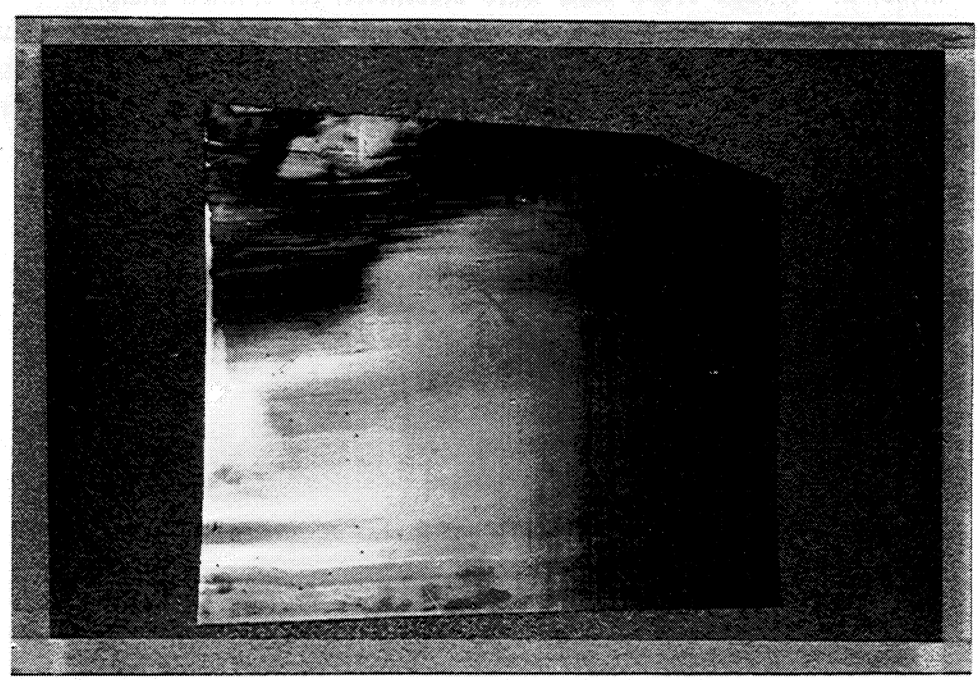

Figure B-5. Staining on 21S

Staining of 21S is reported to be a sporadic problem. Boeing has observed similar instances on IR&D studies dealing with surface preparation. Several participants at the October 1994 Metallic Materials review held at Langley also reported similar encounters. NASA experienced staining on a piece of material that had undergone electron discharge machining. Boeing processed many pieces of vacuum-aged foil through their titanium surface preparation procedure as part of MDOC Task 8 (Hybrid Laminate Development). The chemical solutions for this procedure vary from Boeing Process Specification BAC 5753 method 2, but both contain a nitric hydrofluoric immersion operation. Of the hundreds of foils processed in this manner, one displayed considerable stain as it emerged from this solution.

Boeing analyzed the stain and found it to be molybdenum oxide. This alloy has a relatively high (2.10%) molybdenum content, but no additional investigation was conducted to ascertain why the staining occurs in seemingly random fashion. As stated previously, this problem does not affect the results on this task. At NASA's request, none of the material that was aged in air and subsequently cleaned was used in the test program. Replacement material was ordered and vacuum-aged without incident. This replacement material was not stretched.

The fact that the staining occurred and has occurred elsewhere in a random fashion does raise concerns about the alloy's viability as a HSCT production material. The stain can be removed mechanically but it is a labor-intensive process. Fortunately, there is no evidence to suggest that bonding is affected. Wedge crack tests were conducted on stained material involved in the surface preparation studies. The results did not show a significant difference between stained and unstained material. Also, the stained foil from MDOC Task 8 emerged from the end of the surface preparation procedure in a clean state and was used in one of the hybrid laminates with no apparent adverse results.

APPENDIX C - TI-6-2-2-2-2 LOCKHEED-FURNISHED SUPPLIER CERTIFICATIONS

Supplier certifications for Ti-6-2-2-2-2 are contained on the following page.

Ti-6-2-2-2-2 Data Sheet
T. D. Bayha - Lockheed Martin ASC
Revised 02-03-95

Ti-6-2-2-2-2 Sheet

Lot # 801338
36" (W) x 96" (L) x 0.063"

Nominal Composition:

Al	Sn	Zr	Mo	Cr	Si	O	Fe	C	N	Y
5.74	1.96	2.04	2.10	2.05	0.17	0.11	0.11	0.01	0.004	<50 ppm

Mechanical Properties
(Average of 4 Specimens)

Ultimate Tensile Strength:	L	194.6 ksi
	T	189.0 ksi
Yield Stress:	L	183.2 ksi
	T	178.2 ksi
Elongation to Failure:	L	7.8%
	T	8.0%

Heat Treatment:
SHT: 1650°F/30 minutes
Air Cool
Age: 950°F/10 hours
Air Cool

Other: Micro grain size 10 or finer

APPENDIX D - STATIC TEST DATABASE

The database of static test results for each test specimen for Beta21S and Ti-6-2-2-2-2 is contained on the following pages.

