



**NASA TECHNICAL
HANDBOOK**

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**National Aeronautics and Space Administration
Washington, DC 20546-0001**

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**GUIDELINES FOR THE SPECIFICATION AND CERTIFICATION
OF TITANIUM ALLOYS FOR NASA FLIGHT APPLICATIONS**

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FOREWORD

This Handbook is published by the National Aeronautics and Space Administration (NASA) as a guidance document to provide engineering information; lessons learned; possible options to address technical issues; classification of similar items, materials, or processes; interpretive direction and techniques; and any other type of guidance information that may help the Government or its contractors in the design, construction, selection, management, support, or operation of systems, products, processes, or services.

This Handbook is approved for use by NASA Headquarters and NASA Centers, including Component Facilities and Technical and Service Support Centers.

This Handbook establishes guidelines for specifying and certifying wrought titanium (Ti) alloys for use on NASA Flight Projects for organizations buying such materials.

This Handbook thoroughly describes the procedures and processes that will help mitigate the procurement of nonconforming wrought Ti alloys for flight applications:

- What conditions make a Ti alloy nonconforming.
- What comprises the Ti alloy supply chain.
- Examples of how Ti alloy lot may be nonconforming with respect to processing and properties required by material specifications.

This Handbook does not cover commercially pure Ti since it is not considered a nonconforming issue because of its lack of sensitivity to heat treating and thermo-mechanical processing.

This Handbook provides insight and guidelines in dealing with the Ti alloy supply chain. It recommends the involvement of certain technical disciplines to ascertain whether there is nonconformance and also approaches to monitor and assure compliance of procured materials with the relevant procurement specifications. As of the date of publication of this Handbook, there is no known evidence of nonconforming Ti alloy issues with foreign sources. The same guideline procedures described in this Handbook should be used for foreign Ti alloy sources and foreign contractors. Ti alloys can be procured from a foreign source by a United States (U.S.) or foreign entity associated with a NASA program. The basic issues addressed in this Handbook apply whether the Ti alloy is of U.S. or foreign source.

This Handbook focuses on wrought Ti alloys. During the approximate timeframe of 2008-2010, significant issues (and incurred costs) were encountered through the investigations of multiple Government agencies with respect to nonconforming Ti alloys. Note: the exclusion of other metals in this document is not meant to indicate that no problems can or will occur with other metals. Organizations procuring other metallic and nonmetallic materials for flight applications should use due diligence to ensure such materials meet the requirements for specifications used in the procurement process.

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This Handbook focuses on product forms referred to as sheet, strip, plate, forging, and bar, i.e., forms covered by the American Materials Specifications (AMSs) that supersede MIL-T-9046, Titanium and Titanium Alloy, Sheet, Strip, and Plate, and MIL-T-9047, Titanium and Titanium Alloy, Bars (Rolled or Forged) and Reforging Stock, Aircraft Quality, and that are primarily related to the nonconforming Ti alloy issue. The other AMS specifications covering product forms such as tubing, casting, extruded parts, or fasteners are not implicated in the nonconforming Ti alloy issue.

Requests for information, corrections, or additions to this Handbook should be submitted via “Feedback” in the NASA Standards and Technical Assistance Resource Tool at <http://standards.nasa.gov>.

Original Signed By:

04/24/2014

Ralph R. Roe, Jr.
NASA Chief Engineer

Approval Date

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GUIDELINES FOR THE SPECIFICATION AND CERTIFICATION OF TITANIUM ALLOYS FOR NASA FLIGHT APPLICATIONS

1. SCOPE

1.1 Purpose

The purpose of this Handbook is to describe guideline procedures and processes that will help mitigate the procurement of nonconforming wrought titanium (Ti) alloys for National Aeronautics and Space Administration (NASA) flight applications. These guidelines may be tailored to the program applications to obtain the most cost-effective, best quality product.

1.2 Applicability

This Handbook is applicable to NASA Centers and NASA programs utilizing wrought Ti alloys for flight hardware, mission-critical ground support equipment, and elements thereof.

This Handbook is approved for use by NASA Headquarters and NASA Centers, including Component Facilities and Technical and Service Support Centers. This Handbook may also apply to the Jet Propulsion Laboratory (JPL) or to other contractors, grant recipients, or parties to agreements only to the extent specified or referenced in their contracts, grants, or agreements.

This Handbook, or portions thereof, may be referenced in contract, program, and other Agency documents for guidance. When this Handbook contains procedural or process requirements, they may be cited in contract, program, and other Agency documents for guidance.

Beginning in section 3, this Handbook includes quotes from Ti standards and specifications from various organizations and agencies, and the quoted material may contain “shall” statements. These “shall” statements are not requirements levied by this Handbook but by the quoted organization/agency and are included in this Handbook as guidance/reference information only. The “shall” statements in section 2 of this Handbook are NASA Technical Standard Program Office requirements regarding use of documents applicable to this Handbook.

2. APPLICABLE DOCUMENTS

Reference documents are listed in the Appendix A of this Handbook.

2.1 General

The documents listed in this section are applicable to the guidance in this Handbook. Government specifications were originally developed and subsequently transformed from military specifications to non-Government standard documents, such as the Aerospace Materials

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Specifications (AMSs) for Ti alloys commercially available now. These specifications have documented processing requirements and well-established minimum property values for various product forms.

While the documents listed in this section are applicable to multiple types of Ti alloys for completeness, the following two Ti alloys, Ti-6Al-4V and Ti-6Al-6V-2Sn, are the two primary alloys of interest. Most of the investigations into potential nonconforming Ti alloys occurred in the mid to late 2000s and were centered on these two alloys. United States Air Force (USAF) investigations into nonconforming Ti alloys first addressed Ti-6Al-6V-2Sn and, subsequently in the late 2000s, included Ti-6Al-4V. NASA investigations, predominately in the late 2000s, focused on Ti-6Al-4V, as this alloy had the most flight applications by a large number. However, the procedures and processes described in this document can be applied to other Ti alloys. Commercially pure Ti is generally not considered an issue because of its lack of sensitivity to heat treating and thermo-mechanical processing.

The two original military documents for Ti and Ti alloys (MIL-T-9046, Titanium and Titanium Alloy, Sheet, Strip, and Plate, and MIL-T-9047, Titanium and Titanium Alloy, Bars (Rolled or Forged) and Reforging Stock, Aircraft Quality) have been replaced by approximately 55 AMS non-Government standards. ASTM International (ASTM, formerly the American Society for Testing and Materials) specifications are not listed in this Handbook because of a shortfall of aerospace quality procurement requirements. However, a Center could utilize ASTM specifications for non-flight applications and/or add additional requirements to the procurement documents for flight applications.

2.1.1 The latest issuances of cited documents shall apply unless specific versions are designated.

2.1.2 Non-use of specific document versions as designated shall be approved by the responsible Technical Authority.

The applicable documents are accessible via the NASA Standards and Technical Assistance Resource Tool at <http://standards.nasa.gov> or may be obtained directly from the Standards Developing Organizations or other document distributors.

2.2 Government Documents

Department of Defense (DoD)

AFRL-RX-WP-TR- Quick Reaction Evaluation of Materials and Processes (QRE)
2012-0238

Federal Aviation Administration

MMPDS-06 Metallic Materials Properties Development and Standardization
Handbook, December 27, 2012. Licensed exclusively to Battelle
Memorial Institute for distribution.

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NASA

- JPL D-69922 Report of the Titanium Working Group Concerning the Assessment of Non-Conforming Material as it Affects JPL Flight Projects
- NASA-HDBK-8739.18 Procedural Handbook for NASA Program and Project Management of Problems, Nonconformances, and Anomalies

2.3 Non-Government Documents

ASTM International

- ASTM B348 Standard Specification for Titanium and Titanium Alloy Bars and Billets. (Table 4 specifically references ASTM B348-10; however, all other references to ASTM B348 cite the latest issue of the document.)
- ASTM E8 Standard Test Methods for Tension Testing of Metallic Materials
- ASTM E 1447 Standard Test Method for Determination of Hydrogen in Titanium and Titanium Alloys by Inert Gas Fusion Thermal Conductivity/Infrared Detection Method
- ASTM F 945 Standard Test Method for Stress-Corrosion of Titanium Alloys by Aircraft Engine Cleaning Materials

International Organization for Standardization (ISO)

- AS9100 Aerospace Standard: Quality Management Systems – Requirements for Aviation, Space and Defense Organizations

Society of Automotive Engineers (SAE)

SAE AMS Ti Alloy Specifications Superseding SAE AMS-T-9046, Titanium and Titanium Alloy, Sheet, Strip and Plate

- SAE AMS4903* Titanium Alloy Sheet, Strip, and Plate 6Al – 4V Solution Heat Treated
- SAE AMS4904* Titanium Alloy Sheet, Strip, and Plate 6Al – 4V Solution Heat Treated and Aged
- SAE AMS4907* Titanium Alloy, Sheet, Strip, and Plate 6.0Al – 4.0V, Extra Low Interstitial Annealed

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SAE AMS4909	Titanium Alloy, Sheet, Strip, and Plate 5Al – 2.5Sn, Extra Low Interstitial Annealed
SAE AMS4910	Titanium Alloy, Sheet, Strip, and Plate 5Al – 2.5Sn Annealed
SAE AMS4911*	Titanium Alloy Sheet, Strip and Plate 6Al – 4V Annealed
SAE AMS4915	Titanium Alloy Sheet, Strip, and Plate 8Al – 1V – 1Mo Single Annealed
SAE AMS4916	Titanium Alloy Sheet, Strip, and Plate 8Al – 1Mo – 1V Duplex Annealed
SAE AMS4917	Titanium Alloy Sheet, Strip, and Plate 13.5V – 11Cr – 3.0Al Solution Heat Treated
SAE AMS4918**	Titanium Alloy, Sheet, Strip, and Plate 6Al – 6V – 2Sn Annealed
SAE AMS4919	Titanium Alloy Sheet, Strip, and Plate 6Al – 2Sn – 4Zr – 2Mo – 0.08Si Duplex Annealed
SAE AMS4939	Titanium Alloy Sheet, Strip, and Plate 3Al – 8V – 6Cr – 4Mo – 4Zr Solution Heat Treated
SAE AMS4988**	Titanium Alloy Sheet, Strip, and Plate 6Al – 6V – 2Sn Solution Heat Treated
SAE AMS4989	Titanium Alloy Sheet, Strip, and Plate 3Al – 2.5V Annealed
SAE AMS4990**	Titanium Alloy Sheet, Strip, and Plate 6Al – 6V – 2Sn Solution Heat Treated and Aged

* Ti-6Al-4V material specifications

** Ti-6Al-6V-2Sn material specifications

SAE AMS Ti Alloy Specifications Superseding SAE AMS-T-9047, Titanium and Titanium Alloy, Bars (Rolled or Forged) and Reforging Stock, Aircraft Quality

SAE AMS6900	Titanium Alloy Bars, Forgings and Forging Stock 5Al – 2.5Sn Annealed
SAE AMS6901	Titanium Alloy Bars, Forgings and Forging Stock 5Al – 2.5Sn, Extra Low Interstitial Annealed

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SAE AMS6905	Titanium Alloy Bars, Forgings and Forging Stock 6.0Al – 2.0Sn – 4.0Zr – 2.0Mo Duplex Annealed
SAE AMS6906	Titanium Alloy Bars, Forgings and Forging Stock 6.0Al – 2.0Sn – 4.0Zr – 6.0Mo Solution Heat Treated and Aged
SAE AMS6907	Titanium Alloy Bars, Forgings and Forging Stock 6.0Al – 2.0Sn – 4.0Zr – 6.0Mo Duplex Annealed
SAE AMS6910	Titanium Alloy Bars, Forgings and Forging Stock 8Al – 1Mo – 1V Duplex Annealed
SAE AMS6915	Titanium Alloy Bars, Forgings and Forging Stock 7.0Al – 4.0Mo Annealed
SAE AMS6920	Titanium Alloy Bars, Forgings and Forging Stock 3Al – 8V – 6Cr – 4Mo – 4Zr Solution Heat Treated
SAE AMS6921	Titanium Alloy Bars, Forgings and Forging Stock 3Al – 8V – 6Cr – 4Mo – 4Zr Solution Heat Treated and Aged
SAE AMS6925	Titanium Alloy Bars, Forgings and Forging Stock 13V – 11Cr – 3Al Solution Heat Treated
SAE AMS6926	Titanium Alloy Bars, Forgings and Forging Stock 13V – 11Cr – 3Al Solution Heat Treated and Aged
SAE AMS6930*	Titanium Alloy Bars, Forgings and Forging Stock 6.0Al – 4.0V Solution Heat Treated and Aged
SAE AMS6931*	Titanium Alloy Bars, Forgings and Forging Stock 6.0Al – 4.0V Annealed
SAE AMS6932*	Titanium Alloy Bars, Forgings and Forging Stock 6.0Al – 4.0V Extra Low Interstitial Annealed
SAE AMS6935**	Titanium Alloy Bars, Forgings and Forging Stock 6.0Al – 6.0V – 2.0Sn Solution Heat Treated and Aged
SAE AMS6936**	Titanium Alloy Bars, Forgings and Forging Stock 6Al – 6V – 2Sn Annealed
SAE AMS6940	Titanium Alloy Bars, Forgings and Forging Stock 3.0Al – 2.5V Annealed

* Ti-6Al-4V material specifications

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** Ti-6Al-6V-2Sn material specifications

SAE (Other)

SAE AMS4928* Titanium Alloy Bars, Wire, Forgings, Rings, and Drawn Shapes
6Al – 4V Annealed

SAE AMS-H-81200 Heat Treatment of Titanium and Titanium Alloys

SAE ARP1917 Clarification of Terms Used in Aerospace Metals Specifications

* Ti-6Al-4V material specifications

Other

Calcaterra, J. (November 2009). *Titanium Substitution Issue*. Paper presented at the Western Titanium Workshop. Pasadena, CA. Access to this presentation is limited presentation.

Donachie, Matthew J. (2000). *Titanium – A Technical Guide, Second Edition*. Materials Park, OH: ASM International.

2.4 Order of Precedence

This Handbook provides guidance to help mitigate the procurement of nonconforming Ti alloys for NASA flight applications but does not supersede nor waive established Agency requirements/guidance found in other documentation.

3. ACRONYMS AND DEFINITIONS

3.1 Acronyms and Abbreviations

α	alpha
=	equal
<	less than
ϵ -N	strain versus number of cycles fatigue curve
%	percent
$\sqrt{\quad}$	square root
°C	degree(s) Celsius
°F	degree(s) Fahrenheit
AFRL	Air Force Research Laboratory
Al	aluminum
AMS	Aerospace Materials Specification
ARP	Aerospace Recommended Practice
AS	Aerospace Standard
ASL	Approved Suppliers List
ASM	ASM International (formerly American Society for

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	Metals)
ASTM	ASTM International (formerly American Society for Testing and Materials)
ATI	Allegheny Technologies Incorporated
CA	California
cm	centimeter(s)
cm ²	square centimeter(s)
C of C	certificate of conformance
COT	certificate of test
Cr	chromium
da/dN	fatigue crack growth rate
DCMA	Defense Contract Management Agency
DoD	Department of Defense
DRD	Data Requirement Description
E	tensile elastic modulus
El	elongation
ELI	extra-low interstitial
Fsu	ultimate shear strength
Ftu	tensile ultimate strength
Fty	tensile yield strength
GIDEP	Government-Industry Data Exchange Program
Gpa	gigapascal(s)
HDBK	handbook
HT	heat treatment
in	inch(es)
in ²	square inch(es)
ISO	International Organization for Standardization
JPL	Jet Propulsion Laboratory
K _{Ic}	fracture toughness
ksi	kip(s)/square inch
L	longitudinal direction
ln	natural logarithm
m	meter(s)
M&P	Materials & Processes
MIL	military
MMPDS	Metallic Materials Properties Development and Standardization
mm	millimeter(s)
mm ²	square millimeter(s)
Mo	molybdenum
MPa	megapascal(s)
Msi	megapound(s) per square inch
MSV	minimum specification value
n	number of individual measurements
Nadcap	National Aerospace and Defense Contractors Accreditation Program

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NAS	National Aerospace Specification
NASA	National Aeronautics and Space Administration
NDE	nondestructive evaluation
OH	Ohio
OJT	on-the-job training
ppm	parts per million
psi	pound(s) per square inch
QA	quality assurance
QSL	Qualified Suppliers List
QRE	quick reaction evaluation
RA	reduction of area
RLB	reasonable lower bound
RTI	RTI International (formerly Research Triangle Institute)
S-N	stress versus number of cycles fatigue curve
SAE	Society of Automotive Engineers
SCC	stress corrosion cracking
SDRL	Subcontract Data Requirements List
S_f	fatigue limit
SI	Système International
Si	silicon
Sn	tin
ST	solution treated
STA	solution treated and aged
T	transverse direction
Ti	titanium
Timet	Titanium Metals Corporation
U.S.	United States
USAF	United States Air Force
UT	ultrasonic testing
V	vanadium
Zr	zirconium

3.2 Definitions

Reference or source is listed in parentheses at the end of each definition:

A-Basis: The lower of either a statistically calculated number or the specification minimum (S-basis). The statistically calculated number indicates that at least 99 percent of the population of values is expected to equal or exceed the A-basis mechanical design property, with a confidence of 95 percent. (MMPDS-06 Handbook)

Aging: A change in the properties that occurs with time at ambient or moderately elevated temperatures after working or a heat treatment (natural or artificial aging) or after a cold-working operation (strain aging). The change in properties is often, but not always, related to a phase change (precipitation), but it never involves a change in chemical composition. (Donachie, 2000)

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Alpha (α) Case: The oxygen-, nitrogen-, or carbon-enriched, α -stabilized surface resulting from elevated temperature exposure. (Donachie, 2000)

Annealing: A generic term denoting a treatment, consisting of heating to and holding at a suitable temperature, followed by cooling at a suitable rate. It is used primarily to soften metallic material but also to simultaneously produce desired changes in other properties or in microstructure. The purpose of such changes may be, but is not confined to, improvement of machinability, facilitation of cold work, improvement of mechanical or electrical properties, relief of stresses, and/or increase in stability of dimensions. Specific process names in commercial use are final annealing, full annealing, intermediate annealing, partial annealing, recrystallization, annealing, stress-relief annealing, and annealing to temper. (Donachie, 2000)

As Cast: Castings that have gates and risers removed, that are cleaned free of mold materials but that have been subject to subsequent heat treatment. (SAE ARP1917, Clarification of Terms Used in Aerospace Metals Specifications)

Bar (definition 1): A solid square, rectangular, or round shaped material whose length is greater than its cross section with a diameter of 12.7 mm (0.5 in) and over or distance between parallel surfaces. (SAE ARP1917) Note: This definition is recommended for NASA programs.