Static Tension Tests

Record No.	Test Lab Specimen ID	Alloy	Forming Level (%)	Condition	Solution Treat (Time (min.) @ Temp (deg. F))	Age (Time (hrs) @ Temp (deg. F))	Test Type	Test temp (deg F)	Test Speed	Material Form	Gage (in)	Width (in)
1	BETA 21S-1-1	BETA21S	1.8	STA1000	5@1550	8@1000	TEN	RT	(1)	strip	0.0600	0.4995
2	BETA 21S-1-2	BETA21S	1.8	STA1000	5@1550	8@1000	TEN	RT	(1)	strip	0.0585	0.4970
3	BETA 21S-1-3	BETA21S	1.8	STA1000	5@1550	8@1000	TEN	RT	(1)	strip	0.0590	0.5000
4	BETA 21S-1-4	BETA21S	1.8	STA1000	5@1550	8@1000	TEN	RT	(1)	strip	0.0590	0.5025
5	BETA 21S-1-5	BETA21S	1.8	STA1000	5@1550	8@1000	TEN	RT	(1)	strip	0.0585	0.5005
6	BETA 21S-1-6	BETA21S	1.8	STA1000	5@1550	8@1000	TEN	RT	(1)	strip	0.0600	0.5010
7	BETA 21S-1-7	BETA21S	1.8	STA1000	5@1550	8@1000	TEN	RT	(1)	strip	0.0595	0.5005
8	BETA 21S-1-8	BETA21S	1.8	STA1000	5@1550	8@1000	TEN	RT	(1)	strip	0.0600	0.5010
9	BETA 21S-1-9	BETA21S	1.8	STA1000	5@1550	8@1000	TEN	350	(1)	strip	0.0595	0.5000
10	BETA 21S-1-10	BETA21S	1.8	STA1000	5@1550	8@1000	TEN	350	(1)	strip	0.0600	0.4980
11	BETA 21S-1R	BETA21S	0	ST	5@1550	NA	TEN	RT	(1)	strip	0.0615	0.5018
12	BETA 21S-2R	BETA21S	0	ST	5@1550	NA	TEN	RT	(2)	strip	0.0628	0.5005
13	BETA 21S-3R	BETA21S	0	ST	5@1550	NA	TEN	RT	(3)	strip	0.0636	0.5016
14	BETA 21S-4R	BETA21S	0	ST	5@1550	NA	TEN	RT	(4)	strip	0.0624	0.5010
15	BETA 21S-5R	BETA21S	0	ST	5@1550	NA	TEN	RT	(4)	strip	0.0643	0.4997
16	BETA 21S-5RA	BETA21S	0	ST	5@1550	NA	TEN	RT	(4)	strip	0.0643	0.4997
17	BETA 21S-6R	BETA21S	0	ST	5@1550	NA	TEN	RT	(1)	strip	0.0625	0.5007
18	BETA 21S-7R	BETA21S	0	ST	5@1550	NA	TEN	RT	(2)	strip	0.0619	0.5012
19	BETA 21S-8R	BETA21S	0	ST	5@1550	NA	TEN	RT	(1)	strip	0.0628	0.5003
20	BETA 21S-2-1	BETA21S	1.8	STA1000	5@1550	8@1000	OHT	RT	(14)	strip	0.0595	0.9975
21	BETA 21S-2-2	BETA21S	1.8	STA1000	5@1550	8@1000	OHT	RT	(14)	strip	0.0595	0.9975
22	BETA 21S-2-3	BETA21S	1.8	STA1000	5@1550	8@1000	OHT	RT	(14)	strip	0.0585	0.9980
23	BETA 21S-2-4	BETA21S	1.8	STA1000	5@1550	8@1000	OHT	250	(14)	strip	0.0575	0.9975
24	BETA 21S-2-5	BETA21S	1.8	STA1000	5@1550	8@1000	OHT	250	(14)	strip	0.0590	0.9975
25	BETA 21S-2-6	BETA21S	1.8	STA1000	5@1550	8@1000	OHT	250	(14)	strip	0.0585	0.9970
26	BETA 21S-2-7	BETA21S	1.8	STA1000	5@1550	8@1000	OHT	350	(14)	strip	0.0580	0.9980
27	BETA 21S-2-8	BETA21S	1.8	STA1000	5@1550	8@1000	OHT	350	(14)	strip	0.0590	0.9990
28	BETA 21S-2-9	BETA21S	1.8	STA1000	5@1550	8@1000	OHT	350	(14)	strip	0.0575	0.9975
29	21S-S-1	BETA21S	0	STA1000	5@1550	8@1000	TEN	RT	(1)	strip	0.0605	0.4990
30	21S-S-2	BETA21S	0	STA1000	5@1550	8@1000	TEN	RT	(1)	strip	0.0595	0.4995
31	21S-S-3	BETA21S	0	STA1000	5@1550	8@1000	TEN	RT	(1)	strip	0.0595	0.4990
32	21S-S-4	BETA21S	0	STA1000	5@1550	8@1000	TEN	250	(1)	strip	0.0595	0.4995
33	21S-S-5	BETA21S	0	STA1000	5@1550	8@1000	TEN	250	(1)	strip	0.0595	0.4995