The following additional information can be found in Ti alloys SAE AMS specifications regarding the term bar:

Bar (definition 2): A product shall be processed to the final thickness/diameter by metallurgical working operations prior to any straightening, dimensional sizing, or surface finish operations. Bar shall not be cut from plate. (Information in accordance with SAE AMS6931, Titanium Alloy Bars, Forgings and Forging Stock 6.0Al – 4.0V Annealed, section 3.3.1)

Bar (definition 3): The product shall be produced using standard industry practice designed strictly for production of bar stock to the procured thickness. Cut plate shall not be supplied in lieu of bar. (Information in accordance with SAE AMS4928R, Titanium Alloy Bars, Wire, Forgings, Rings, and Drawn Shapes 6Al – 4V Annealed, section 3.3.1)

For historical and cross-referencing purposes, the following definitions of the term bar are included:

Bar (definition 4): A finished mill product intended for structural applications in airborne vehicle and equipment. (MIL-T-9047G, section 6.1.1)

Bar (definition 5): A hot rolled, forged, or cold worked semi-finished solid section product whose cross sectional area is equal to or less than 103.23 cm^2 (16 in^2); rectangular bar must be less than or equal to 254 mm (10 in) in width and greater than 4.76 mm (0.1875 in) in thickness. (ASTM B348, Standard Specification for Titanium and Titanium Alloy Bars and Billets, section 3.1.1)

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Bar (definition 6): A finished mill product intended for application in vehicles and equipment. Bars are hot/cold finished to final dimensions and are not cut to achieve the required thickness. The maximum cross-sectional size of Ti alloy bar is based on the alloy but is no larger than 309.68 cm² (48 in²). (An amalgam of SAE ARP1917, SAE AMS6931, and SAE AMS-T-9047.)

Best Commercial Practice: The workmanship of metal products that meet the commonly recognized industry quality standard for a particular alloy, surface condition, product form, heat-treat condition, and, most importantly, the method of fabrication. This term is no longer used in specifications since the standard can vary from mill to mill and product to product and is subject to interpretation. (SAE ARP1917)

Billet (Reforging, Rerolling, or Extrusion Stock) (definition 1): A solid metal product that is intended for subsequent hot working into finished or semi-finished products. (SAE ARP 1917)
Note: This definition is recommended for NASA programs.

For cross-referencing purposes, the following definition of the term billet is included:

Billet (definition 2): A solid semi-finished section hot rolled or forged from an ingot with a cross sectional area greater than 103.23 cm² (16 in²) whose width is less than five times its thickness. (ASTM B348, section 3.1.2)

Certification: A formal written document attesting that a specific operation or product meets standards and/or requirements specified within the applicable document. (SAE ARP1917)

Cold Working: Process by which metal is strain hardened by mechanical deformation that is performed at a temperature that is below the recrystallization temperature. (SAE ARP1917)

Conversion House: An industrial company, known also as conversion shop, mill conversion, or forging house, that performs forging and/or hot rolling operations on the Ti alloy ingot and that can produce intermediate products referred to as billets, slabs, or blocks. The company may also further hot roll or forge intermediate products to fabricate end product forms.

Heat: All material identifiable to a single molten metal source. All material from a heat is considered to have the same composition. A heat may yield one or more ingots. A heat may be divided into several lots by subsequent processing. (MMPDS-06 Handbook)

Hydrogen Embrittlement: A condition of low ductility in metals resulting from the absorption of (excess) hydrogen. (Donachie, 2000)

Interstitial Element: An element with a relatively small atom that can assume a position in the interstices of the Ti lattice. Common examples are oxygen, nitrogen, hydrogen, and carbon. Extra low interstitial (ELI) content can be specified.

Lot (definition 1): Material taken from a single heat of metal, processed at the same time into the same size and shape of product, and heat treated as a single heat-treat lot. (SAE

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ARP1917) Note: This definition is recommended for NASA programs.

Lot (definition 2): All product of the same nominal size from the same heat, processed at the same time. (SAE AMS6931, section 4.3)

Lot (definition 3): All product of the same nominal size from the same heat, processed at the same time, and solution heat treated and annealed as a heat-treat batch. (SAE AMS4928, section 4.3)

Lot (definition 4): All material from a heat or single molten metal source of the same product type having the same thickness or configuration and fabricated as a unit under the same condition. If the material is heat treated, a lot is the above processed through the required heat-treated operations as a unit. (MMPDS-06 Handbook)

For historical cross-referencing purposes, the following definition is included:

Lot (definition 5): Products of the same mill heat, size, and shape processed at the same time. (MIL-T-9047G, section 4.2)

Material Certificate: A package of information and test reports required by governing specification, including the description of ingot through billet to final product processing history with all relevant mechanical and chemical testing identified with results, inspection type and results, heat-treat certifications, procured metal size, and lot number.

Metallurgical Working Operations: General terminology referring to various thermo-mechanical means for reducing the cross-sectional area of large diameter Ti alloy ingots, first into slabs or billets and then into various product forms, such as bars, plates, and sheet, for example. Hot rolling would be an example of a thermo-mechanical operation to reduce the thickness of billets or plate stock.

Mechanical Properties: The properties of a material that reveal its elastic and inelastic (plastic) behavior when force is applied, thereby indicating its suitability for mechanical (load-bearing) applications. Examples are elongation, fatigue limit, hardness, modulus of elasticity, tensile strength, and yield strength. For instance, the A-basis values of Ti-6Al-4V annealed plate with thickness of 50.8 to 101.6 mm (2 to 4 in) are: tensile strength = 896 MPa (130 ksi); yield strength = 827 MPa (120 ksi); and elongation = 10 percent. (MMPDS-06 Handbook)

Nonconformance: A condition of any article, material, process, or service in which one or more characteristics do not conform to requirements specified in the contract, drawings, specifications, or other approved documents. Includes failures, defects, anomalies, and malfunctions. This term is used interchangeably with discrepancy and noncompliance. (NASA-HDBK-8739.18, Procedural Handbook for NASA Program and Project Management of Problems, Nonconformances, and Anomalies)

Plate (definition 1): Flat rolled product having the nominal thickness 4.76 mm (0.1875 in) and over. (SAE ARP1917) Note: This definition is recommended for NASA programs.

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Plate (definition 2): A product produced using standard industry practices designed strictly for the production of plate stock to the procured thickness. Bar, billet, forgings, or forging stock shall not be supplied in lieu of plate. (SAE AMS4911, Titanium Alloy Sheet, Strip and Plate 6Al – 4V Annealed, section 3.3.2)

For historical cross-referencing purposes, the following definition of the term plate is also included:

Plate (definition 3): A flat rolled product of 4.78 mm (0.188 in) and over in thickness and over 30.48 cm (12 in) in width, with the width at least five times the thickness. (MIL-T-9046J, section 6.4.3)

Primary Mills: Mills involved in the initial refinement of Ti and Ti alloys. At a high level, this process consists of the production of Ti and Ti alloys from an ore, through the sponge, to form an ingot. Primary mills may also produce subsequent shapes of Ti and Ti alloy as either intermediate products or final product shapes.

For historical cross-referencing purposes, the following definition of the term re forging stock is included:

Re forging Stock: A semi-finished mill product, which requires further hot reduction and appropriate thermal treatment to meet the tensile properties and microstructure requirements of this specification (referring to MIL-T-9047) or applicable forging specification prior to structural use. (MIL-T-9047G, section 6.1.2)

S-Basis: Minimum property value specified by the governing industry specification or federal or military standards for the material. (MMPDS-06 Handbook)

Shall: The word used to express a mandatory requirement. (SAE ARP1917)

Sheet/Strip (definition 1): A flat rolled product within the thickness of 0.13-4.76 mm (0.005–0.1875 in), excluding 4.76 mm (0.1875 in). (SAE ARP1917)

For historical cross-referencing purposes, the following definition of the terms sheet/strip is included:

Sheet/Strip (definition 2): A flat rolled product up to and including 4.78 mm (0.187 in) in thickness and 61 cm (24 in) and over in width. (MIL-T-9046J section 6.4.1)

Should: The word used to express a recommendation that is desirable but not mandatory. (SAE ARP1917)

Slab: A piece of metal, intermediate between ingot and plate, with the width at least twice the thickness. (Donachie, 2000)

Solution Heat Treatment: A heat treatment in which an alloy is heated to a suitable temperature, held at that temperature long enough to cause one or more constituents to enter into

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solid solution, then cooled rapidly enough to hold these constituents in solution. (Donachie, 2000)

Wrought: A metal or alloy that has been deformed plastically one or more times and exhibits little or no evidence of cast structure. (Donachie, 2000)

4. GENERAL

4.1 General

Information about Ti alloy specifications and how Ti alloys are fabricated, procured, and certified is included in this section.

4.2 Specifications used to Procure Ti Alloys

Government agencies, such as NASA and the DoD, and their contractors procured aircraft-/space-quality Ti alloys for many years (until the late 1990s) through two military specifications: MIL-T-9047 and MIL-T-9046.

MIL-T-9047 was issued on June 16, 1953, and covered Ti and Ti alloy rolled or forged bar and reworking stock products. MIL-T-9046 was issued on May 20, 1955, and encompassed Ti and Ti alloy metal sheet, strip, and plate products. Both specifications were revised many times over their years of use. As more Ti alloys were developed and more test data acquired, the procurement specifications were altered accordingly. High-performance requirements for new aircraft and space hardware designs resulted in ever more stringent specification requirements for processing, chemical composition, mechanical testing, and inspection.

For further information about the content of these now-canceled Government specifications, see Appendix A in this Handbook.

4.2.1 SAE AMS-T-9047 and Subsequent AMS Specifications used to Procure Ti Alloys

SAE AMS-T-9047 was a word-for-word translation of MIL-T-9047, Notice 3, containing only minor editorial and format changes. This specification was subsequently canceled by the Aerospace Materials Division, SAE, as of May 2006 and has been superseded by the applicable AMS specifications listed in table 1, List of SAE AMS Specifications Superseding SAE AMS-T-9047 (MIL-T-9047). The requirements of the latest issue of the AMS specifications listed in table 1 should be fulfilled whenever reference is made to the canceled SAE AMS-T-9047 specification.

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Table 1—List of SAE AMS Specifications Superseding SAE AMS-T-9047 (MIL-T-9047)

Type	Alloy	Condition	Superseding Specification
Alpha Ti Alloys	5Al-2.5Sn	Annealed	SAE AMS6900
	5Al-2.5Sn (ELI)	Annealed	SAE AMS6901
	8Al-1Mo-1V	Duplex Annealed	SAE AMS6910
Alpha-Beta Ti Alloys	3Al-2.5V	Annealed	SAE AMS6940
	6Al-4V	Annealed	SAE AMS6931
		STA	SAE AMS6930
	6Al-4V (ELI)	Annealed	SAE AMS6932
	6Al-6V-2Sn	Annealed	SAE AMS6936
		STA	SAE AMS6935
	6Al-2Sn-4Zr-2Mo	Duplex Annealed	SAE AMS6905
	6Al-2Sn-4Zr-6Mo	Duplex Annealed	SAE AMS6907
STA		SAE AMS6906	
7Al-4Mo	Annealed	SAE AMS6915	
Beta Ti Alloys	3Al-8V-6Cr-4Mo-4Zr	ST	SAE AMS6920
		STA	SAE AMS6921
	13V-11Cr-3Al	ST	SAE AMS6925
		STA	SAE AMS6926
ST = solution treated			
STA = solution treated and aged			

NASA Centers mainly procure two alpha-beta Ti alloys: Ti-6Al-4V and Ti-6Al-6V-2Sn. These metals are usually procured in the annealed condition and may be used as annealed in flight hardware or later solution treated and aged (STA) during fabrication/assembly phases. Therefore, according to table 1, the applicable procurement specifications for Ti-6Al-4V annealed bars and forgings and Ti-6Al-6V-2Sn annealed bars and forgings are SAE AMS6931 and SAE AMS6936, respectively.

These two SAE AMS specifications have similar requirements to the last revised MIL-T-9047G, Amendment 2. There is one divergence of interest with respect to maximum cross-sectional area of tested material: SAE AMS6931 specifies minimum mechanical properties for stock with a maximum cross-sectional area of 309.68 cm² (48 in²) instead of 103.23 mm² (16 in²) in MIL-T-9047G, Amendment 2. See section 4.4 for more information regarding the topic of maximum cross-sectional area. In addition, the latest SAE AMS6931B asserts in section 3.3.1, “The product shall be processed to the final thickness/diameter by metallurgical working operations prior to any straightening, dimensional sizing or surface finishing operations. Bar shall not be cut from plate.”

4.2.2 SAE AMS-T-9046 and Subsequent SAE AMS Specifications used to Procure Ti Alloys

SAE AMS-T-9046 was a word-for-word translation of MIL-T-9046J, Amendment 2, containing only minor editorial and format changes. This specification was canceled by the Aerospace Materials Division, SAE, as of May 2006 and has been superseded by the applicable SAE AMS specifications listed in table 2, List of SAE AMS Specifications Superseding SAE AMS-T-9046

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(MIL-T-9046J, Amendment 2). The requirements of the latest issue of the AMS listed in table 2 should be fulfilled whenever reference is made to the canceled SAE AMS-T-9046 specification.

Table 2—List of SAE AMS Ti Alloy Specifications Superseding SAE AMS-T-9046 (MIL-T-9046J, Amendment 2)

Type	SAE AMS-T-9046 Material Designation	Alloy	Condition	Superseding Specification
Alpha Ti Alloys	A-1	5Al-2.5Sn	Annealed	SAE AMS4910
	A-2	5Al-2.5Sn (ELI)	Annealed	SAE AMS4909
	A-4	8Al-1Mo-1V	Annealed	SAE AMS4915
			Duplex Annealed	SAE AMS4916
Alpha-Beta Ti Alloys	AB-1	6Al-4V	Annealed	SAE AMS4911
			ST	SAE AMS4903
			STA	SAE AMS4904
	AB-2	6Al-4V (ELI)	Annealed	SAE AMS4907
	AB-3	6Al-6V-2Sn	Annealed	SAE AMS4918
			ST	SAE AMS4988
			STA	SAE AMS4990
	AB-4	6Al-2Sn-4Zr-2Mo	Duplex Annealed	SAE AMS4919
AB-5	3Al-2.5V	Annealed	SAE AMS4989	
Beta Ti Alloys	B-1	13V-11Cr-3Al	ST	SAE AMS4917
	B-3	3Al-8V-6Cr-4Mo-4Zr	ST	SAE AMS4939

NASA Centers mainly procure two alpha-beta Ti alloys: Ti-6Al-4V and Ti-6Al-6V-2Sn in the annealed condition. As indicated in table 2, applicable procurement specifications for Ti-6Al-4V annealed sheet, strip, and plate and Ti-6Al-6V-2Sn annealed sheet, strip, and plate are SAE AMS4911 and SAE AMS4918, respectively.

These two AMS specifications have requirements similar to MIL-T-9046J, Amendment 2. In addition, the latest SAE AMS4911 and SAE AMS4918 assert in section 3.3.2, “Plate product shall be produced using standard industry practices designed strictly for the production of plate stock to the procured thickness. Bar, billet, forgings, or forging stock shall not be supplied in lieu of plate.”

4.2.3 Other Non-Government Specifications

SAE AMS4928 and ASTM B348 are other examples of SAE AMS and ASTM specifications that might be relevant to procurement of Ti-6Al-4V material in the annealed condition, specifically in bar and forging forms. SAE AMS4928 covers Ti-6Al-4V bars, wires, forgings, rings, and drawn shapes in annealed condition. When compared with SAE AMS6931, which superseded SAE AMS-T-9047, SAE AMS4928 does not specify any maximum cross-sectional area of tested material nor does it specify macrostructure and ultrasonic inspection requirements. SAE AMS4928 also allows a solution heat treatment (HT) in a mill-annealed material. This is

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not permitted in any other mill-annealed specification. Solution HT increases strength at the expense of fracture toughness. However, SAE AMS4928 has a more stringent requirement on hydrogen content (maximum 125 ppm versus 150 ppm in SAE AMS6931) and higher tensile and yield strength requirements for bars up to 50.8 mm (2 in) in thickness (931 MPa (135 ksi) and 862 MPa (125 ksi) versus 896 MPa (130 ksi) and 827 MPa (120 ksi) in SAE AMS6931). Additional requirements can always be added to procurement documentation if this specification needs to be utilized, thereby facilitating material purchased in accordance with this specification to be acceptable for flight.

ASTM B348 encompasses annealed Ti and Ti alloy bars and billets, including Ti-6Al-4V material. However, this specification does not include requirements for microstructure, macrostructure, and ultrasonic inspection and is not recommended for procurement of aircraft-/space-quality Ti and Ti alloys for flight application without the use of additional requirements to address noted shortfalls or performance of additional testing by procuring organizations.

Detailed knowledge of the certification requirements associated with the various Ti alloy specifications, coupled with careful review of the certification data package, is required to assure that material has been properly processed and certified.

4.3 How Wrought Ti Alloys are Produced and Processed and in What Shapes

Processing of Ti alloys, as with many metal alloys, involves multiple steps. A wrought Ti alloy product begins as an ingot: in vacuum, a molten Ti alloy is allowed to solidify in a mold. Example Ti alloy ingot diameters are 71.1 cm (28 in), 76.2 cm (30 in), and 91.4 cm (36 in).

The ingot is then typically hot worked in a forging press into the products referred to as billets, slabs, or blocks. These partially forged, semi-finished materials are created as feedstock for final processing. The semi-finished materials are intermediate products generally not intended for finished products. Intermediate products require additional hot rolling, hot forging, or extruding processes (also generally referred to as metallurgical working operations) to produce wrought end-product shapes for aerospace applications. A typical fabrication process for aerospace-quality wrought Ti alloy finished products is shown in figure 1, Fabrication Process of Wrought Ti Alloys. (Figure 1 is modified from Calcaterra, 2009.)

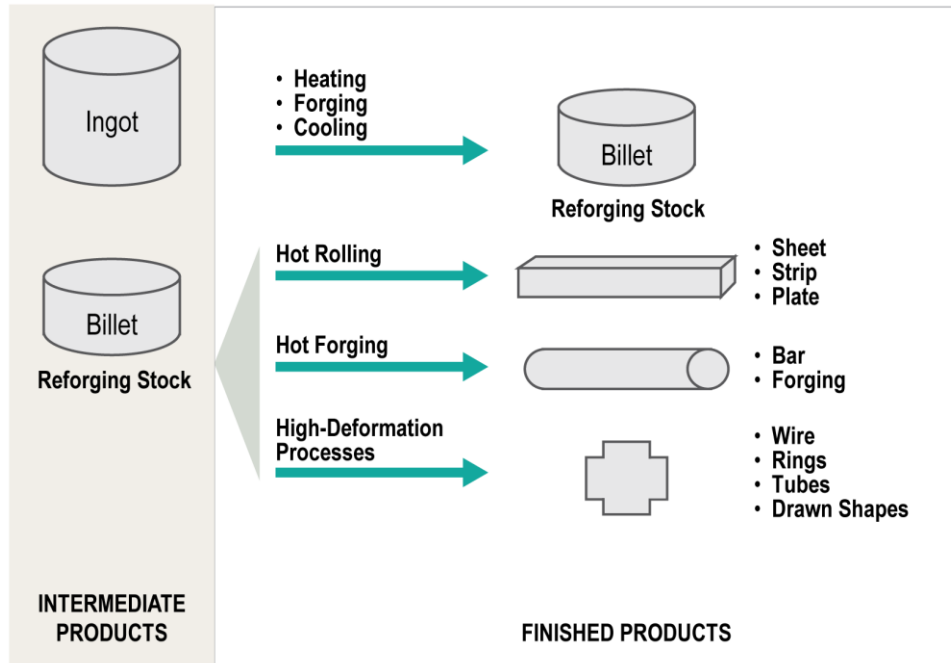


Figure 1—Fabrication Process of Wrought Ti Alloys

The primary mill sources for ingots of Ti alloy in the U.S. include Allegheny Technologies Incorporated (ATI) Allvac, RTI International (formerly Research Triangle Institute), and Titanium Metals Corporation (Timet). These companies supply ingots to conversion houses that forge and/or hot roll the ingot into intermediate products. Primary mill sources may also produce intermediate or end-product forms.

Examples of end-product shapes intended for use in aerospace systems include bar (round or rectangular), plate, sheet, strip, and wire. Some specifications also include a product form called forging stock, which is the same as billet or intermediate product to be used for further processing.

The complex microstructures of Ti alloys are developed from combined thermal-mechanical processing of as-cast ingots through intermediate to the final product forms. The microstructure and hence the mechanical properties of Ti alloys are dependent on the fabrication scheme and the thermal history. Multiple cycles of work (heating, forging, rolling, and cooling) are required to achieve the desired microstructure required for thin plate and sheet products used for flight applications. Intermediate product forms may not have been worked sufficiently to produce the microstructure necessary to achieve minimum acceptable specification-based mechanical properties across the entire cross section. If, because of the size of a Ti alloy part to be fabricated, intermediate product sizes such as billets of greater than 15.2 cm (6 in) thickness need to be procured, the procuring organization can specify slightly lower minimum mechanical properties than typical for thinner plate material. Based on information from USAF and JPL test programs (discussed in sections 5.3.2 and 5.3.3 in this Handbook), only 5 to 10 percent reductions in tensile ultimate strength (F_{tu}) and tensile yield strength (F_{ty}), respectively, may be sufficient to bound the minimum mechanical properties of the billet material. However, there are significant deviations in secondary properties. Specifically noteworthy are impacts to fatigue and

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other dynamic mechanical properties, which are described further in section 5.3.2 of this Handbook.

In addition to thermo-mechanical processing, Ti alloy mechanical properties are strongly dependent on heat treatment. Ti-6Al-4V is commonly specified in either an annealed or an STA condition. Annealing requires that the entire cross section be maintained at 704.4 °C (1,300 °F) for 1 hour minimum, followed by furnace cooling, if maximum ductility, i.e., high percent elongation and percent reduction of area at failure, is required. Note: Most specifications give a temperature range with 704.4 °C (1,300 °F) as a minimum. Also, most specifications make a reference to section thickness driving the time at temperature. SAE AMS-H-81200, Heat Treatment of Titanium and Titanium Alloys, offers the following guidance in selecting soak times:

- a. 20 minutes for the thickness of 3.175 mm (0.125 in) and under.
- b. 1 hour minimum plus an additional 15 minutes for each 3.175 mm (0.125 in) of thickness over 25.4 mm (1 in).

The most common minimum specification values for tensile yield and ultimate strength of annealed Ti 6Al-4V material are 827 MPa (120,000 psi) and 896 MPa (130,000 psi), respectively. Carefully developed thermal processes exist for STA conditions. The resulting effects of these thermal processes on minimum strength values as a function of plate thickness can be seen in figure 2, Specification Minimum Strength Sensitivity of Ti-6Al-4V Sheet, Strip, and Plate as a Function of Heat Treatment, Thickness, and Interstitial Element Level.

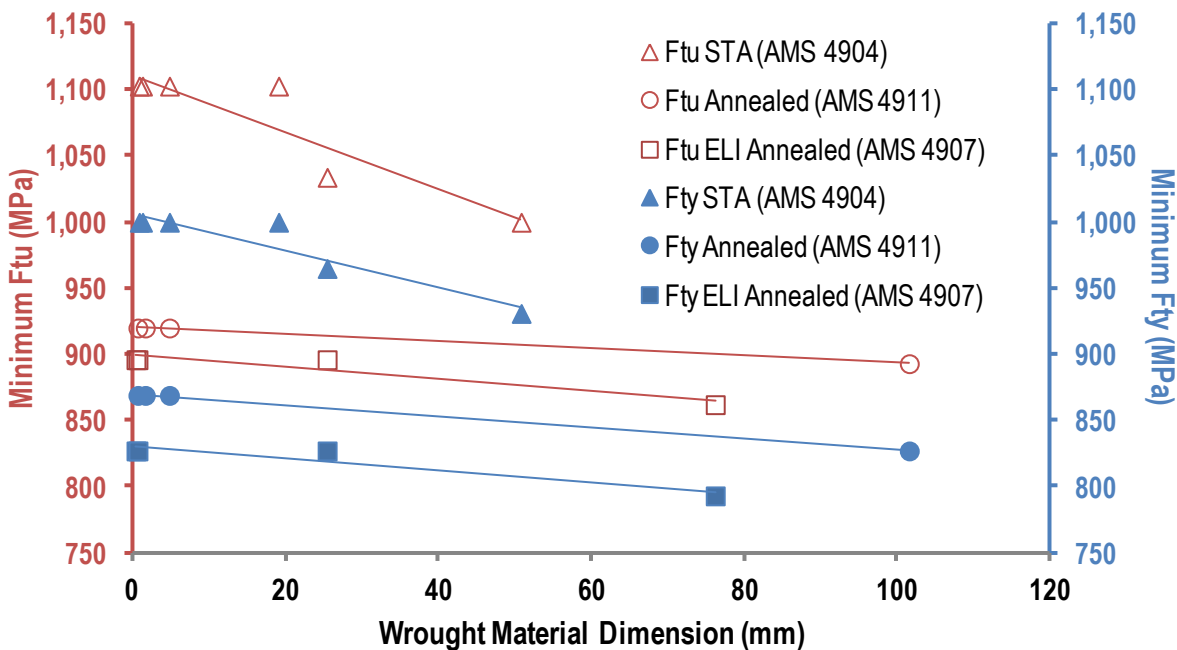


Figure 2— Specification Minimum Strength Sensitivity of Ti-6Al-4V Sheet, Strip, and Plate as a Function of Heat Treatment, Thickness, and Interstitial Element Level

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Mills, conversion houses, or heat treatment shops use an acid treatment, referred to as pickling, to remove the scale and/or an alpha case from material not heat treated in vacuum or suitable inert gas environments. This etching process can be an issue regarding the generation of hydrogen embrittlement; therefore, a hydrogen content determination test, e.g., in accordance with ASTM E 1447, Standard Test Method for Determination of Hydrogen in Titanium and Titanium Alloys by Inert Gas Fusion Thermal Conductivity/Infrared Detection Method, of final products is required, and the test result should be included in the material certification package. Also, because of the tendency of prestressed Ti alloys to crack while in contact with certain chemical reagents, it is necessary to ensure that materials used during processing, testing, and inspection, including ultrasonic couplants, will not initiate stress corrosion of titanium alloys. ASTM F 945, Standard Test Method for Stress-Corrosion of Titanium Alloys by Aircraft Engine Cleaning Materials, can be used for dealing with the contact material compatibility issue.

SAE AMS4911 for annealed sheet, strip, and plate Ti-6Al-4V clearly states in section 3.3.2 that a “plate product shall be produced using standard industry practices designed strictly for the production of plate stock to the procured thickness. Bar, billet, forgings, or forging stock shall not be supplied in lieu of plate.” No matter whether the previous practice for any Ti alloy supplier has included cutting down billet thicknesses, this practice is not standard.

SAE AMS6931 for bars and forgings processing affirms in section 3.3.1 that a bar product shall be processed to the final thickness/diameter by metallurgical working operations. Bar shall not be cut from plate. It is not allowed to cut a plate along its longitudinal direction and make a bar. If cutting in the longitudinal direction is done, the product still needs to be identified as plate stock. The customer may agree on the substitution, but the bar product from the plate stock cannot be certified as bar stock. Cut strip from the plate without further thickness reductions is acceptable, as noted above. However, it is important to maintain grain direction knowledge of cut samples. In addition, it should be clear that cutting billet is permitted if the cut pieces are subsequently hot or cold worked. This is a common industrial practice and completely acceptable.

4.4 How Ti Alloys can be Supplied to a NASA Organization or Contractor

Finished forms of Ti alloy materials such as plate, sheet, strip, bar, tube, and wire are supplied to NASA organizations or associated contractors by material distributors or secondary processing plants/companies, also referred to as conversion houses. For NASA flight program applications, the use of an appropriate material specification as a part of the procurement process is standard practice.

Ti alloy distributors by and large do not have any capabilities to hot work (forge, hot roll, or extrude) starting material into finished forms. Conversion houses have the in-house capability to perform some or all of the standard hot-working operations. Starting material for conversion houses may be referred to as forging stock, billet, or various other names. On the other hand, most Ti alloy distributors have only capabilities to cut stock with low-speed band saws or high-speed circular saws to meet size demands (different lengths and/or widths of a given thickness plate) of customers. Neither low- nor high-speed cutting is considered to be a metallurgical working operation or hot working.

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A material distributor may place orders to build up internal stock from conversion houses for finished products or procure intermediate products, e.g., billets or thick plate stock, or even procure Ti alloy ingots directly from Ti alloy mills. These intermediate products and ingots would subsequently be sent back out for hot working to meet a specific customer need. When an ingot is hot worked, it is considered a wrought product. Wrought products are divided into intermediate products and finished products. The thickness of wrought products is reduced through the hot-working process. An ingot is considered a cast shape.

Usually wrought Ti alloy finished products are intended for use in NASA systems, except when there is a part configuration issue, e.g., size/thickness, which precludes the use of finished products. If the stock to be used is larger than what the specification allows/requires, it still should be worked in the alpha-beta range to its final dimensions. Also, a purchaser needs to have an agreement on the minimum non-specification-based mechanical properties. However, all of the other specification requirements should apply. SAE AMS6931 and SAE AMS4911 specifications define what are considered finished plate and bar materials, respectively, and describe how these products shall be processed. (See section 4.3 in this Handbook.) Exceptions must be carefully dealt with by knowledgeable design, stress, and materials/processing engineers or manufacturing engineering personnel so that the proper minimum property values are used in the design, analysis, and verification activities.

The boundary size between billet and end product is alloy dependent. For example, Ti-6Al-6V-2Sn is generally 20,645 mm² (32 in²), Ti-6Al-4V is 309.68 cm² (48 in²), and Ti-6Al-4V ELI is 103.23 cm² (16 in²). Intermediate product forms for Ti-6Al-4V, such as billets, are generally considered to possess cross sections of greater than 309.68 cm² (48 in²), but some specifications are more stringent and stipulate that product forms with greater than 103.23 cm² (16 in²) be considered an intermediate product form. For example, ASTM B348 defines a billet as a solid semi-finished section hot rolled or forged from an ingot with a cross-sectional area greater than 103.23 cm² (16 in²) whose width is less than 5 times its thickness. SAE AMS6931 alternatively requires a maximal cross-sectional area of 309.70 cm² (48 in²) (with no stipulation for relationship of width to thickness) of tested forging product instead of the original 103.23 cm² (16 in²) maximum required by MIL-T-9047G, Amendment 2. The specification words referring to “of tested material” are related to the requirement to extract mechanical test coupons, such as tensile test coupons, from material that has less than the 309.68 cm² (48 in²) cross section.

For cross sections below the maximum cross-sectional area or thickness/diameter, the minimum mechanical properties are a requirement, and if the material does not meet them, it can be rejected. If the cross-sectional area is above the limit, then the mechanical properties are for information only and cannot be used to reject the material, unless there is a pre-established agreement between the procuring parties. While any size can be ordered, the procuring party should be aware of when the specifications apply and when they do not.

As discussed in section 5.3.2 of this document, some data have emerged recently (AFRL-RX-WP-TR-2012-0238, Quick Reaction Evaluation of Materials and Processes (QRE), tending to show that barely acceptable tensile property values are attainable for semi-finished billets with cross-sectional areas several times greater than 309.68 cm² (48 in²). Caution is urged in this area as the testing only represents large billets from one conversion house. On the other hand, the

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USAF test program on large cross-sectional area billets indicated up to 70-percent knockdown in fatigue life when compared with the control plate.

Intermediate product forms may not have been worked sufficiently to produce the microstructure necessary to achieve minimum specification mechanical properties across the entire cross section. It is possible, based on the above-mentioned extensive mechanical testing conducted by the USAF, with some supporting evidence from JPL D-69922, Report of the Titanium Working Group Concerning the Assessment of Non-Conforming Material as it Affects JPL Flight Projects, that Ti-6Al-4V billet (unlike Ti-6Al-6V-2Sn material produced to USAF requirements) can just meet the minimum mechanical values specified in AMS specifications for plate material greater than 152 mm (6 in) thick. However, JPL has also performed mechanical testing on suspected Ti-6Al-4V billet material provided as if the material was in a finished product shape with relevant material certifications and found several lots of material that exhibited mechanical properties just below minimum specification values. For example, out of 122 tensile test coupons made from 4 suspect lots of Ti-6Al-4V, 25 percent of test coupons failed to meet the specified minimum tensile yield strength, 4 percent of coupons failed to meet the minimum ultimate strength, and 53 percent of coupons failed to meet the minimum reduction in area. These data are discussed further in section 5.3.3 in this Handbook.