Static Tension Tests

Record No.	Test Lab Specimen ID	Hole Dia (in)	Grain direction	Elastic mod (Msi)	Fty (ksi)	Ftu (ksi)	Ultimate gross stress (ksi)	Ultimate net stress (ksi)	Ult. Load (lbs)	% Elong.	Notes
1	BETA 21S-1-1	NA	L	15.71	173.8	199.9			5990.0	5	
2	BETA 21S-1-2	NA	L	16.11	176.8	204.3			5940.0	5	
3	BETA 21S-1-3	NA	L	15.87	175.6	202.7			5980.0	5	
4	BETA 21S-1-4	NA	L	15.87	173.2	199.3			5910.0	5	
5	BETA 21S-1-5	NA	L	16.29	177.1	205.3			6010.0	5	
6	BETA 21S-1-6	NA	L	16.12	172.9	199.9			6010.0	5	
7	BETA 21S-1-7	NA	L	15.93	173.2	200.5			5970.0	5	
8	BETA 21S-1-8	NA	L	15.64	171.2	195.3			5870.0	5	
9	BETA 21S-1-9	NA	L	14.64	152.3	184.5			5490.0	11	
10	BETA 21S-1-10	NA	L	14.74	148.9	183.1			5470.0	11	
11	BETA 21S-1R	NA	L	10.56	128.1	128.5			3965.6	14	
12	BETA 21S-2R	NA	L	10.42	123.4	123.7			3888.1	22	
13	BETA 21S-3R	NA	L	10.29	126.8	127.4			4064.3	13	
14	BETA 21S-4R	NA	L	(4)	(4)	(4)			(4)	(4)	
15	BETA 21S-5R	NA	L	(4)	(4)	(4)			(4)	(4)	
16	BETA 21S-5RA	NA	L	(4)	(4)	(4)			(4)	(4)	
17	BETA 21S-6R	NA	L	10.65	125.0	125.6			3930.5	15	
18	BETA 21S-7R	NA	L	10.47	124.3	124.6			3865.6	21	
19	BETA 21S-8R	NA	L	10.32	126.3	126.6			3977.6	15	
20	BETA 21S-2-1	0.1875	L	NA			146.8	180.7	8710.0	(6)	
21	BETA 21S-2-2	0.1875	L	NA			146.6	180.5	8700.0	(6)	
22	BETA 21S-2-3	0.1875	L	NA			148.0	182.2	8640.0	(6)	
23	BETA 21S-2-4	0.1875	L	NA			151.0	185.9	8660.0	3	(7)
24	BETA 21S-2-5	0.1875	L	NA			144.9	178.5	8530.0	3	(7)
25	BETA 21S-2-6	0.1875	L	NA			144.5	178.0	8430.0	3	(7)
26	BETA 21S-2-7	0.1875	L	NA			144.6	178.1	8370.0	4	(7)
27	BETA 21S-2-8	0.1880	L	NA			144.4	177.9	8510.0	4	(7)(8)
28	BETA 21S-2-9	0.1875	L	NA			144.9	178.4	8310.0	4	(7)
29	21S-S-1	NA	L	15.64	192.1	203.7			6149.6	8	
30	21S-S-2	NA	L	15.69	189.5	200.5			5958.9	8	
31	21S-S-3	NA	L	15.82	190.8	202.1			6000.5	8	
32	21S-S-4	NA	L	15.08	171.5	185.4			5510.1	9	
33	21S-S-5	NA	L	15.33	170.9	184.7			5489.3	9	

Static Tension Tests

Record No.	Test Lab Specimen ID	Alloy	Forming Level (%)	Condition	Solution Treat (Time (min.) @ Temp (deg. F))	Age (Time (hrs) @ Temp (deg. F))	Test Type	Test temp (deg F)	Test Speed	Material Form	Gage (in)	Width (in)
34	21S-S-6	BETA21S	0	STA1000	5@1550	8@1000	TEN	250	(1)	strip	0.0595	0.4995
35	21S-S-7	BETA21S	0	STA1000	5@1550	8@1000	TEN	350	(1)	strip	0.0595	0.4995
36	21S-S-8	BETA21S	0	STA1000	5@1550	8@1000	TEN	350	(1)	strip	0.0600	0.5000
37	21S-S-9	BETA21S	0	STA1000	5@1550	8@1000	TEN	350	(1)	strip	0.0600	0.4990
38	21S-S-10	BETA21S	0	STA1000	5@1550	8@1000	TEN	400	(1)	strip	0.0590	0.4990
39	21S-S-11	BETA21S	0	STA1000	5@1550	8@1000	TEN	400	(1)	strip	0.0600	0.5000
40	21S-S-12	BETA21S	0	STA1000	5@1550	8@1000	TEN	400	(1)	strip	0.0585	0.4995
41	21S-S-13	BETA21S	0	STA1000	5@1550	8@1000	OHT	RT	(14)	strip	0.0595	1.0090
42	21S-S-14	BETA21S	0	STA1000	5@1550	8@1000	OHT	RT	(14)	strip	0.0595	1.0065
43	21S-S-15	BETA21S	0	STA1000	5@1550	8@1000	OHT	RT	(14)	strip	0.0595	1.0085
44	21S-S-16	BETA21S	0	STA1000	5@1550	8@1000	OHT	250	(14)	strip	0.0595	1.0065
45	21S-S-17	BETA21S	0	STA1000	5@1550	8@1000	OHT	250	(14)	strip	0.0595	1.0090
46	21S-S-18	BETA21S	0	STA1000	5@1550	8@1000	OHT	250	(14)	strip	0.0595	1.0080
47	21S-S-19	BETA21S	0	STA1000	5@1550	8@1000	OHT	350	(14)	strip	0.0590	1.0060
48	21S-S-20	BETA21S	0	STA1000	5@1550	8@1000	OHT	350	(14)	strip	0.0590	1.0080
49	21S-S-21	BETA21S	0	STA1000	5@1550	8@1000	OHT	350	(14)	strip	0.0595	1.0081
50	D6-4671-877-2-1	6-2-2-2-2	0	STA	30@1650	10@950	TEN	RT	(1)	strip	0.0650	0.5003
51	D6-4671-877-2-2	6-2-2-2-2	0	STA	30@1650	10@950	TEN	RT	(1)	strip	0.0683	0.5008
52	D6-4671-877-2-3	6-2-2-2-2	0	STA	30@1650	10@950	TEN	RT	(1)	strip	0.0682	0.5001
53	D6-4671-877-2-4	6-2-2-2-2	0	STA	30@1650	10@950	TEN	250	(1)	strip	0.0682	0.5006
54	D6-4671-877-2-5	6-2-2-2-2	0	STA	30@1650	10@950	TEN	250	(1)	strip	0.0666	0.5008
55	D6-4671-877-2-6	6-2-2-2-2	0	STA	30@1650	10@950	TEN	250	(1)	strip	0.0683	0.5002
56	D6-4671-877-2-7	6-2-2-2-2	0	STA	30@1650	10@950	TEN	350	(1)	strip	0.0680	0.5000
57	D6-4671-877-2-8	6-2-2-2-2	0	STA	30@1650	10@950	TEN	350	(1)	strip	0.0673	0.5006
58	D6-4671-877-2-9	6-2-2-2-2	0	STA	30@1650	10@950	TEN	350	(1)	strip	0.0683	0.5003
59	D6-4671-877-2-10	6-2-2-2-2	0	STA	30@1650	10@950	TEN	400	(1)	strip	0.0679	0.5001
60	D6-4671-877-2-11	6-2-2-2-2	0	STA	30@1650	10@950	TEN	400	(1)	strip	0.0680	0.4999
61	D6-4671-877-2-12	6-2-2-2-2	0	STA	30@1650	10@950	TEN	400	(1)	strip	0.0686	0.4998
62	256342N-01	6-2-2-2-2	0	STA	30@1650	10@950	OHT	RT	(14)	strip	0.0669	0.9940
63	256342N-07	6-2-2-2-2	0	STA	30@1650	10@950	OHT	RT	(14)	strip	0.0681	0.9990
64	256342N-011	6-2-2-2-2	0	STA	30@1650	10@950	OHT	RT	(14)	strip	0.0681	0.9970
65	256342N-22	6-2-2-2-2	0	STA	30@1650	10@950	OHT	250	(14)	strip	0.0683	0.9994
66	256342N-23	6-2-2-2-2	0	STA	30@1650	10@950	OHT	250	(14)	strip	0.0678	0.9994

Static Tension Tests

Record No.	Test Lab Specimen ID	Hole Dia (in)	Grain direction	Elastic mod (Msi)	Fty (ksi)	Ftu (ksi)	Ultimate gross stress (ksi)	Ultimate net stress (ksi)	Ult. Load (lbs)	% Elong.	Notes
34	21S-S-6	NA	L	15.11	167.9	181.4			5391.3	9	
35	21S-S-7	NA	L	14.79	160.9	177.3			5269.4	10	
36	21S-S-8	NA	L	14.42	161.1	177.3			5319.0	10	
37	21S-S-9	NA	L	15.46	161.8	178.0			5329.3	10	
38	21S-S-10	NA	L	17.56	159.5	172.8			NA	(15)	(15)
39	21S-S-11	NA	L	17.52	160.1	173.0			NA	10	
40	21S-S-12	NA	L	17.67	(16)	172.3			NA	10	(16)
41	21S-S-13	0.1875	L	NA			165.4	203.2	9930.0	4	(9)
42	21S-S-14	0.1875	L	NA			165.5	203.4	9910.0	4	(9)
43	21S-S-15	0.1870	L	NA			167.2	205.2	10030.0	4	(9)
44	21S-S-16	0.1875	L	NA			150.3	184.7	9000.0	6	(9)
45	21S-S-17	0.1880	L	NA			152.9	187.9	9180.0	6	(9)
46	21S-S-18	0.1880	L	NA			151.9	186.7	9110.0	6	(9)
47	21S-S-19	0.1880	L	NA			147.6	181.5	8760.0	7	(9)
48	21S-S-20	0.1875	L	NA			145.3	178.5	8640.0	7	(9)
49	21S-S-21	0.1875	L	NA			145.1	178.2	8702.0	7	(9)
50	D6-4671-877-2-1	NA	L	18.25	178.3	187.6			NA	7	
51	D6-4671-877-2-2	NA	L	17.10	174.6	186.8			NA	8	
52	D6-4671-877-2-3	NA	L	17.53	174.5	186.5			NA	8	
53	D6-4671-877-2-4	NA	L	16.82	149.8	172.5			NA	8	
54	D6-4671-877-2-5	NA	L	16.64	149.6	172.1			NA	8	
55	D6-4671-877-2-6	NA	L	17.43	152.1	173.3			NA	8	
56	D6-4671-877-2-7	NA	L	17.29	141.7	166.5			NA	9	
57	D6-4671-877-2-8	NA	L	17.57	146.5	170.7			NA	9	
58	D6-4671-877-2-9	NA	L	16.82	144.2	168.0			NA	9	
59	D6-4671-877-2-10	NA	L	17.06	136.6	164.9			NA	(12)	(11), (12)
60	D6-4671-877-2-11	NA	L	17.13	139.6	165.3			NA	(12)	(12), (13)
61	D6-4671-877-2-12	NA	L	17.16	138.8	164.2			NA	(12)	(12), (13)
62	256342N-01	0.1875	L				149.5	184.2	9940.0		
63	256342N-07	0.1875	L				149.2	183.7	10150.0		
64	256342N-011	0.1885	L				149.9	184.9	10180.0		
65	256342N-22	0.1875	L				134.3	165.4	9170.0		
66	256342N-23	0.1880	L				136.1	167.6	9220.0		

Static Tension Tests

Record No.	Test Lab Specimen ID	Alloy	Forming Level (%)	Condition	Solution Treat (Time (min.) @ Temp (deg. F))	Age (Time (hrs) @ Temp (deg. F))	Test Type	Test temp (deg F)	Test Speed	Material Form	Gage (in)	Width (in)
67	256342N-26	6-2-2-2-2	0	STA	30@1650	10@950	OHT	250	(14)	strip	0.0686	0.9990
68	256342N-012	6-2-2-2-2	0	STA	30@1650	10@950	OHT	350	(14)	strip	0.0682	0.9975
69	256342N-014	6-2-2-2-2	0	STA	30@1650	10@950	OHT	350	(14)	strip	0.0680	0.9980
70	256342N-021	6-2-2-2-2	0	STA	30@1650	10@950	OHT	350	(14)	strip	0.0682	0.9960

(1)Specimen was loaded at 0.005 inches per inch per minute until 0.150 inches of stroke was obtained; then loading was increased to 0.01 until failure occured
(2) Specimen was loaded at 0.003 inches per inch per minute throughout the test.
(3) Specimen was loaded at 0.03 inches per inch per minute until failure occurred.
(4) Specimen was loaded at 0.005 in/in/min then held at 3500 lbs. for 5 minutes then unloaded to zero. No yield load was obtained.
(5) Testing suspended per test requestors instruction.
(6) Specimen elongation was not taken.
(7) Elongation was measured by marking every 0.10 inch over 0.5 inches on both sides of hole per test requestors instruction.
(8) Specimen was loaded to 500 lbs. when extensometer slipped. Test stopped rezeroed and retested to failure.
(9) Ultimate gross stress (ksi)
(10) Ultimate net stress (ksi)
(11) Extensometer was not used for this test per test requestors instructions.
(12) Elongation was not taken due to strain gage installation.
(13) E based on strain gage data.
(14) Specimen was loaded at 0.05 inches per inch per minute.
(15) No elongation taken.
(16) Strain gage debonded prior to 2 percent offset