4.5 How Ti Alloys are Certified for Compliance to Procurement Specification

Wrought Ti alloys, with their associated certification packages, are provided by material distributors, conversion houses, or mills as part of standard procurement or acquisition processes. In the case of procured finished products or parts, certification packages are supplied by the vendors providing the finished parts. The certification package is to contain, as a minimum, the information outlined in the material specification for finished material provided by a mill. In addition, if material is processed by a conversion house, the original mill certification, the conversion house certification, the heat treatment certification, the hydrogen content test report, mechanical test data, ultrasonic inspection test report, micro/macrostructure evaluation, and any other quality assurance data required by the specification are also to be provided.

The material certification should contain all the test results and/or verification that the material meets all of the requirements contained in the applicable material specification. If the material was procured from a mill or from a distributor that obtained the material in its final form from a mill, this information will be in a mill certification. If the distributor had an intermediate product converted into the final form, the certification should contain the original certification for the ingot or billet, the certification from the conversion house (including starting size of billet and the finish size), the certification from the heat-treat supplier, and the results for the ultrasonic inspection, mechanical property testing, and the macrostructure and microstructure examinations.

5. NONCONFORMING TI ALLOYS

5.1 Definition of Nonconforming Ti Alloys

A nonconforming Ti alloy is:

- A material that was not processed properly as required by the Government or non-Government specification to which it was certified specifically to the final products, such as a plate, sheet, and forged bar.
- A lot of Ti alloy that fails to meet any material property required by an applicable procurement specification.

A key aspect of the Government-Industry Data Exchange Program (GIDEP) documents associated with nonconforming Ti alloys (listed in Appendix B of this Handbook) has been the allegation that some suppliers have delivered final product forms, namely bar and plate, that have been cut from intermediate product forms without the necessary additional thermo-mechanical working, a product called a cut-down billet. Moreover, it is alleged that material certification data associated with these final product forms were derived from test coupons drawn from prime locations within the intermediate products that may not be representative of the cross section from which the final products were obtained.

There appeared to be at least two categories of nonconforming Ti alloys:

- A plate fabricated by forging was substituted for rolled plate specified in SAE AMS4911 and SAE AMS4904, Titanium Alloy Sheet, Strip, and Plate 6Al-4V Solution Heat Treated and Aged. A forged plate thickness is produced as a part of the forging operation, i.e., no cutting of plate thickness occurs. These two specifications, along with most other Ti alloy specifications, require plate to be fabricated by rolling, not forging. Forging is not a valid method to produce Ti alloy plate. A plate fabricated by forging may not have been worked sufficiently to meet the minimum mechanical property specifications required by rolled plate in the aforementioned specifications.
- Cut-down billet. This material is unlikely to have been sufficiently mechanically worked to meet the minimum mechanical specifications of SAE AMS4911 and SAE AMS4904 for rolled sheet and plate or by SAE AMS6931 for forged bar. The lack of mechanical work is related to the larger cross section. Ti alloys supplied to DoD and NASA contracts are to conform to all contract requirements, including specifications cited in such contracts. When rolled plate is specified, the Ti alloy is to be rolled to the required thickness using industry standard practices. When bar is specified, the Ti alloy is to be hot worked to the required dimensions. The required Ti alloy dimensions are not to be accomplished by cutting down a thicker material. Almost all Ti alloy specifications specifically prohibit this practice. Cutting plate and bar stock to create the desired length of product to meet customer requirements is standard acceptable practice.

5.2 How Nonconforming Ti Alloys can be Supplied

Suspicion that nonconforming Ti alloy had entered the aerospace supply chain grew gradually in response to GIDEP releases dating from as early as 2004. The concern for inappropriate processing of Ti alloys does not extend to primary mills but rather to the distributors.

Evidence began accumulating that Ti alloys were being delivered from metal distributors to the industrial supply chain without having been processed in accordance with specification and that these materials could have strength properties below specification minimum values.

Investigation by the Air Force Research Laboratory (AFRL), the Air Force's repository of materials and manufacturing expertise for Ti, ultimately led to a federal indictment (case number 3:08-cr-04229 in the U.S. District Court for the Southern District of California) by the U.S. Department of Justice against the primary and other distributor companies. The case proceeded to trial in the fall of 2010, resulting in a plea agreement involving the imposition of a fine and payment of restitution to the U.S. Government.

The federal indictment alleged that nonconforming, cut-down Ti alloy billet was being sold as forged and rolled sheet, strip, bar, and plate. Other finished product forms (castings, sheet, strip, extrusions, die forgings, rod, and wire) were not implicated.

Appendix B provides a chronological history for nonconforming Ti alloy GIDEPs.

5.3 Key Mechanical Properties of Interest

NASA and NASA contract engineers must design components assuming minimum strength and ductility related values that will be delivered by procured materials. If a material is not processed in accordance with relevant specification, the engineer's design can be unknowingly compromised. This could lead to flight project hardware designs having inadequate structural margin, leading to structural failures and possibly mission failures.

Beside reduced strength, nonconforming material may exhibit detrimental yielding and larger deflections, such as in cantilever beam members, lower buckling margins for compression structure, and changes in natural frequencies.

Relatively complex material microstructures are developed in Ti alloys through a combination of thermal and mechanical processing, which gives them their superior mechanical properties. These microstructures and, hence, the alloy's mechanical properties are sensitive to the material's processing history. Failure to properly process Ti alloy can result in lower than specified (nonconforming) mechanical properties. The key mechanical properties are:

- Tensile Ultimate Strength (Ftu)
- Tensile Elastic Modulus (E)
- Tensile Yield Strength (Fty)
- Elongation (El)
- Reduction of Area (RA)

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- Fatigue Limit (S_f)
- Fracture Toughness (K_{Ic})
- Fatigue Crack Growth Rate (da/dN)
- Corrosion and Stress Corrosion Cracking (SCC) resistance.

Previously mentioned JPL mechanical testing (JPL D-69922) was focused on tensile properties. In addition to extensive static mechanical property testing, the nonconforming Ti alloy testing at AFRL (Calcaterra, 2009) included dynamic and damage tolerance properties. Reduced dynamic properties could result in possible service life impacts such as decreased crack initiation life, increased fatigue crack growth rate, and decreased fracture toughness. These impacts can result in shorter part lives and reduced inspection intervals.

Summaries of several nonconforming Ti alloy test programs are described in the following subsections.

5.3.1 Nonconforming Ti Alloy Testing at AFRL

The following are results of initial USAF tests on actual parts made for aircraft applications from suspect Ti-6Al-6V-2Sn material in the 2006 and 2008 timeframe (Calcaterra, 2009):

- Microstructural examination uncovered variability in grain structure that indicated improperly processed material inconsistent with plate in accordance with SAE AMS-T-9046.
- A high percentage of material failed to meet specification minimums.
 - 32 specimens (37 percent) did not meet F_{tu} specification minimum.
 - 19 specimens (22 percent) did not meet F_{ty} specification minimum.
 - Crack growth rate on 37 specimens was 4 times faster than rolled plate.

5.3.2 Billet Characterization Testing at AFRL

Subsequent to the testing discussed in section 5.3.1 above, the USAF embarked on a large billet-level test program for assessing the degree to which mechanical properties of such material met minimum specification values. This test program was designed to develop property data on a specific billet form obtained from one conversion house of two Ti alloys (Ti-6Al-4V and Ti-6Al-6V-2Sn) representing incomplete thermal-mechanical processed material.

Two Ti-6Al-4V billets were purchased with nominal width x length x thickness dimensions of 61 cm (24 in) x 48.3 cm (19 in) x 16.5 cm (6.5 in) and of 61 cm (24 in) x 114 cm (45 in) x 16.5 cm (6.5 in). Two Ti-6Al-6V-2Sn billets were fabricated for this program to thicknesses prescribed by AFRL to produce two different levels of hot working in the material. These billets had nominal dimensions of 30.4 cm (12 in) x 267 cm (105 in) x 11.4 cm (4.5 in) and 30.4 cm (12 in) x 203 cm (80 in) x 20.3 cm (8 in). Both alloys were produced in accordance with the SAE AMS-T-9047 specification that covers reforging stock and were delivered in the mill-annealed heat-treat condition.

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Significant numbers of test coupons were fabricated for tensile, fatigue (both stress versus number of cycles fatigue curve (S-N) and strain versus number of cycles fatigue curve (ϵ -N)), da/dN , K_{Ic} , and SCC testing. For example, for the Ti-6Al-4V material alone, over 300 tensile test coupons were fabricated and tested.

The key test results are summarized in table 3, Summary of AFRL Property Data for Incompletely Processed Ti Alloys in Annealed Condition. The test data are compared with the required tensile properties of plate and sheet in accordance with SAE AMS-T-9046. The decision to refer to these baseline values as reasonable lower bounds (RLBs) was based on the fact that an insufficient quantity of material heats and lots were represented for the calculation of traditional MMPDS A- or B-, or even S-basis allowables (AFRL-RX-WP-TR-2012-0238). However, the number of specimens tested (often in replicate) is significant. Thus RLB was chosen by the USAF Ti Task Force as an acceptable term to describe properties derived from the testing of multiple specimens from the two heats (per alloy) of material in this program. While these do not meet the requirements for standard baseline property determination, they are, nevertheless, significant. Under normal circumstances, three heats of material would be needed for establishing a specification minimum (S-basis) value; whereas 10 heats of material would be required for A- and B-basis allowables.

Statistical analyses were utilized to determine RLB for tensile strength (F_{tu} and F_{ty}). Tensile ductility (El and RA) RLB values were determined by the lowest value in the population. For the durability and damage tolerance properties (S_f , da/dN , and K_{Ic}), a life factor was determined that compared the properties of the improperly processed alloys with baseline properties generated from control plates.

For stiffness-driven designs of space structures, there can be concerns over degraded (lower) elastic modulus values. There were no independent tests, such as ultrasonics, conducted and/or vibration techniques to verify degraded values indicated in this section. Organizations are encouraged to verify off-nominal elastic modulus test values through an independent test technique if there are structural deflection concerns.

A major conclusion of the report is that engineers and designers should account for reduced properties when assessing the integrity and safety of components made with non-conforming materials.

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Table 3—Summary of AFRL Tensile Property Data on Incompletely Processed Ti Alloys in Annealed Condition (AFRL-RX-WP-TR-2012-0238)

Property	Alloy	RLB/Life Factor	Difference from SAE AMS-T-9046 Minimum Values (5.1 to 10.2 cm (2 to 4 in thick))
F _{tu}	Ti-6Al-4V	896 MPa (130 ksi)	No difference
	Ti-6Al-6V-2Sn	945 MPa (137 ksi)	55 MPa (8 ksi) lower
F _{ty}	Ti-6Al-4V	814 MPa (118 ksi)	14 MPa (2 ksi) lower
	Ti-6Al-6V-2Sn	903 MPa (131 ksi)	28 MPa (4 ksi) lower
El	Ti-6Al-4V	6.7%	3.3% lower than minimum specification value of 10%
	Ti-6Al-6V-2Sn	8%	No difference
RA	Ti-6Al-4V	10%	15% lower than SAE AMS-T-9047 <10.2 cm (<4 in) thick)
	Ti-6Al-6V-2Sn	19%	1% lower than SAE AMS-T-9047 7.6 to 10.2 cm (3 to 4 in) thick
E	Ti-6Al-4V	105.5 GPa (15.3 Msi)	4.8 GPa (0.7 Msi) lower than MMPDS-06 typical
	Ti-6Al-6V-2Sn	97.9 GPa (14.2 Msi)	12.4 GPa (1.8 Msi) lower than MMPDS-06 typical
K _{IC}	Ti-6Al-4V	65.7 MPa√m (59.8 ksi√in)	n/a†
	Ti-6Al-6V-2Sn	61.2 MPa√m (55.7 ksi√in)	n/a†
S-N Fatigue*	Ti-6Al-4V	0.61	n/a†
	Ti-6Al-6V-2Sn	0.14	n/a†
ε-N Fatigue*	Ti-6Al-4V	0.71	n/a†
	Ti-6Al-6V-2Sn	0.69	n/a†
da/dN*	Ti-6Al-4V	1x	n/a†

†: No specification minimum value exists for this property. Data from tested control plates were used in the determination of RLB or life factor.

*: Fatigue and crack growth rate life factors discussed in this report that describe the relationship between Ti alloy billet and plate should be used for initial screening purposes only. These factors represent worst-case comparisons **for only two stress ratios** (R=0.05 and -1 for fatigue, R=0.1 and 0.7 for da/dN); factors approach 1.0 at certain regions of the curves from which the factors were derived. If a program's initial screening indicates that sufficient maintenance intervals continue to exist for Ti alloy components, no further analysis is required. However, if maintenance intervals are found to be unacceptable during an initial screening using the published factors, a program may conduct further analysis using the full range of the test data provided by AFRL, supplemented, as appropriate, with test data and analysis generated by the program.

5.3.3 JPL Material Certificate of Conformance Assessment and Mechanical Testing

During the course of the nonconforming Ti alloy assessment at JPL, materials and process (M&P) engineers reviewed approximately 1,000 Ti alloy certification packages. Of these certification packages, 120 were found to contain suspicious omissions or other irregularities. While the investigation primarily focused on assessing if there was evidence of an improperly processed material, specifically regarding the cutting-down billet issue, the review indicated there were also material lots that could not be traced back to the source. Also, this investigation revealed that heat treatment, composition, and inspection could also be issues. Out of the dozens of lots of Ti alloy associated with these irregular certification packages, residual material from 4 lots happened to exist in sufficient quantity to facilitate the fabrication of 121 (total) tensile test coupons. The summary of tensile test results of Ti-6Al-4V materials in annealed condition from four certification packages indicating possible improper processing is shown in table 4, JPL Tensile Test Results Summary of Suspected Nonconforming Ti-6Al-4V in Annealed Condition.

Table 4—JPL Tensile Test Results Summary of Suspected Nonconforming Ti-6Al-4V in Annealed Condition

Lot	Procurement Specification¹	Number of Test Results	Fty (% of results below minimum)	Ftu (% of results below minimum)	EI (% of results below minimum)	RA (% of results below minimum)
A	MIL-T-9046J	30	0	0	10.0	No minimum specified
B	MIL-T-9047G	30	56.7	6.7	0	36.7
C	ASTM B348-10 ²	24	37.5	12.5	50.0	95.8
D	MIL-T-9047G	37	2.7	0	2.7	37.8

Notes:

1. MIL-T-9046J, MIL-T-9047G and ASTM B348-10 minimum values: Ftu = 896 MPa (130 ksi), Fty = 827 MPa (120 ksi), E = 10%, RA = 20%. MIL-T-9046J does not specify the minimum RA.
2. ASTM B348-10 minimum RA = 25%. Percentages shown represent data from the longitudinal and transverse directions. This specification was initially used for procurement of material to produce engineering model hardware; subsequently, with additional in-house testing, this lot of material was deemed acceptable for one part used on a flight project.

Subsequent to the testing indicated in table 4, six additional coupons were tested. These coupons were machined from extra component parts that were known to be fabricated from nonconforming material. The test data from these six coupons were combined with the 121 test results listed in table 4, and the total set of test data was analyzed to determine a pseudo S-basis minimum specification value (MSV) or knockdown, which could then be used in an on-going (at the time of the nonconforming Ti alloy investigations only) Flight Projects schedule-critical Ti alloy parts assessment process to determine if stress analyses yielded positive design margins for specific spacecraft components. The resulting approximate S-basis MSVs are summarized in table 5, JPL-Established Pseudo S-Basis Nonconforming Ti Alloy Minimum Specification Values. This assessment process should not be used as a part of standard part design/test/analysis processes for flight applications. This information is provided to indicate what one organization did to assess flight load margins for existing schedule-critical flight hardware where there was the possibility of having used a nonconforming Ti alloy lot.

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Table 5— JPL-Established Pseudo S-Basis Nonconforming Ti Alloy Minimum Specification Values¹

Ti-6Al-4V Annealed ²							
S-Basis ³	F _{tu} (MPa (ksi))	F _{ty} (MPa (ksi))	EI (%)	RA (%)	E (GPa (Msi))	Specification Knockdown F _{tu} (%)	Specification Knockdown F _{ty} (%)
All ⁴	853.67 (123.81)	747.07 (108.35)	5.9	4.4	118.6 (17.2)	4.8	9.7
L ⁵	872.70 (126.57)	760.45 (110.29)	8.2	9.1	117.2 (17.0)	2.6	8.1
T ⁶	846.22 (122.73)	730.18 (105.90)	7.1	9.5	121.4 (17.6)	5.6	11.7

Notes:

1. Data at room temperature.
2. Tested in accordance with ASTM E8, Standard Test Methods for Tension Testing of Metallic Materials.
3. All data are S-basis except E (mean) and Knockdown (%).
4. All = Results for all 121 test coupons described in table 4, plus 6 additional test coupons for a total of 127 test coupons.
5. L = Longitudinal direction; parallel to the principal of flow in a worked metal.
6. T = Transverse direction; perpendicular to the principal direction of flow in a worked metal

The results are to be interpreted in accordance with the following:

- S-basis values are in accordance with MMPDS-06, section 9.4.1. A-basis is a statistical value, where at least 99 percent of the population of values is expected to equal or exceed the minimum value with a confidence of 95 percent.
- k_{99} : one-sided tolerance limit factor for T_{99} (MMPDS-06).
- T_{99} : statistically based lower tolerance bound for a mechanical property such that at least 99 percent of the population is expected to exceed with 95 percent confidence (MMPDS-06).
- $k_{99} = 2.326 + \exp [1.34 - 0.522 \ln(n) + 3.87/n]$, or $k_{99} = 2.326 + \exp [1.34 - 0.522 \ln(127) + 3.87/127] = 2.64$, in accordance with MMPDS-06, table 9.10.1. (n = Number of individual measurements.)
- MMPDS-06 minimum values for annealed 6Al-4V are 896 MPa (130 ksi) tensile ultimate and 827 MPa (120 ksi) yield for thicker section bar and plate.
- Use “all” data values if grain direction in part is unknown.

The methodology and results of these calculations were reviewed by the Secretariat for the MMPDS Handbook, of Battelle, and were found to be acceptable. The person who performed the review is an expert in statistical treatment of materials property data. S-basis analysis of the residual material test results indicated that yield and ultimate strength of the nonconforming material fell short of specification minimum values by about 10 percent and 5 percent,

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respectively. These knockdown property values were used to assess whether there was still positive stress margin for affected JPL flight parts.

5.4 How to Recognize Suspect Nonconforming Material

Detailed knowledge of the certification requirements associated with the various specifications, coupled with a careful review of the certification data package (ideally, before material is received), is needed to assure that material has been properly processed and certified. A useful test of the integrity of the manufacturing process is to establish the chain of custody of the material through the various stages of processing, as discussed in section 6.2 in this Handbook. The absence of information in certificates about who hot worked the product to final dimensions and what lot number is associated with the hot-working operation seems to have increased in recent years.

The threat of nonconforming Ti alloys being used on one of many dozens of flight projects at JPL resulted in an exhaustive component-by-component assessment in the late 2000s. Based on the new pseudo S-basis mechanical properties established in testing (described in section 5.2.3 above) and detailed reviews of respective materials certifications, a disposition of use-as-is, retest, or remanufacture was made on over 1,000 parts already fabricated from Ti-6Al-4V. These were in-process parts for which the launch had not yet occurred. For a further description of this nonstandard and temporary effort used to screen Ti alloy parts for in-process projects, refer to Appendix C in this Handbook. This type of screening is not recommended as standard practice.

5.5 Example of Suspect and Nonsuspect Material Certifications

Appendix D in this Handbook contains specific examples of four irregular certification packages and a description of typical missing information that is either required by the specification or expected in accordance with industry standard practice, as well as information not in conformance with referenced specifications.

An example of a “clean,” i.e., acceptable, Certification Package is provided in Appendix E in this Handbook.

6. MITIGATING THE PROCUREMENT OF NONCONFORMING TI ALLOYS

6.1 General

Based on a thorough investigation of the quality of both certification documentation and the supply chain for aerospace-grade Ti alloy material, some mitigation actions have been identified to help avoid the chances of procuring and using nonconforming material. Some or all of these steps and even more conservative steps can be implemented to help prevent nonconforming material from finding its way into NASA’s and its contractors’ flight hardware. These measures can help secure high-quality Ti alloy raw material, as well as Ti alloy components supplied through subcontracted manufacturers and industry partners.

Based on information gathered throughout the referred investigation, the risk of procuring nonconforming material was judged to reside primarily with metal distributors. There has been no indication of improper Ti alloy processing on the part of mills or conversion houses. Independent testing laboratories have been known to be under pressure at times from customers on such issues as test sample location selection and discarding of samples that have failed to meet specification minimums. Since procurements from metal distributors have grown, the mitigation efforts noted in this section are directed toward assuring that, when material is procured from distributors, the buyer can be assured that it meets all requirements.

6.2 Thorough Review of Certification Data Package

An important aspect of determining whether final product forms may be nonconforming involves careful inspection of the associated certification data package. Most metal suppliers will provide an electronic or faxed copy of the applicable, lot-specific certification package(s) before the procurement is placed with them. This affords an opportunity to avoid rejecting any lot of material after it shows up at the place of use.

A useful test of the integrity of the manufacturing process is to establish the chain of custody of the material through the various stages of processing to determine whether each stage was performed by a firm having the necessary processing capability. For example, if a final product form of plate is produced from an intermediate product form of larger thickness, additional rolling of the intermediate form is required. If the supplier is known not to have rolling capability, which is the case for most Ti alloy distributors, and if there is no indication that the material was rolled by a conversion house or other facility, then one should be suspicious that the final product may be cut-down billet.

Detailed knowledge of the certification requirements associated with the various specifications, coupled with careful review of the certification data package, including verification of claimed chemical composition, is needed to help assure that material has been properly processed and certified.

6.3 Use of M&P Engineering and Quality Assurance Disciplines

Organizations such as Quality Assurance (QA), M&P Engineering, Technical Inventory, Mechanical Inspection, and Acquisition can all help mitigate the potential risk of procuring and using nonconforming Ti alloys. Because of the options and conditions necessary for Ti alloys to be compliant with a given specification, the use of appropriately trained/experienced M&P engineers and/or QA personnel is recommended for review and acceptance of Ti alloys for flight applications.

6.4 Securing the Supply Chain

The process enhancements and improvements described in the following subsections may help secure the Ti alloy supply chain.

6.4.1 Supply Chain Surveys and Audits

Supply chain surveys and audits are recommended to be performed by QA or equivalent and M&P engineers. An example survey/audit list is shown in Appendix F in this Handbook. Qualified suppliers can be placed on a Qualified Suppliers List (QSL)/Approved Suppliers List (ASL) at JPL. An organization can then establish an internal practice that aerospace-quality wrought Ti alloys to be used for flight application should be procured only from QSL/ASL suppliers. Frequency of re-audits may be dependent on performance factors. Note: The same guideline procedures described in this Handbook should be used for foreign Ti alloy sources and foreign contractors.

6.4.2 Quality Clauses Improvements

Ensure that quality clauses regarding material are sufficiently spelled out to assure that mill certifications, processing certifications, and testing certifications are received with material or procured metal parts.

An example quality clause entitled Raw Material Traceability, included as Appendix G in this Handbook, requires mill certifications, processing certifications, and independent material testing reports for any material that has been altered subsequent to mill processing. Mills should provide the original material test report to purchasing organizations. Original mill material purchasing organizations who, in turn, sell portions of any given mill lot of material are expected to provide a copy of the original mill material test report to subsequent purchasers.

6.4.3 Material Specifications

All procurements should require the material type and specifications to be listed on the contract, e.g., Ti-6Al-4V annealed bar in accordance with SAE AMS6931 and Ti-6Al-4V annealed plate in accordance with SAE AMS4911.

Each drawing should require that the material type and specification are identified, e.g., Ti-6Al-4V annealed bar in accordance with SAE AMS6931 for the Isolator of Feed Assembly drawing.

6.4.4 Certification Review

Because of the complexity of Ti processing, it is recommended that all Ti alloys should require review of certifications by M&P engineers and/or trained/experienced QA or equivalent personnel.

6.4.5 Independent Material Testing

One potential issue is how valid the independent mechanical test results provided in the certification package are. Variations have occurred between outside test laboratory report results for mechanical testing, as provided with supplied material certification packages, and internal post-material delivery testing.

For one of the four lots of materials tested at JPL as part of a nonconformance Ti alloy assessment, a detailed evaluation of mechanical test report values was conducted between values reported in the certificate package and values from internal tests at JPL. The 24 test coupons created 96 data points of mechanical test data for tensile ultimate, tensile yield, percent elongation, and percent reduction of area. Out of the total 96 data points, 93 in-house test values were less than any of the independent test laboratory reported values. The independent test lab provided two test values for each mechanical property, i.e. eight total test values. For a detailed comparison of the two sets of mechanical property values, see Appendix H in this Handbook.

One way to enhance the process of obtaining valid mechanical test data would be to periodically perform additional independent spot-check material testing to compare selected supplier's material test reports. The independent testing laboratory should be certified for specific testing, such as mechanical testing, chemical analysis, nondestructive evaluation (NDE), etc., by the National Aerospace and Defense Contractors Accreditation Program (Nadcap) or ISO in accordance with AS9100, Aerospace Standard: Quality Management Systems - Requirements for Aviation, Space and Defense Organizations. The Nadcap or ISO certification does not guarantee accurate results; therefore, it is recommended that, along with looking for this certification, the Center perform an audit of the testing house to ensure compliance with the test standards or specifications and follow up with test laboratories that have demonstrated test result deviations of concern.

Another potential issue is material test reports that contain typical or average test values rather than actual test values. When the material specification requires quantitative limits for chemical, mechanical, or physical properties, the test report should contain the actual test and/or inspection values obtained. Certificates for physical properties should show actual values.

The process enhancements identified above reduce the likelihood of procuring and using nonconforming material. The enhancements are in the vein of industry best practices and offer the greatest amount of protection for the least cost.

6.5 Component-Level Subcontractor

6.5.1 Purchase Order Subcontractors

In addition to the acquisition organization's role in utilizing the revised approach for the procurement of raw metal, it is recommended to use the same requirements when acquiring machined/fabricated items when the supplier is responsible for acquiring the raw material to be used. This requires an approach similar to that used for raw material, i.e., the ASL process, to assure conforming materials are acquired and used for these part or multiple part/assembly-level procurements. The same material requirements and specifications, mill/processing certifications, and test reporting and review are as needed for raw metal. This can be accomplished by incorporation of the already described quality clause entitled Raw Material Traceability.

6.5.2 Subcontractors

For the larger subcontracted efforts (system, subsystem, major component, instruments), a different approach may be needed, since these efforts may not be controlled through the procuring organization's QA and/or M&P Engineering organizations. One approach can be to establish standard Subcontract Data Requirements Lists (SDRLs)/Data Requirement Descriptions (DRDs), that an organization's contracting personnel can use. This would provide the QA/M&P Engineering organizations standards to be used for these subcontracts and may be tailored, with appropriate document-owner approval. Included in this set of DRDs is the Hardware End Item Data Package DRD in which the applicable material certification requirements are contained. In addition to using the recommended language contained in the standard SDRLs/DRDs, it is important that the institutional Mission Assurance organization support and verify that the appropriate requirements are included in these subcontracts. Examples of recommended language for such SDRLs/DRDs are:

- Reports shall be annotated to include the applicable Contract/Purchase Order identification and specific line item numbers.
- When a contractor supplies converted material produced by a raw material manufacturer, the contractor shall submit all pre- and post-conversion chemical/physical tests reports and any contractor arranged retests.

APPENDIX A

REFERENCE DOCUMENTS AND
MILITARY SPECIFICATIONS

A.1 Purpose and/or Scope

This Appendix provides guidance in the form of (1) a list of documents for further reference and (2) background information on the last revisions of MIL-T-9047 and MIL-T-9046, for historical reference with respect to the source of present day non-Government standards related to Ti alloys.

A.2 Reference Documents

A.2.1 Government Documents

DoD

MIL-H-81200B	Heat Treatment of Titanium and Titanium Alloys
MIL-T-9046	Titanium and Titanium Alloy, Sheet, Strip, and Plate
MIL-T-9047	Titanium and Titanium Alloy, Bars (Rolled or Forged) and Reforging Stock, Aircraft Quality

A.2.2 Non-Government Documents

SAE

SAE AMS2750	Pyrometry
SAE AMS4926	Titanium Alloy, Bars, Wire, and Rings 5Al – 2.5Sn Annealed, 110 ksi (758 MPa) Yield Strength
SAE AMS4944	Titanium Alloy Tubing, Seamless, Hydraulic 3.0Al – 2.5V Cold Worked, Stress Relieved
SAE AMS4945	Titanium Alloy Tubing, Seamless, Hydraulic 3.0Al – 2.5V, Controlled Contractile Strain Ratio Cold Worked, Stress Relieved
SAE AMS4957	Titanium Alloy, Round Bar and Wire 3Al – 8V – 6Cr – 4Mo – 4Zr Consumable Electrode Melted Solution Heat Treated and Cold Drawn

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SAE AMS4958	Titanium Alloy Bars and Rods 3Al – 8V – 6Cr – 4Mo – 4Zr Consumable Electrode Melted Solution Heat Treated and Centerless Ground
SAE AMS4965*	Titanium Alloy, Bars, Wire, Forgings, and Rings 6.0Al – 4.0V Solution Heat Treated and Aged
SAE AMS4967*	Titanium Alloy, Bars, Wire, Forgings, and Rings 6.0Al – 4.0V Annealed, Heat Treatable
SAE AMS4978	Titanium Alloy Bars, Wire, Forgings, and Rings 6Al – 6V – 2Sn Annealed
SAE AMS4979	Titanium Alloy Bars, Wire, Forgings, and Rings 6Al – 6V – 2Sn Solution and Precipitation Heat Treated
SAE AMS-T-9046	Titanium and Titanium Alloy, Sheet, Strip, and Plate
SAE AMS-T-9047	Titanium and Titanium Alloy, Bars (Rolled or Forged) and Reforging Stock, Aircraft Quality

*Ti-6Al-4V material specifications

A.3 MIL-T-9047 and Related SAE AMS Specification

MIL-T-9047G, issued December 15, 1978, was the last revision of this specification. Requirements for final product hydrogen content, maximum thickness, and cross-sectional area for certification testing of material, coupon sample location, macrostructure and microstructure confirmation, and ultrasonic inspection were specified. In addition, the heat number, lot number, and size (thickness by width by length) of the product were required to be provided by the distributor. This last revision had two following amendments:

- MIL-T-9047G, Amendment 2, identified the required multiple melting process and reduced the maximum cross-sectional area for certification tested material from 309.68 cm² (48 in²) to 103.23 cm² (16 in²). This amended specification became inactive for new design on April 4, 1998, and was only allowed for Ti and Ti alloy replacement purposes for hardware designed/built before April 14, 1998.
- MIL-T-9047, Notice 3, canceled this specification on February 10, 2005, and indicated that future acquisition of these items should refer to SAE AMS-T-9047. SAE AMS-T-9047 was a word-for-word translation of MIL-T-9047, containing only minor editorial and format changes.

A.4 MIL-T-9046 and Related SAE AMS Specification

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MIL-T-9046J, issued January 11, 1983, was the last revision of this specification. Requirements for final product hydrogen content, maximum thickness for certification testing of material, coupon sample location, macrostructure and microstructure confirmation, and ultrasonic inspection were specified. In addition, the heat number, lot number, and size (thickness by width by length) of the product were required to be provided by the distributor. The maximum cross-sectional area was not specified. This last revision had two amendments (Amendment 1 and Amendment 2), which specified the controls of multiple melting processes of Ti alloys.

MIL-T-9046J, Amendment 2, was canceled on September 17, 1999. Future acquisition of these items was referred to SAE AMS-T-9046.

APPENDIX B

CHRONOLOGICAL HISTORY FOR NONCONFORMING TI ALLOY
GIDEPs

B.1 Purpose and/or Scope

This appendix provides guidance in the form of a brief description and chronological history for nonconforming Ti GIDEPs.

B.2 Chronological History for Nonconforming Ti Alloy GIDEPs

B.2.1 March 9, 2004

GIDEP F4-P-04-01 was issued by Boeing making the following claims:

1. Primary company certified and sold Ti-6Al-4V and Ti-6Al-6V-2Sn forged bar as rolled plate/bar.
2. It cut Ti-6Al-4V to final thickness from thicker stock without prior authorization.

B.2.2 September 15, 2009

GIDEP AAN-U-09-401 was issued by the Defense Contract Management Agency (DCMA) with the following claim:

1. Primary company sold nonconforming, cut-down titanium billet as forged and rolled sheet, strip, bar, and plate.

B.2.3 October 5, 2009

GIDEP AAN-U-09-401A had been issued by DCMA but was superseded on October 5, 2009, by GIDEP AAN-U-10-005. The following are changes made to the original GIDEP:

1. All companies, with the exception of primary company, which had previously been identified as having sold nonconforming material, were removed from the GIDEP together with their corresponding GIDEPs.
2. The list of “known buyers” was removed due to the fact that it did not represent a complete list of primary company customers.

B.2.4 June 1, 2010

GIDEP AAN-U-10-005B was issued by DCMA as an amendment to GIDEP AAN-U-10-005. The following amendments were included:

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1. Titanium and titanium alloys supplied to DoD and NASA contracts must conform to all contract requirements, including specifications cited in such contracts. When rolled plate is specified, the titanium material must be rolled to the required thickness using industry standard practices. When bar is specified, the titanium material must be hot worked to the required dimensions. The required titanium material dimensions must not be accomplished by cutting down a thicker material. Forged material must not be substituted for rolled material requirements. Rolled material must not be substituted for forged material requirements.
2. Supplying or using titanium material that is cut down to achieve the specified thickness is unacceptable product substitution under a government contract when the controlling specification does not allow it.
3. The superseding indictment referenced in the October 5, 2009, issuance of AAN-U-10-005 was filed in the U.S. District Court, southern district of California, in criminal case no. 08-cr4229-JLS. A second superseding indictment dated February 23, 2010, was also filed in this case.

APPENDIX C

**SCREENING OF TI ALLOY PARTS
FOR IN-PROCESS PROJECTS AT JPL**

C.1 Purpose and/or Scope

This appendix provides guidance in the form of additional background information regarding an internal JPL assessment of nonconforming Ti alloy.