Static Tension Tests

Record No.	Test Lab Specimen ID	Hole Dia (in)	Grain direction	Elastic mod (Msi)	Fty (ksi)	Ftu (ksi)	Ultimate gross stress (ksi)	Ultimate net stress (ksi)	Ult. Load (lbs)	% Elong.	Notes
67	256342N-26	0.1875	L				135.7	167.1	9300.0		
68	256342N-012	0.1880	L				131.0	161.4	8910.0		
69	256342N-014	0.1875	L				133.2	164.0	9040.0		
70	256342N-021	0.1875	L				130.6	160.9	8870.0		

APPENDIX E - FATIGUE TEST DATABASE

The database of fatigue test results for each test specimen for Beta21S and Ti-6-2-2-2-2 is contained on the following pages. These results include tests completed at the time of this report. A complete fatigue database and formal report will be released at the conclusion of fatigue testing on Ti-6-2-2-2-2.

Fatigue Test Summary

Record Number	Alloy	Condition	Solution Treat (time (min) @ temp (deg F))	Heat Treat (time (hrs) @ temp (deg F))	Material Form	Grain	Forming Level (%)	Test Type	Spec Type (KT)	Test Temp (deg F)	Cycle Rate (Hz)	Max. Stress (ksi)
1	Beta21S	STA	5@1550	8@1000	Strip	L	1.9	FL	1.0	RT	5	110
2	Beta21S	STA	5@1550	8@1000	Strip	L	1.9	FL	1.0	RT	5	100
3	Beta21S	STA	5@1550	8@1000	Strip	L	1.9	FL	1.0	RT	5	90
4	Beta21S	STA	5@1550	8@1000	Strip	L	1.9	FL	1.0	RT	5	70
5	Beta21S	STA	5@1550	8@1000	Strip	L	1.9	FL	1.0	RT	0.5	110
6	Beta21S	STA	5@1550	8@1000	Strip	L	1.9	FL	1.0	RT	0.5	70
7	Beta21S	STA	5@1550	8@1000	Strip	L	1.9	FL	1.0	RT	5	60
8	Beta21S	STA	5@1550	8@1000	Strip	L	0	FL	1.0	RT	5	70
9	Beta21S	STA	5@1550	8@1000	Strip	L	0	FL	1.0	RT	5	80
10	Beta21S	STA	5@1550	8@1000	Strip	L	0	FL	1.0	RT	5	100
11	Beta21S	STA	5@1550	8@1000	Strip	L	0	FL	1.0	RT	5	120
12	Beta21S	STA	5@1550	8@1000	Strip	L	0	FL	1.0	RT	5	140
13	Beta21S	STA	5@1550	8@1000	Strip	L	0	FL	1.0	RT	5	135
14	Beta21S	STA	5@1550	8@1000	Strip	L	0	FL	1.0	RT	5	130
15	Beta21S	STA	5@1550	8@1000	Strip	L	0	FL	1.0	RT	5	125
16	Beta21S	STA	5@1550	8@1000	Strip	L	0	FL	1.0	RT	5	120
17	Beta21S	STA	5@1550	8@1000	Strip	L	0	FL	1.0	RT	5	115
18	Beta21S	STA	5@1550	8@1000	Strip	L	0	FL	1.0	RT	5	125
19	Beta21S	STA	5@1550	8@1000	Strip	L	0	FL	1.0	RT	5	130
20	Beta21S	STA	5@1550	8@1000	Strip	L	0	FL	1.0	RT	5	135
21	Beta21S	STA	5@1550	8@1000	Strip	L	0	FL	1.0	RT	5	120
22	Beta21S	STA	5@1550	8@1000	Strip	L	0	FL	1.0	RT	5	120
23	Beta21S	STA	5@1550	8@1000	Strip	L	0	FL	1.0	RT	5	120
24	Beta21S	STA	5@1550	8@1000	Strip	L	0	FL	1.0	RT	5	130
25	Beta21S	STA	5@1550	8@1000	Strip	L	0	FL	1.0	RT	5	130
26	Beta21S	STA	5@1550	8@1000	Strip	L	0	FL	1.0	RT	5	130
27	Beta21S	STA	5@1550	8@1000	Strip	L	0	FL	1.0	250	5	120
28	Beta21S	STA	5@1550	8@1000	Strip	L	0	FL	1.0	350	5	120
29	Beta21S	STA	5@1550	8@1000	Strip	L	0	FL	1.0	RT	0.5	130
30	Beta21S	STA	5@1550	8@1000	Strip	L	0	FL	2.8	RT	5	50
31	Beta21S	STA	5@1550	8@1000	Strip	L	0	FL	2.8	RT	5	40
32	Beta21S	STA	5@1550	8@1000	Strip	L	0	FL	2.8	RT	5	50
33	Beta21S	STA	5@1550	8@1000	Strip	L	0	FL	2.8	RT	5	50
34	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	1.0	RT	5	120
35	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	1.0	RT	5	120
36	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	1.0	RT	5	120