C.2 Screening of Ti Alloy Parts for In-Process Projects at JPL

A 33-column spreadsheet was generated and included such information as Ti alloy specification used, material distributor, heat number, mill source, mill product size, mill certification, lot number, name of conversion house, certification of conversion processing, billet or starting material size, final product size, final product condition, mechanical test report, nondestructive testing certification, heat-treatment certification, and more.

A process was developed for categorizing the hardware with respect to its material certification. Additionally, a method was developed to assess the risk of components with suspect or incomplete certification paper. Ultimately, each Ti alloy component was reviewed by an M&P Engineering specialist and assigned a category number, as described below:

Category 1. “Clean”/complete material certification, not from suspect source.

Category 2. Suspect source supplied material with material certification considered “incomplete.”

Category 3. Suspected source material referred to as “pass-through.”

Category 4. Suspect source and “Suspect Material.”

The Ti part identification triggered a review of material certifications if a suspect source was observed in the certification trail. Then, an emphasis was placed on obtaining a full certification package for review by M&P Engineering.

Suspect source material was considered “pass-through” when:

- Material was provided by a mill to a suspect source at a finished size and condition.
- Accompanying the material was a full Certificate of Test (COT) generated by the mill source.
- The suspect source supplied the finished material without altering the thickness or diameter.

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Suspect source material conditions that triggered a “suspect certification/suspect material rating” were:

- Suspect source generated Certificate of Analysis:
 - No mill certification, no heat information, etc.
 - Some level of hot working may have been performed; however, this was not always clear from the material certification.
 - No conclusive evidence that material was worked to final bar or plate dimensions.
- Material may have been cut to final size from billet exceeding specification maximum cross section.
- In some cases, cut material was highly probable.

Suspected source material was considered “suspect processing” when:

- The source ordered “as-cast” ingot from a mill source.
 - Mill-only certified ingot chemistry was provided with final product.
 - Lacks conclusive evidence of adequate hot working.
- Suspect source certifications may lack information/data about:
 - Test methods used to generate data.
 - What standards were used.
 - Test laboratories/certifications.
 - Mill certification/source.
 - Heat treatment/thermal processing information.
 - Properties indicate on certificate that they do not meet specification requirements.

Note: Cut material is not specifically prohibited by ASTM Ti alloy specification; however, the certificate should contain information to determine if material was bar or billet.

Other suspect processing sample certification issues/concerns included:

- Suspect source supplied test reports indicating all forged bar (SAE AMS-T-9047) specification requirements were satisfied; however, supplied material was cut from billet that exceeded allowable cross-sectional area of 309.68 cm² (48 in²).
 - No conclusive evidence of hot working.

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- No known methodology to assess the validity of mechanical test data from cross sections greater than 309.68 cm² (48 in²).

To help focus efforts on suspect forms of Ti alloy used in flight projects, several conditions were excluded from the Nonconforming Titanium Alloy Investigation. These conditions were:

- Ti alloy plate, sheet, or strip material less than or equal to 4.8 mm (0.188 in) thickness.

Justification: Producing Ti alloy plate, sheet, or strip material in thicknesses less than or equal to 4.8 mm (0.188 in) for multi-square feet of product via machining billet stock material is considered more challenging (potato chip effect) and costly and, therefore, highly unlikely to be used by suppliers, than typically used sheet production techniques, i.e., rolling operations, used in industry.

- Ti alloy wire/round bar material less than or equal to 7.9 mm (0.312 in) diameter.

Justification:

- Producing Ti alloy wire form in diameters less than or equal to 7.9 mm (0.312 in) in any reasonable lengths (multi-meters) via machining of Ti alloy billet stock material is considered more challenging and costly, hence, highly unlikely to have been used by suppliers, than typically used wire drawing operations used in industry.
- Typically used wire drawing operations require the original Ti alloy billet material to be thermo-mechanically processed, i.e., drawn through smaller and smaller dies, interspersed with annealing operations, to create required wire gage (diameter) product form.

- Ti alloy fasteners procured to JPL and National Aerospace Specifications (NAS)

Justification:

- Suppliers making Ti alloy fasteners are required to provide mechanical property testing reports at the fastener level. This practice provides a standard measure of quality on which JPL has relied for years.
- The costs and complexity of producing fasteners to meet NAS or JPL standard procurement specifications, e.g., NAS 4004, Fastener, 6AL-4V Titanium Alloy, Externally Threaded, 160 ksi Ft_u, 95 ksi Fs_u, 450 °F, for inch fasteners and NAS NA0007, Procurement Specification Metric Fasteners, Titanium Alloy, Externally Threaded, 1100 MPa Tensile, 660 MPa Shear, for metric fasteners, via machining Ti alloy billet material are considered too high to be credible. Fasteners are made with highly specific fastener head upset forge operations, and threads are roll

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forged. No difficulties have been observed with JPL's fastener procurement process.

- Non NAS/JPL specification-based procurements, i.e., specialty fasteners, were not excluded from consideration.

Also, some other Ti alloy forms were excluded from the JPL review:

- Casting parts.
- Extruded parts.
- Die (open or closed) forging producing final parts.

APPENDIX D

EXAMPLE SUSPECT MATERIAL CERTIFICATIONS

D.1 Purpose and/or Scope

This appendix provides guidance in the form of specific examples of nonconforming Ti alloy certifications for reference information only.

D.2 Example Suspect Material Certifications

D.2.1 Material Certification Package A

Company A delivered Ti-6Al-4V alloy 5.1 cm x 45.7 cm x 55.9 cm (2 in x 18 in x 22 in) certified to MIL-T-9046J. Deficiencies with respect to this specification included:

- a. A lot number was not listed in any certification document as required by MIL-T-9046J.
- b. Conversion processing certifications from ingot-to-billet and billet-to-final product were not included in the certification package in accordance with industry standard practice.
- c. No conversion houses were listed in the package.

D.2.2 Material Certification Package B

Company A delivered forged block Ti-6Al-4V alloy 15.2 cm x 17.8 cm x 22.9 cm (6 in x 7 in x 9 in) certified to SAE AMS4928R. Deficiencies related to SAE AMS4928R requirements included:

- a. Lot number and conversion processing certifications from ingot-to-billet and billet-to-final product were not provided.
- b. The independent mechanical test laboratory certified the material to MIL-T-9047G.
- c. The independent mechanical test laboratory certification contained within the material certification package did not provide a lot number as required by both SAE AMS4928R and MIL-T-9047G.
- d. The thickness and the cross-sectional area listed in the tensile test certification did not conform to the requirements of MIL-T-9047 referenced by the test laboratory.
- e. Time at temperature during heat treatment did not conform to the guidance by MIL-H-81200B, Heat Treatment of Titanium and Titanium Alloys, which was referenced by the heat-treating contractor.

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D.2.3 Material Certification Package C

A one-page certification package was provided. Company B certified the Ti-6Al-4V material to meet specification ASTM B348 Grade 5. The 1.9 cm x 15.2 cm x 21.6 cm (0.75 in x 6 in x 8.5 in) plate was cut from 15.5 cm (6.1 in) x random/width x random/length material. Deficiencies with respect to this certification package included:

- a. The provided cut information is not sufficient to determine the cross-sectional area of this material as required in accordance with the specification.
- b. The following information was not provided in the material certification package: ingot certification, heat number, conversion processing certifications from ingot-to-billet and billet-to-final product, thickness, cross-sectional area, and test coupon location pertaining to mechanical testing and final product hydrogen content certification.
- c. As reported on the certification provided, one of the two mechanical test coupons tested failed to meet the minimum percent reduction in cross-sectional area required by ASTM B348-10.
- d. Chemical analysis results and mechanical test results were summarized, but certification by independent test laboratories was not included in the package.

D.2.4 Material Certification Package D

Company B delivered two pieces of Ti-6Al-4V 30.5 cm dia x 19.1 cm length (12 in dia x 7.5 in length) along with copies of certifications from the mill that cast the ingot and from the independent test laboratories performing certification tests of the alloy. The independent test laboratories certified the material to meet requirements in accordance with MIL-T-9047G, SAE AMS4928R, and ASTM B348-10. Company B added the following statement on the cover page of the material certification package: "We hereby certify that these are correct copies of reports now on file at Company B." In accordance with reasonable industry standard practice, it was assumed that this statement by Company B, as distributor, certified the material to the specifications listed in the independent test laboratories and ingot material certifications.

As required by one or more of the above noted specifications, the material certification package provided did not include:

- a. Conversion processing certifications from ingot-to-billet and billet-to-final product.
- b. Lot number.
- c. A listing of thickness or cross-sectional area that conformed to the requirements in accordance with the specifications that were referenced by the mechanical test laboratories.
- d. Information on the tensile sample location as required by the specification that was referenced by the test laboratories.

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e. A time at temperature during heat treatment that conformed to the guidance in MIL-H-81200B or SAE AMS-H-81200C, Heat Treatment of Titanium and Titanium Alloys, specified in MIL-T-9047G.

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APPENDIX E

EXAMPLE OF AN ACCEPTABLE (“CLEAN”) CERTIFICATION PACKAGE

E.1 Purpose and/or Scope

This appendix provides guidance in the form of an example of a “clean,” i.e., acceptable, Certification Package. This example is one of the better Certification Packages, but even it does not include the reference to the tensile test specification used. The names and addresses of subcontractor, distributor, and mill and JPL purchase order numbers, job numbers, and part numbers have been intentionally removed.

E.2 Example of Acceptable Certification Package

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Home Page Data Entry Reporting Search Help Log Out

Purchase Request Worksheet

[Generate JET Delivery Request](#)

JEMS Order Number:
Log Number:
Order Status: **Processed**

PR Type: **PCARD**
Control: **FLIGHT**
Buy Type: **RAW**

Date Entered: **02/08/2011 11:11:22 AM**
Date In-Process: **02/08/2011 11:29:39 AM**
Date Processed: **02/08/2011 12:56:36 PM**
File Attachments: **None**

Item(s) Details

[Costing Received >>>](#)

Item	Qty.	Part Number, Rev.	Description (Oracle Item Number)	Item Charge	Price Each	Price Total
1	9		TITANIUM PLATE, 6AL-4V, .250" THICK x .75" x 12"		\$11.11	\$100.00
Order Total:						\$100.00

Order Details

Supplier:

Contact:
Phone:
Fax:

Work Order #:

Date Required: 02/10/2011

Requestor:

Office:
Cell:

Customer Name:

SI
9

Comments: VENDOR TO SUPPLY DOMESTIC MATERIAL WITH CERTS (DFARS IF APPLICABLE)

Quality Clauses: QC06b

*** NEED TO ADD PCARD HOLDER CUSTOM COMMENTS ***

Flight Hardware/Software? Yes

R&D with Flight Potential? No

Critical Ground Data System (GDS)? No

DSN Critical? No

JPL Critical Item? No

Delivery Information: WILLCALL

Delivery Type: NA

Package Description: NA

Dimensions: NA

Weight: 0

Ready for Pickup:

Delivery Comments:

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Packing Slip

Subcontractor

Date

2/15/2011

Bill To
JPL Accounts payable 4800 Oak Grove M/S 601-209 Pasadena, CA. 91109 Attn: Accounts Payable

Ship To
will call

P.O. Number	Terms	Rep	Ship Date	SHIP VIA	FOB	Job #
	Credit Card	KDJ	2/15/2011		will call	
Item	Description	Unit	Shipped	B/O		
1	6AL-4V Titanium .25" x .75" x 12" Mill: Heat# N61F credit card Call	ea	1			

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Certification of Conformance

Subcontractor

Date

2/15/2011

Customer

JPL Accounts payable
 4800 Oak Grove
 M/S 601-209
 Pasadena, CA. 91109
 Attn: Accounts Payable

P.O. Number

Job #

Item	Description	Unit	Shipped
1	6AL-4V Titanium .25" x .75" x 12" Mill: Heat# N61F credit card Call	ea	1

Material while in Subcontractor possession did not come into contact with Mercury or Mercury Bearing Compounds.
 Q.C. Inspected and approved in accordance with MIL-I-45208A, Am-2
 Q.C. Inspected and approved in accordance with ISO 9002
 We certify the material furnished for you on subject Purchase Order conforms to the above material description.

All claims for errors, Shortages and defective material must be made within 10 days from receipt of material. Our responsibility is limited to the replacing of the material if available from stock or refund of invoice amount, providing material has not been processed. Improper handling, machining or forming of these materials may be hazardous. Refer to material safety data sheets

Quality Control

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Traveler(s) Heat # Ingot# CERTIFICATE OF TEST
 15018 B N61F

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Mill A				Prof	Rev 1
Customer Name	Purchase Order	Size	Alloy		
P-card 1264702377 1/4 x 3/4 x 12" 1 EA		0.250"	6Al-4V TITANIUM PLATE		
	PCS	Weight			
	8	2730 lbs.			

Completion Date: 07/23/2010 Quality Auditor:

SPECIFICATIONS

AMS 4911	L	AMS-T-9046	B	CODE AB-1	COND. A
ASTM B265	2010	ASTM F1472	2008*1		
DMS 1592	G	F-14	11/15/05		
F-17	07/31/07	F-22	10/31/04		
F-23	09/30/06	MIL-T-9046	J AM2	CODE AB-1	COND. A
S-1000	03/02/2010	S-400	10/10/2008		

PLATE IDENTITY: A4A1, A4A2, A4B1, A4B2, A4C1, A4C2, A4D1, A4D2

	C	C Tested At	CHEMISTRY							CR EQ = Chromium Equiv			Cb = Nb	XRF Tested At
			Si	Mn	Mo	Ti	Al	Ti+Al	V	Fe	Cu			
TOP	.027	Mill A	.02	<.01	.02	BAL	6.48	-	4.05	.18	.01		Mill A	
BOT	.026	Mill A	.02	<.01	.02	BAL	6.52	-	3.92	.14	<.01		Mill A	

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Traveler(s)	Heat #	Ingot#	Mill A												Page 2 of 5	
15018	B	N61F	B	B Tested At	Zr	Y	Y Tested At	O	N	O/N Tested At	Sn	Sn Tested At	Cr	Cb	Ta	Ni
TOP	<.01	Mill A	.01	<.0005 ATI WAH CHANG	.1630	.0075	ATI WAH CHANG	<.01	Mill A	-	-	-	-	-	-	-
BOT	<.01	Mill A	.01	<.0005 ATI WAH CHANG	.1820	.0091	ATI WAH CHANG	<.01	Mill A	-	-	-	-	-	-	-

H

PLT A4A1 .0100
 PLT A4D2 .0093

CHEMISTRY METHOD	ELEMENTS TESTED BY METHOD
ALBANY-AL	AL
ALBANY-V	V
ALBANY-FE	FE
ALBANY-O	O
ALBANY-N	N
ALBANY-C	C
ALBANY-SI	SI
ALBANY-B	B
ALBANY-Y	Y
ALBANY-MO	MO
ALBANY-MN	MN
ALBANY-CU	CU
ALBANY-SN	SN
ALBANY-ZR	ZR
GAS-H	H

CHEMISTRY REMARKS

Chemistry tested at Mill A unless otherwise noted.

Note: Metallics are analyzed by ICP, gases are analyzed by inert gas fusion or combustion.

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Traveler(s) Heat # Ingot#
 15018 B N61P

Mill A

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CHEMISTRY REMARKS

BETA TRANSUS CALCULATED BY CHEMISTRY:
 TOP = 1831F
 BOTTOM = 1847F

Operation	Ingot	Heat Treat Code	Test Dir	Temp F	As Shipped			Tensile Test			Gage Length		Tensile Diameter	Tested At
					UTS ksi	.2% Yield ksi	.02% Yield ksi	%EL 4D	5D	%RA	4D	5D		
SUPER		VCF4	LC	ROOM	151.0	138.7		18.0		40.0	1.0			Test Lab A
SUPER		VCF4	LTC	ROOM	158.3	149.7		19.0		44.0	1.0			Test Lab A
SUPER		VCF4	LC	ROOM	147.1	139.1		19.0		41.0	1.0			Test Lab A
SUPER		VCF4	LTC	ROOM	153.5	144.3		20.0		42.0	1.0			Test Lab A

Test Dir: L = Longitudinal, T = Transverse, ST = Short Transverse, LT = Long Transverse,
 TC = Transverse Center At Size, TM = Transverse Mid-Radius At Size,
 PC = Pancake, DB = Drawbar, PD = Paddle, TT = Top Transverse At Size,
 BT = Bottom Transverse At Size, LC = Long Center, TX = Top Transverse Mid-Radius At Size,
 LM = Longitudinal Mid Radius, LS = Longitudinal Surface, TS = Transverse Surface
 Operation: SUPER = Crosshead Sep Rate of .10 inches/minute

TENSILE/STRESS RUPTURE HEAT TREATMENT

Location	HT Code: VCF4			Furnace Cool Rate Per Hrs (F)	Cool Code
	Temp F	Hours	Mins		
PLANT	1425	8		FC	VCF4 NRS. MIN.

METALLOGRAPHY

Microstructure evaluated in accordance with the referenced specifications and found acceptable.
 Material evaluated and determined to be free of alpha case.

SONIC

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Mill A

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MATERIAL ULTRASONICALLY INSPECTED BY TEST LAB B AT INTERMEDIATE SLAB AND FOUND TO BE
ACCEPTABLE TO THE REQUIREMENTS OF THE FOLLOWING SPECIFICATIONS:
AMS 2631 Rev C CLASS A1 (IMMERSION METHOD)

MACRO

Material macro evaluated in accordance with AMS 2380E and found to meet or exceed Level 10.

CONDITION SHIPPED

HEAT TREATMENT: VCF ANNEALED AT 1425F (+/- 25F) FOR 6 HOURS MINIMUM

SURFACE CONDITION: DESCALED

Hot Rolling performed at Conversion House A

Heat Treatment and Final Inspection performed at Test Lab B

REMARKS

Material has been produced, sampled, inspected, and tested in accordance with the customer purchase order and referenced specifications and conforms to the requirements unless otherwise noted in this certificate of test.

Any deviations to specification or customer purchase order requirements relative to testing, test values, hot working fixed practices, have been resolved in writing with customer prior to shipment.

The recording of false, fictitious, or fraudulent statements or entries on this document may violate Federal statutes, including but not limited to Title 18, Chapter 47 of the United States Code, and may be punishable as a felony.

If customer purchase order does not specifically reference a revision to a specification, Mill A will work to the latest revision on file and in effect at time of order placement.

Test methods are per the latest ASTM Standards, currently recognized industry practices, or as agreed upon between Mill A and customer.

Any chemical elements analyzed and found to have values below the actual limits of detection may be reported as < less than or reported at the detection level.

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Traveler(s) Heat# Ingot#
15018 B N61P

Mill A

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When values are reported to the significant places called for in the specifications, rounding will be done in accordance with ASTM E-29.

This is to certify that during manufacturing, handling, testing and inspection, this material did not come in direct contact with mercury or any device employing a single boundary of containment.

This Certificate of Test shall not be reproduced except in full, without the written approval of Mill A Quality.

No weld repair has been performed on this material.

Material Safety Data Sheets (MSDS) - View or print from our site: www.allvac.com. Printed copies available on request from the Mill A Sales Department.

Mill A products have not come in contact with radioactive, fertile or fissionable materials during manufacturing or processing.

Melt source in compliance with DFAR 252.225-7014, Alternate 1.

SPECIAL REMARKS

Material has been controlled to P & W requirements for LCS per P & W MCL Manual Section F-17.

Material melted and manufactured in the United States of America.

INGOT SOURCE: Mill A

Mill A Laboratories approved to S400 (Certified Materials Test Laboratory - Metallic Materials).

This material has been produced and qualified in accordance with the manufacturing and approval requirements of DMS 1592 and DMS 2442.

TEST METHODS: C = ASTM E1941 (2004); O/N = ASTM E1409 (2008); H = ASTM E1447 (2009); Plasma Emission = ASTM E2371 (2004), ASTM E1097 (2007 Wah Chang only); XRF = ASTM E539 (2007); RTT = ASTM E8 (2008); ETT = ASTM E21 (2009); Creep = ASTM E139 (2006); Fracture Toughness = ASTM E399 (2008); Rockwell Hardness = ASTM E18 (2008B); Brinell Hardness = ASTM E10 (2008); Grain Size = ASTM E112 (1996/2004*2)

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APPENDIX F

RAW MATERIAL SUPPLIER AUDIT CHECKLIST

F.1 Purpose and/or Scope

This appendix provides table 6, An Example Raw Material Supplier Audit Checklist, as guidance information.

F.2 Raw Material Supplier Audit Checklist

Table 6—An Example Raw Material Supplier Audit Checklist

	Question	Guidance	Accept/Concern	Audit Notes
1	General Information			
1.1	What types of raw materials does the company sell?	Review listing of all material being manufactured by the supplier. Verify if it includes Ti alloy.		
1.2	What sizes of bar and plate does the company sell?	Verify the size of bar and plate material being sold by the supplier. Review several purchase orders, and check if the shipping records match customer orders.		
1.3	Does the company sell material in billet or ingot form?	Seek evidence regarding the form in which material is being sold. Is it sold as ingot or billet?		
1.4	What lot sizes are produced?	Review several manufacturing travellers to verify how lot sizes are produced.		
1.5	How does the company classify bar versus plate?	Verify how the supplier classifies bar versus plate and how the distinction is being made during the manufacturing process. Note: Bar is always rolled or forged, and plate is always rolled.		
1.6	Are any bars supplied in sizes greater than allowed by SAE AMS-T-9047? Are any plates greater than 10.2 cm (4 in) thick?	Review specifications being utilized and several dimensional test records to ensure plates are not greater than 10.2 cm (4 in) thick.		
1.7	Has the company ever sold cut intermediate product as bar or plate?	Assess several travellers and shipping documents. Verify if the supplier has ever sold cut intermediate product as bar or plate. Note : Answer should be no.		
1.8	Has the company ever substituted bar for plate?	Interview quality management and ask if there has been any substitution of bar for plate. Note: Answer should be no. If the answer is yes, it should be something the company did in the past.		

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	Question	Guidance	Accept/Concern	Audit Notes
2	Procurement			
2.1	How does the company qualify its suppliers?	Request and verify criteria for qualifying suppliers. Review list of suppliers being procured from and cross check to verify they exist in the ASL.		
2.2	How does the company measure performance of suppliers and address issues?	Review supplier rating criteria. Is rating based on quality (acceptable parts received, on time deliver...?) Select sample of lowest rating suppliers, and verify how issues are being addressed. What constitutes a withheld status?		
2.3	How does the company flow requirements (material, processing and testing) to suppliers, and who is qualified to do this?	Review several purchase orders to verify type of requirements flowed down to suppliers. Interview the person performing this function to assess whether he/she is qualified.		
2.4	How is it determined what conversion methods should take place, and who is qualified to determine this?	Verify whether customer conversion requirements have been met. Review customer communication documentation for several customers. Note: Conversion requirements should be consistent with end product requirements.		
2.5	What documentation and certifications are required from suppliers of material and/or processes?	Review several sub-tier supplier folders, and verify that documentation received with product, e.g., Certificate of Conformance (C of C), test records certification, material condition, etc., is in accordance with specification.		
2.6	Does the company buy from third parties rather than going direct to a mill? If yes, how does the company maintain traceability?	Seek evidence of whether supplier maintains complete traceability records specifying material condition and properties.		
2.7	Does the company buy from Western Titanium?	Select sample of receiving inspection records to assess whether material has been purchased from Western Titanium, Inc. Verify how the company assures that JPL does not receive that material.		
3	Receipt Verification			
3.1	How does the company assure that the material procured meets specification requirements?	Interview receiving and in-process inspection personnel, and verify records of testing performed on material received. Also, verify if testing is performed according to specification.		
3.2	How does the company measure and maintain dimensional tolerance in its products? How is dimensional tolerance measured?	Review inspection records generated throughout the manufacturing process to verify that dimensional tolerance is measured and kept within limits. Note: Verify that equipment is calibrated and that personnel are trained.		
3.3	How are personnel who perform material verification trained?	Interview personnel performing dimensional verification. Verify that training records show evidence that personnel have received adequate training. Note: Personnel should have formal or, at minimum, on-the-job training (OJT) for understanding material processing, testing, and verification to specification.		

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	Question	Guidance	Accept/Concern	Audit Notes
3.4	How is acceptance documented?	Request to see material inspection areas (receiving inspection, in-process inspection, etc.), and verify that material acceptance records include stamp or signature with date.		
3.5	What is the company's process for dispositioning nonconforming material?	Seek evidence on action taken on rejected material. Is it documented as nonconforming, tagged, and segregated to ensure that it is not mixed with conforming material?		
3.6	How much billet material is rejected by QA? How much bar/plate?	Select sample of inspection records to verify the amount of billet, bar/plate material rejected by QA.		
3.7	How is nonconforming material and/or scrap segregated?	Request to see area where nonconforming material is kept. Assess whether it is suitable to ensure bad material is not mixed with conforming material. Is scrapped material permanently marked to identify that it is scrapped?		
4 Testing				
4.1	If the company sends material out for testing, is the testing house a Nadcap- or ISO-approved laboratory? If not, how are the laboratories approved?	Identify several testing houses listed in the ASL, and verify whether those are Nadcap or ISO certified. If they are not, ask how they are approved.		
4.2	How are test samples taken to be sent out for testing?	Verify that test samples are taken in accordance with specification and/or procedure. Note: Does the sample need to be taken across the entire piece of material?		
4.3	What is the test sampling plan for large lots of material?	Review test procedures and/or test documentation to verify sampling plan used for large lots. Do the sampling plan and acceptance level meet specification requirements?		
5 Marking of Billet/Finished Products				
5.1	Where are final products marked?	Verify process for marking of billet/finished products and location of marking on the part.		
5.2	How are billets distinguished from bar/plate?	Seek evidence on how billets are distinguished from bar/plate. Verify how they are labeled to avoid mixing with other material.		
5.3	What information is included in the marking? (specification, producers name, lot/heat number, composition, heat treat, finish)	Review procedure and marking information. Select several products to verify marking information is done in accordance with procedure or specification.		
5.4	Are the markings permanent in nature?	Select several products, and verify marking is painted or stamped on per procedure.		
6 Stocking				
6.1	How is traceability maintained from purchase through stocking to sale?	Select several part numbers of completed products, and verify that numbers are traceable to incoming inspection records and throughout manufacturing.		
6.2	How is the material protected from degradation, contamination, and corrosion?	Review supplier's Storage, Handling, and Preservation procedure, and verify controls are being followed to protect material.		

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	Question	Guidance	Accept/Concern	Audit Notes
7	Cutting			
7.1	What equipment is used to cut material?	Request to see the cutting procedure, and seek evidence on the type of equipment used to cut material. Cutting may cause a heat-affected zone when using a saw. Check if the materials are cooled during the cutting process.		
7.2	When in the process do you cut billet, bar, or plate?	Seek evidence on point during material processing at which material is cut, including type: billet, bar, or plate? Is this done in accordance with specification and procedure?		
7.3	How is finished product segregated from intermediate product during cutting?	Select several travellers or manufacturing documentation to verify how finished product is segregated from other product?		
7.4	Is bar or plate ever cut on the thickness? Width?	Review cutting procedure, and verify how bar or plate is cut, whether through thickness or width? Note: Answer should be no.		
7.5	Is billet ever cut on the thickness? Width?	Assess manufacturing practices, and check if billet is ever cut on the thickness or width. Note: Answer should be no.		
7.6	How does the company maintain traceability for your stock? Does the company track traceability by weight?	Review the material control procedure and/or stock procedure. Seek evidence on how traceability is achieved.		
7.7	How is cutting annotated on the manufacturing paperwork?	Verify on several travellers how cutting is annotated. Are there specific instructions related to material cutting?		
7.8	How is cutting annotated on the certification?	Select several certifications, and verify how cutting is annotated.		
7.9	Are the products remarked after cutting to maintain traceability?	Review several travellers to verify if remarking of material after cutting is performed. Is it being done in accordance with procedure? Permanent marking methods such as stamping or scribing are recommended over paint or adhesive labels.		
8	Certification Packages for Delivery			
8.1	How does the company provide certifications and test reports with complete traceability from mill through finished product delivery?	Verify several final delivery packages. Is all relevant paper work included to ensure entire traceability of material?		
8.2	Can auditor trace work documents back to specific lots of material?	Take a sample of finished products, and verify whether documentation allows traceability to lots of material. Note: Answer must be yes.		
8.3	Is final hot-worked size shown on all certification packages?	Select several certification packages, and assess whether final hot-worked size is included.		
8.4	Is heat-treatment condition shown?	On final delivery packages, verify that heat-treatment condition is included. Is this step also in the procedure?		

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	Question	Guidance	Accept/Concern	Audit Notes
8.5	Are heat/lot numbers shown on all certifications?	While reviewing certification packages, verify that heat and lot numbers are included.		
8.6	Is size ordered shown on the certification package, and does it match size of hot-worked product? Is thickness the same?	Verify in certification packages that size ordered and hot-worked product size match. Also, verify the thickness. Sometimes the pieces are identified by their weights instead of lengths. The dimensions can be verified from the weight.		
8.7	Are appropriate specifications and revisions to which the material has been tested/inspected shown on certification package?	Ensure certification packages selected also reference appropriate test/inspection specifications.		
8.8	Do bar or plate certification packages include specification number, composition, heat-treat condition, finish, melting practice, tensile properties, ultrasonic testing (UT) results, microstructures, reforging stock identification, and sampling for quality conformance, identification of UT'd products and packing level?	From reviewing certification packages, verify that all of the information listed to the left is included. Are these characteristics also called out in the certification package procedure?		
8.9	Is melt source identified?	Check to make sure the melt source is identified in the certification packages.		
8.10	Are all conversion certifications and/or C of Cs included in the package?	While reviewing certification packages, verify that conversion certifications and/or C of C is included.		
8.11	Are all non-destructive testing certifications and/or C of Cs included in the package?	Verify that nondestructive testing certifications and/or C of Cs are included.		
8.12	Would the company have any problem meeting JPL's quality clause entitled "Raw Material Traceability" (QC06B)?	Show supplier copy of QC-06B. Make sure supplier can meet the requirements.		
9	Rolling/Forging (if company does rolling/forging itself)			
9.1	What are the typical rolling/forging temperatures?	Ask if supplier performs rolling/forging. Verify at what temperatures this process is being performed. Determine if the working temperatures are stated on the traveller or as a part of a standard procedure.		
9.2	How many reheats are allowed?	Review rolling/forging procedure or specification used to verify how many reheats are allowed and whether the company complies with this number.		
9.3	How much reduction is typically completed in final finishing? What is the minimum required reduction?	Verify the amount of reduction at final finish and what would be the minimum. Traveller should show this information.		

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	Question	Guidance	Accept/Concern	Audit Notes
9.4	How are rolling and forging controlled?	Review the company's processes to assess how rolling and forging are controlled. Are they being done in accordance with the specification and/or procedure?		
9.5	How is work piece temperature monitored?	During process verification, check how temperature is monitored on a sample of work pieces.		
9.6	Are conversion furnaces compliant with SAE AMS2750, Pyrometry?	Review procedure to verify above procedure is invoked and if it is being followed and complied with in regard to conversion of furnaces.		
9.7	What kinds of furnaces are used?	Document the type of furnaces being used. Verify furnaces' capabilities to ensure they meet requirements delineated in the specification.		
9.8	What is the distance of the furnace to the press/mill?	Verify the distance from the furnace to the press/mill. Does it meet what is called out on the specification and procedure? Is there a minimum temperature that must be kept?		
9.9	Are dies/rolls heated?	Request temperature information on dies/rollers. Is heating being done? If dies/rollers are not heated, is insulating material used to prevent direct surface contact between the dies/rolls and the material?		
9.10	Is cold finishing allowed?	Review specification and/or procedure to check if cold finishing is allowed. If so, does it comply with the specification?		
9.11	Which certifications go with rolling/forging?	Rolling/forging certifications should be identified in the procedure. Is procedure in compliance with specification?		
9.12	How does the company determine where to place material in furnace?	Verify that specification and procedure identify location within the oven where material must be placed. Witness the process being done, and verify travellers indicate the location as well and are complied with.		
10 Heat Treat (only if heat treat is done in house)				
10.1	When heat treat is performed, does the company mix JPL material with other customers' materials?	Identify whether heat treat is done in house. If so, review the procedure. Verify how material is being handled: by customer, part number, lot number, etc.		
10.2	What heat-treat specification(s) does the company use?	Request a copy of the heat-treat specification being used. Was it flowed down as a requirement?		
10.3	How does the company calculate soak time?	Verify that specification or procedure identifies how soak time is calculated and whether it is calculated in accordance with specification. Note: This operation only applies to Ti.		
10.4	How do you control the temperature, i.e., thermocouples?	Verify if temperature is controlled in accordance with specification or customer-specific requirements. Make note of the number of thermocouples that are used during heat treat.		
10.5	Does the company specify thermocouple placement for suppliers or allow them to do it?	If heat treat is outsourced, is thermocouple placement requirement flowed down to suppliers? Select sample of suppliers, and review several purchase orders for this requirement.		

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	Question	Guidance	Accept/Concern	Audit Notes
10.6	How does the company assure that its oven is suitable for the specification?	Identify the oven type and its capability. Can it meet heating specification requirements?		
10.7	Does the company make a practice of overloading the furnace?	Review heat-treat specification. Does it have a requirement for maximum number of parts that can be placed in the oven at one time? Is this complied with?		
10.8	Does the company provide furnace maps?	Verify several documents on parts that have gone through heat treat. Is there a map included, indicating where parts were placed within the oven during heat treating?		
10.9	Is your heat-treat facility Nadcap approved?	If heat-treat process is Nadcap approved, request to see the certification.		
10.10	Who does the flattening of warped material? Is it done hot or cold?	Identify within the specification and/or procedure whether flattening is performed and at what temperature.		
10.11	For solution treating, how does the company quench the material?	Witness the quenching process. Is it being performed in accordance with specification/procedure and at specified temperatures? Make note of the proximity of the furnace to the quench tank. Some specifications may have a requirement on the maximum time the part can be out of the furnace before it is quenched.		
10.12	How does the company maintain the temperature during quench?	Verify if temperature is maintained during quenching in accordance with specification. Is the quenching medium recalculated? Are there instruments used to monitor quench temperature?		
10.13	Does the company base the heat-treat temperature on the beta transus?	Seek evidence whether heat-treat temperature is based on the beta transus. Note: This operation only applies to Ti alloys.		