Fatigue Test Summary

Record Number	Test Lab Specimen ID	Nominal Spec. Length (in)	Gage (in)	Width (in)	Hole Dia (in)	Area (sq in)	Stress Ratio R	Max. Load (kips)	Min. Load (kips)	Cycles to first crack	Cycles to failure	Total cycles run	Notes
1	B-5-1	7.5	0.0585	0.5030	NA	0.0294	0.1	3.24	0.32	-	11,336		
2	B-5-2	7.5	0.0605	0.5020	NA	0.0304	0.1	3.04	0.30	-	19198		
3	B-5-3	7.5	0.0600	0.5000	NA	0.0300	0.1	2.70	0.27	-	27500		(1)
4	B-5-4	7.5	0.0607	0.4770	NA	0.0290	0.1	2.03	0.20	-	129446		
5	B-13-1	7.5	0.0600	0.5020	NA	0.0301	0.1	3.31	0.33	-	11183		
6	B-13-2	7.5	0.0605	0.5030	NA	0.0304	0.1	2.13	0.21	-	59404		
7	B-9-1	7.5	0.0595	0.5000	NA	0.0298	0.1	1.79	0.18	-		1116006	No failure.
8	21S-L-1	7.5	0.0590	0.5007	NA	0.0295	0.1	2.07	0.21	-		1000000	No failure.
9	21S-L-2	7.5	0.0595	0.5006	NA	0.0298	0.1	2.38	0.24	-		1000000	No failure.
10	21S-L-3	7.5	0.0606	0.5008	NA	0.0303	0.1	3.03	0.30	-		1000000	No failure.
11	21S-L-4	7.5	0.0607	0.5011	NA	0.0304	0.1	3.65	0.37	-		3000000	No failure.
12	21S-L-5	7.5	0.0608	0.5011	NA	0.0305	0.1	4.27	0.43	-	47297		
13	21S-L-6	7.5	0.0597	0.5009	NA	0.0299	0.1	4.04	0.40	-	35633		
14	21S-L-7	7.5	0.0606	0.5003	NA	0.0303	0.1	3.94	0.39	-	30281		
15	21S-L-8	7.5	0.0600	0.5008	NA	0.0300	0.1	3.76	0.38	-	26740		
16	21S-L-9	7.5	0.0605	0.5006	NA	0.0303	0.1	3.63	0.36	-	69172		
17	21S-L-10	7.5	0.0605	0.5024	NA	0.0304	0.1	3.50	0.35	-		1000000	No failure.
18	21S-L-11	7.5	0.0606	0.5008	NA	0.0303	0.1	3.79	0.38	-	26992		
19	21S-L-12	7.5	0.0608	0.5048	NA	0.0307	0.1	3.99	0.40	-	23501		
20	21S-L-13	7.5	0.0602	0.5006	NA	0.0301	0.1	4.07	0.41	-	25965		
21	21S-L-14	7.5	0.0608	0.4998	NA	0.0304	0.1	3.65	0.36	-	234386		Failed at grip.
22	21S-L-15	7.5	0.0607	0.5009	NA	0.0304	0.1	3.65	0.36	-	(2)		
23	21S-L-16	7.5	0.0601	0.5016	NA	0.0301	0.1	3.62	0.36	-	58170		
24	21S-L-17	7.5	0.0600	0.5049	NA	0.0303	0.1	3.94	0.39	-	27270		
25	21S-L-18	7.5	0.0600	0.5005	NA	0.0300	0.1	3.90	0.39	-	42230		
26	21S-L-19	7.5	0.0608	0.5000	NA	0.0304	0.1	3.95	0.40	-	26360		
27	21S-L-20	7.5	0.0604	0.5007	NA	0.0302	0.1	3.63	0.36	-	118590		
28	21S-L-21	7.5	0.0605	0.5005	NA	0.0303	0.1	3.63	0.36	-		1000000	No failure.
29	21S-L-22	7.5	0.0605	0.5003	NA	0.0303	0.1	3.93	0.39	-	23200		
30	21S_L_53	8.3	0.0603	1.0000	0.1878	0.0603	0.1	3.02	0.30	-	13430		Failed at hole.
31	21S_L_54	8.3	0.0598	1.0000	0.1883	0.0598	0.1	2.39	0.24	-	35510		Failed at hole.
32	21S_L_55	8.3	0.0594	1.0000	0.1881	0.0594	0.1	2.97	0.30	-	22700		Failed at hole.
33	21S_L_56	8.3	0.0600	1.0000	0.1884	0.0600	0.1	3.00	0.30	-	14290		Failed at hole.
34	6-22-22-5-6	7.5	0.0684	0.5010	NA	0.0343	0.1	4.11	0.41	-		2000000	No failure.
35	6-22-22-5-9	7.5	0.0685	0.5015	NA	0.0344	0.1	4.12	0.41	-		2000000	No failure.
36	6-22-22-5-5	7.5	0.0683	0.5015	NA	0.0342	0.1	4.11	0.41	104240	104400		

Fatigue Test Summary

Record Number	Alloy	Condition	Solution Treat (time (min) @ temp (deg F))	Heat Treat (time (hrs) @ temp (deg F))	Material Form	Grain	Forming Level (%)	Test Type	Spec Type (KT)	Test Temp (deg F)	Cycle Rate (Hz)	Max. Stress (ksi)
37	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	1.0	RT	0.5	130
38	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	1.0	RT	0.5	130
39	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	1.0	RT	0.5	130
40	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	1.0	RT	0.5	130
41	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	1.0	RT	0.5	130
42	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	1.0	RT	5	130
43	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	1.0	RT	5	130
44	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	1.0	RT	5	130
45	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	1.0	RT	5	130
46	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	1.0	RT	5	130
47	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	1.0	RT	0.5	140
48	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	1.0	RT	5	140
49	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	1.0	RT	5	140
50	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	1.0	RT	5	140
51	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	1.0	RT	5	140
52	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	1.0	RT	5	140
53	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	1.0	RT	5	140
54	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	1.0	250	5	120
55	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	1.0	250	5	130
56	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	1.0	250	5	130
57	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	1.0	250	5	130
58	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	1.0	250	5	130
59	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	1.0	250	5	130
60	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	1.0	250	5	140
61	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	1.0	250	5	140
62	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	1.0	250	5	140
63	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	1.0	250	5	140
64	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	1.0	350	5	130
65	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	1.0	350	5	130
66	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	1.0	350	5	130
67	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	1.0	350	5	130
68	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	1.0	350	5	130
69	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	1.0	350	5	130
70	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	1.0	350	5	140
71	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	1.0	350	5	140
72	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	FL			

Fatigue Test Summary

Record Number	Test Lab Specimen ID	Nominal Spec. Length (in)	Gage (in)	Width (in)	Hole Dia (in)	Area (sq in)	Stress Ratio R	Max. Load (kips)	Min. Load (kips)	Cycles to first crack	Cycles to failure	Total cycles run	Notes
37	6-22-22-5-14	7.5	0.0686	0.5000	NA	0.0343	0.1	4.46	0.45	-	42720		
38	6-22-22-5-25	7.5	0.0682	0.4995	NA	0.0340	0.1	4.43	0.44	-	36640		
39	6-22-22-5-15	7.5	0.0686	0.4995	NA	0.0343	0.1	4.45	0.45	-	626270		
40	6-22-22-5-26	7.5	0.0682	0.5005	NA	0.0341	0.1	4.44	0.44	-	42700		
41	6-22-22-5-12	7.5	0.0682	0.5020	NA	0.0342	0.1	4.45	0.44	-	34190		
42	6-22-22-5-7	7.5	0.0682	0.4995	NA	0.0340	0.1	4.43	0.44	-	80160		
43	6-22-22-5-8	7.5	0.0679	0.5015	NA	0.0340	0.1	4.42	0.44	-	68910		
44	6-22-22-5-28	7.5	0.0669	0.5000	NA	0.0335	0.1	4.35	0.43	-	45950		
45	6-22-22-5-10	7.5	0.0688	0.4990	NA	0.0343	0.1	4.46	0.45	-		1200000	No failure.
46	6-22-22-5-27	7.5	0.0683	0.4995	NA	0.0341	0.1	4.44	0.44	-	63790		
47	6-22-22-5-11	7.5	0.0680	0.5000	NA	0.0340	0.1	4.76	0.48	-	40740		
48	6-22-22-5-4	7.5	0.0664	0.5010	NA	0.0332	0.1	4.65	0.47	29810	29820		
49	6-22-22-5-2	7.5	0.0684	0.5000	NA	0.0342	0.1	4.79	0.48	-	21710		
50	6-22-22-5-34	7.5	0.0679	0.5000	NA	0.0339	0.1	4.75	0.47	-	46970		
51	6-22-22-5-30	7.5	0.0679	0.4990	NA	0.0339	0.1	4.74	0.47	-	30050		
52	6-22-22-5-3	7.5	0.0680	0.5005	NA	0.0340	0.1	4.76	0.48	39010	39070		
53	6-22-22-5-1	7.5	0.0682	0.5000	NA	0.0341	0.1	4.77	0.48	305120	305250		
54	6-22-22-5-13	7.5	0.0684	0.5000	NA	0.0342	0.1	4.10	0.41	-		1000000	No failure.
55	6-22-22-5-18	7.5	0.0680	0.4995	NA	0.0340	0.1	4.42	0.44	-	464830		
56	6-22-22-5-16	7.5	0.0686	0.5005	NA	0.0343	0.1	4.46	0.45	-		1000000	No failure.
57	6-22-22-5-17	7.5	0.0685	0.5015	NA	0.0343	0.1	4.46	0.45	-	31280		
58	6-22-22-5-20	7.5	0.0686	0.5005	NA	0.0343	0.1	4.46	0.45	-	70550		
59	6-22-22-5-19	7.5	0.0685	0.5020	NA	0.0344	0.1	4.47	0.45	-		1000000	No failure.
60	6-22-22-5-35	7.5	0.0675	0.5005	NA	0.0338	0.1	4.73	0.47	-	31980		
61	6-22-22-5-32	7.5	0.0685	0.5005	NA	0.0343	0.1	4.80	0.48	-	54000		
62	6-22-22-5-33	7.5	0.0677	0.4990	NA	0.0338	0.1	4.73	0.47	-	46410		
63	6-22-22-5-36	7.5	0.0684	0.5005	NA	0.0342	0.1	4.79	0.48	-	70010		
64	6-22-22-5-21	7.5	0.0684	0.5015	NA	0.0343	0.1	4.46	0.45	-	999970		
65	6-22-22-5-31	7.5	0.0681	0.5020	NA	0.0342	0.1	4.44	0.44	-		1000000	No failure.
66	6-22-22-5-29	7.5	0.0689	0.5000	NA	0.0344	0.1	4.48	0.45	-		1000000	No failure.
67	6-22-22-5-24	7.5	0.0688	0.5015	NA	0.0345	0.1	4.48	0.45	-		1000000	No failure.
68	6-22-22-5-22	7.5	0.0682	0.4985	NA	0.0340	0.1	4.42	0.44	-	100770		Failed close to grip.
69	6-22-22-5-23	7.5	0.0678	0.5020	NA	0.0340	0.1	4.42	0.44	-	626560		
70	6-22-22-5-38	7.5	0.0681	0.4995	NA	0.0340	0.1	4.76	0.48	-	24560		
71	6-22-22-5-37	7.5	0.0684	0.4985	NA	0.0341	0.1	4.77	0.48	-	29570		
72		7.5	0.0685	0.5005	NA	0.0343	0.1	0.00	0.00				