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APPENDIX G

**EXAMPLE QUALITY CLAUSE ENTITLED
“RAW MATERIAL TRACEABILITY”**

G.1 PURPOSE AND/OR SCOPE

This appendix provides guidance in the form of an example quality clause statement pertaining to raw material traceability.

G.2 Example Quality Clause Entitled Raw Material Traceability

The following wording is suggested when developing a standard quality clause for raw material traceability:

“All certifications and test reports required below shall be traceable through some method of identification, i.e., heat, lot, part, and serial numbers; purchase order; invoice number; etc., from mill through finished product delivery.

“Manufacturer Test Certifications

“The contractor shall include with each shipment the raw material manufacturer's test report, i.e., mill test report, that states that the lot of material furnished has been tested, inspected, and found to be in compliance with the applicable material specifications. The test specimen shall come from the same thickness/diameter that is being supplied. The test report shall contain the following information:

- Test specimen gage diameter in accordance with ASTM E8.
- Specifications, including revision numbers or letters, to which the material has been tested and/or inspected.
- Heat and lot number(s).
- When the material specification requires quantitative limits for chemical, mechanical, or physical properties, the test report shall contain the actual individual test and/or inspection values obtained, not summarized values.”

“Processing Certifications

- Certifications shall be provided to demonstrate that all required processing, i.e., forming, heat treating, thermal cycling, conversion, etc., has occurred and that the results meet all specification and testing requirements.
- No unauthorized processes, i.e., re-melt, shall be allowed.”

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“Nondestructive Evaluation, also known as Nondestructive Testing, Certifications

- When non-destructive evaluation is required, the contractor shall provide a Certificate of Conformance to certify that the material meets the related requirements.”

“Independent Laboratory Testing

- If the material was altered (forged, rolled, heat treated, etc.) subsequent to procurement from the mill and before delivery to the place of use, an independent laboratory test shall be submitted with the material. The testing shall be performed after all subsequent conversion processing. The test report shall comply with requirements above for manufacturer test certifications. The independent testing laboratory shall be Nadcap or ISO certified.

Note: To periodically assess the credibility of independent testing laboratories and the organizations on the ASL, random procurement organization facilitated mechanical testing is recommended. The frequency of such testing can be reduced as confidence is gained in test results provided by the metal supplier and its independent testing company.”

“Prohibited

- The contractor shall not provide material that has been machined down, sawed, or reduced by any other means to achieve the requested thickness or diameter.
- The contractor shall not substitute cut plate for bar stock.
- Questionable practices by changing letterhead and altering original documents by suppliers, such as copying of material test Reports with the company’s letterhead pasted over the existing letterhead, shall be prohibited.”

APPENDIX H

**MECHANICAL TEST RESULTS IN MATERIAL CERTIFICATION
VERSUS IN-HOUSE TEST DATA FOR TI-6AL-4V**

H.1 Purpose and/or Scope

This appendix provides, for guidance only, detailed mechanical test data for one lot of material (Lot C in table 4), based on independent test laboratory results in material certification versus additional JPL in-house test data. For more information, see section 6.4.5 in this Handbook.

H.2 Mechanical Test Results in Materials Certification versus Additional In-House Test Data

Figure 3, Tensile Yield Strength Results Comparing Independent Test Laboratory Values of 876 MPa (127 ksi) and 889 MPa (129 ksi) (illustrated by two upper blue lines) with JPL Internal Test Results Shown by Bars on Graph; figure 4, Ultimate Tensile Strength Results Comparing Independent Test Laboratory Values of 945 MPa (137 ksi) and 952 MPa (138 ksi) (illustrated by two upper blue lines) with JPL Internal Test Results Shown by Bars on Graph; figure 5, Elongation Results Comparing Independent Test Laboratory Values of 14 percent and 13 percent (illustrated by two upper blue lines) with JPL Internal Test Results Shown by Bars on Graph; and figure 6, Reduction of Area Results Comparing Independent Test Laboratory Values of 31 percent and 19 percent (illustrated by upper and lower blue lines) with JPL Internal Test Results Shown by Bars on Graph, provide these mechanical test result comparisons.

The JPL internal tensile test results summary of suspected nonconforming Ti-6Al-4V is shown in table 4, Lot C, section 5.3.3 in this Handbook.

0.2 Yield Strength Results

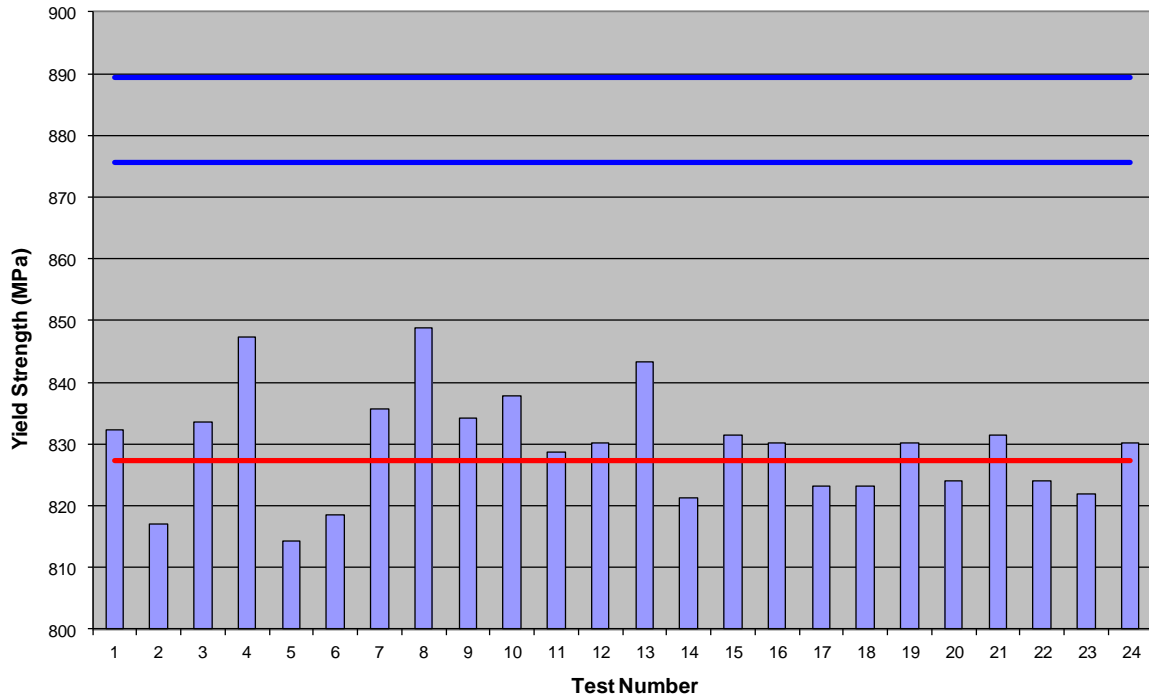


Figure 3—Tensile Yield Strength Results Comparing Independent Test Laboratory Values of 876 MPa (127 ksi) and 889 MPa (129 ksi) (illustrated by two upper blue lines) with JPL Internal Test Results Shown by Bars on Graph (minimum specification test value = 827 MPa (120 ksi) shown by lower red line)

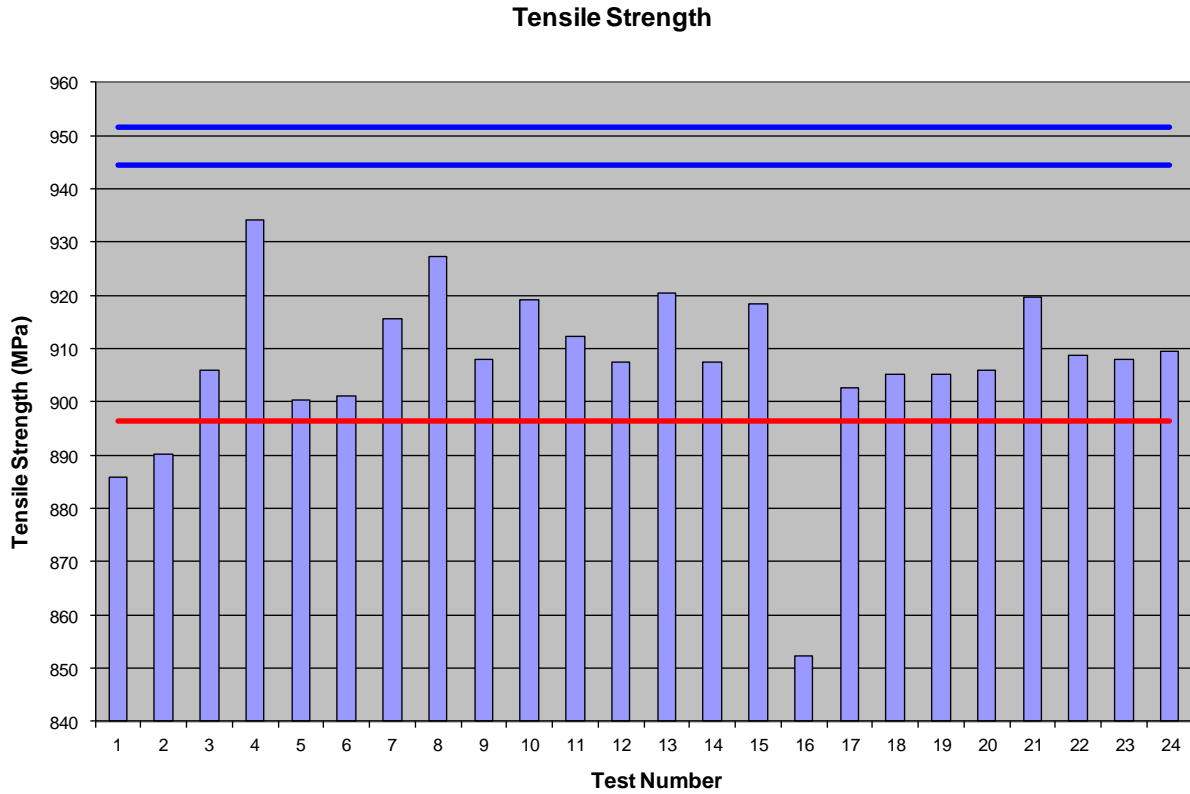


Figure 4—Ultimate Tensile Strength Results Comparing Independent Test Laboratory Values of 945 MPa (137 ksi) and 952 MPa (138 ksi) (illustrated by two upper blue lines) with JPL Internal Test Results Shown by Bars on Graph (minimum specification test value = 896 MPa (130 ksi) shown by lower red line)

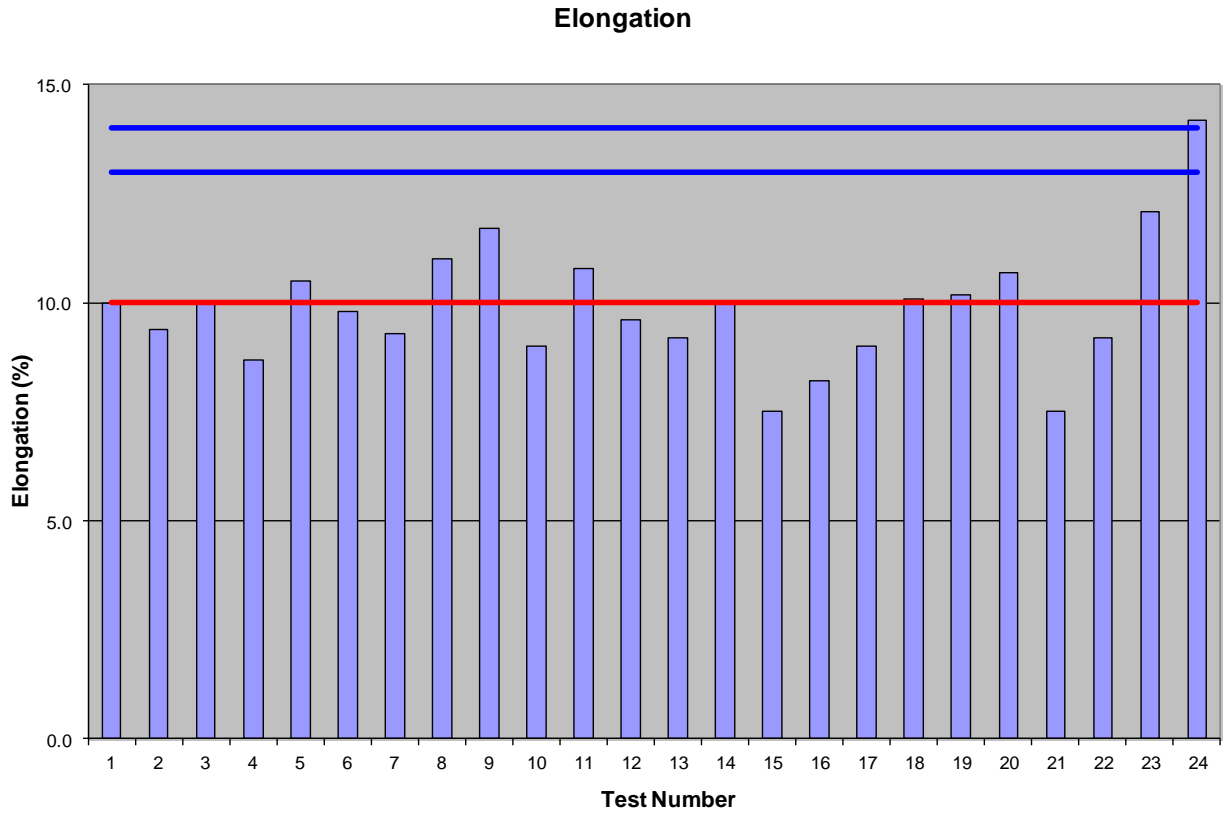


Figure 5—Elongation Results Comparing Independent Test Laboratory Values of 14 percent and 13 percent (illustrated by two upper blue lines) with JPL Internal Test Results Shown by Bars on Graph (minimum specification test value = 10 percent shown by lower red line)

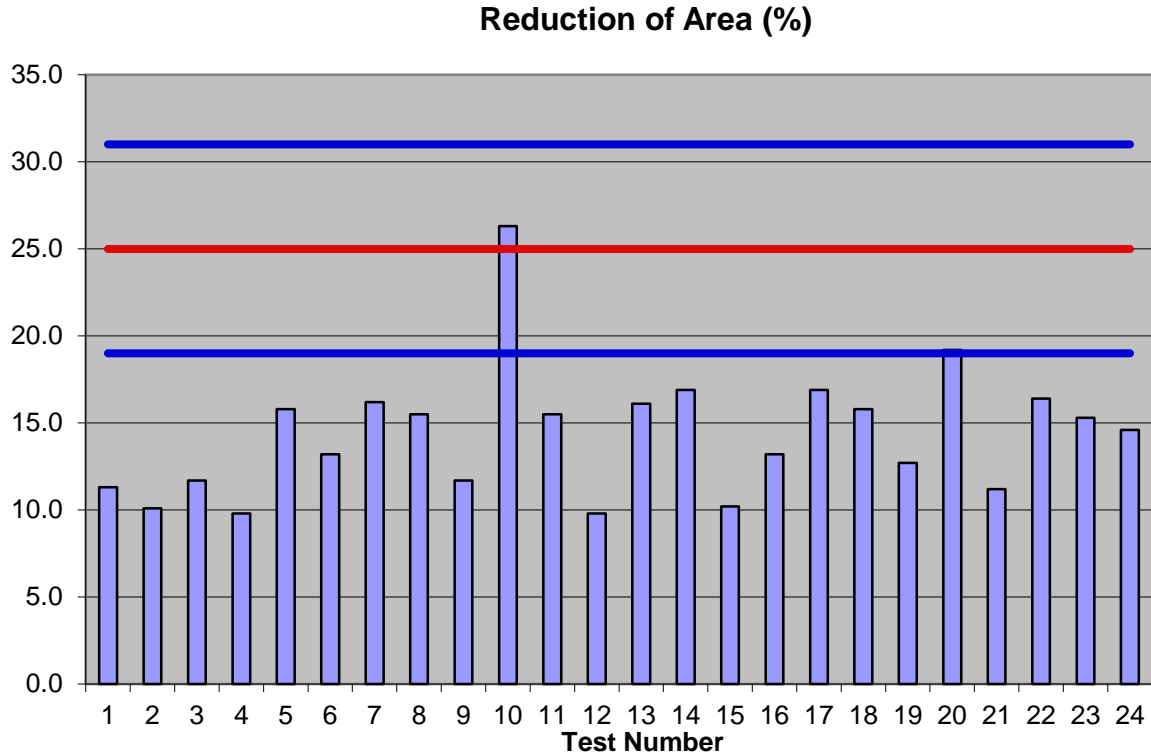


Figure 6—Reduction of Area Results Comparing Independent Test Laboratory Values of 31 percent and 19 percent (illustrated by upper and lower blue lines) with JPL Internal Test Results Shown by Bars on Graph
 (minimum specification test value = 25 percent shown by middle red line)