Fatigue Test Summary

Record Number	Alloy	Condition	Solution Treat (time (min) @ temp (deg F))	Heat Treat (time (hrs) @ temp (deg F))	Material Form	Grain	Forming Level (%)	Test Type	Spec Type (KT)	Test Temp (deg F)	Cycle Rate (Hz)	Max. Stress (ksi)
73	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	FL			
74	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	FL			
75	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	FL			
76	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	FL			
77	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	FL			
78	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	FL			
79	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	FL			
80	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	FL			
81	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	FL			
82	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	FL			
83	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	FL			
84	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	FL			
85	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	FL			
86	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	FL			
87	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	FL			
88	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	FL			
89	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	FL			
90	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	FL	RT	5	45
91	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	FL	RT	5	45
92	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	FL	RT	5	45
93	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	FL	RT	5	45
94	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	FL	RT	5	47
95	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	FL	RT	5	50
96	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	FL	RT	5	55
97	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	FL	RT	5	65
98	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	FL			
99	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	FL			
100	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	FL			
101	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	FL			
102	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	FL			
103	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	FL			
104	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	FL			
105	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	FL			
106	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	FL			
107	Ti-6-2-2-2-2	STA	30@1650	10@950	Sheet	L	0	FL	FL			

Fatigue Test Summary

Record Number	Test Lab Specimen ID	Nominal Spec. Length (in)	Gage (in)	Width (in)	Hole Dia (in)	Area (sq in)	Stress Ratio R	Max. Load (kips)	Min. Load (kips)	Cycles to first crack	Cycles to failure	Total cycles run	Notes
73		7.5	0.0669	0.4985	NA	0.0333	0.1	0.00	0.00				
74		7.5	0.0682	0.5000	NA	0.0341	0.1	0.00	0.00				
75		7.5	0.0677	0.5000	NA	0.0338	0.1	0.00	0.00				
76		7.5	0.0673	0.4985	NA	0.0335	0.1	0.00	0.00				
77		7.5	0.0675	0.4975	NA	0.0336	0.1	0.00	0.00				
78		7.5	0.0685	0.4985	NA	0.0341	0.1	0.00	0.00				
79		7.5	0.0690	0.4990	NA	0.0344	0.1	0.00	0.00				
80		7.5	0.0670	0.5005	NA	0.0335	0.1	0.00	0.00				
81		7.5	0.0680	0.4995	NA	0.0340	0.1	0.00	0.00				
82		7.5	0.0682	0.5005	NA	0.0341	0.1	0.00	0.00				
83		7.5	0.0684	0.5000	NA	0.0342	0.1	0.00	0.00				
84		7.5	0.0681	0.4990	NA	0.0340	0.1	0.00	0.00				
85		7.5	0.0685	0.5000	NA	0.0343	0.1	0.00	0.00				
86		7.5	0.0678	0.5010	NA	0.0340	0.1	0.00	0.00				
87		7.5	0.0682	0.5000	NA	0.0341	0.1	0.00	0.00				
88		7.5	0.0684	0.5010	NA	0.0343	0.1	0.00	0.00				
89		7.5	0.0678	0.4995	NA	0.0339	0.1	0.00	0.00				
90	6-22-22-19-7	8.3	0.0682	1.0005	0.1885	0.0683	0.1	3.07	0.31	84640	85850		Failed at hole.
91	6-22-22-19-6	8.3	0.0680	1.0000	0.1877	0.0680	0.1	3.06	0.31	80480	81880		Failed at hole.
92	6-22-22-19-4	8.3	0.0680	1.0000	0.1885	0.0680	0.1	3.06	0.31	-		2000000	No failure.
93	6-22-22-19-8	8.3	0.0685	0.9990	0.1881	0.0684	0.1	3.08	0.31	95960	98420		Failed at hole.
94	6-22-22-19-5	8.3	0.0683	0.9995	0.1879	0.0682	0.1	3.21	0.32	42630	44930		Failed at hole.
95	6-22-22-19-3	8.3	0.0680	0.9990	0.1881	0.0680	0.1	3.40	0.34	59280	60190		Failed at hole.
96	6-22-22-19-2	8.3	0.0683	0.9980	0.188	0.0681	0.1	3.75	0.37	43260	46090		Failed at hole.
97	6-22-22-19-1	8.3	0.0680	1.0000	0.1879	0.0680	0.1	4.42	0.44	19290	19410		Failed at hole.
98		8.3	0.0686	0.9990	0.1878	0.0685	0.1	0.00	0.00				
99		8.3	0.0683	1.0005	0.1878	0.0683	0.1	0.00	0.00				
100		8.3	0.0686	0.9985	0.1872	0.0685	0.1	0.00	0.00				
101		8.3	0.0680	0.9985	0.1885	0.0679	0.1	0.00	0.00				
102		8.3	0.0682	0.9995	0.1878	0.0682	0.1	0.00	0.00				
103		8.3	0.0679	1.0000	0.1876	0.0679	0.1	0.00	0.00				
104		8.3	0.0679	1.0000	0.1877	0.0679	0.1	0.00	0.00				
105		8.3	0.0683	0.9990	0.1876	0.0682	0.1	0.00	0.00				
106		8.3	0.0680	1.0000	0.1882	0.0680	0.1	0.00	0.00				
107		8.3	0.0681	0.9985	0.1878	0.0680	0.1	0.00	0.00				

Fatigue Test Summary

(1) Specimen failed between 20,000 and 21,000 cycles
(2) Specimen failed away from edge - only surface dimple visible at first crack cycle count.
UF: Unnotched fatigue
OHF: Open hole fatigue
RT: Room temperature
ST: Solution treated
STA: Solution treated and aged
NA: Not applicable
'-': Data not available

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13. ABSTRACT *(Maximum 200 words)*
This report covers a portion of an ongoing investigation of the durability of titanium alloys for the High Speed Civil Transport (HSCT). Candidate alloys need to possess an acceptable combination of properties including strength and toughness as well as fatigue and corrosion resistance when subjected to the HSCT operational environment. These materials must also be capable of being processed into required product forms while maintaining their properties. Processing operations being considered for this airplane include forming, welding, adhesive bonding, and superplastic forming with or without diffusion bonding. This program was designed to develop the material properties database required to lower the risk of using advanced titanium alloys on the HSCT.

14. SUBJECT TERMS
Beta 21S; Fatigue life; High Speed Civil Transport (HSCT); Metallic materials database; Static strength; Stretch forming; Ti-6-2-2-2-2; Titanium alloys

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