INCH-POUND
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DETAIL SPECIFICATION

ROD, BAR, AND BILLET, TITANIUM ALLOY TI-5111 FOR USE IN CRITICAL SEAWATER APPLICATIONS

This specification is approved for use by all Departments and Agencies of the Department of Defense.

1. SCOPE

1.1 Scope. This specification covers hot worked and beta annealed plus alpha-beta annealed titanium alloy Ti-5111 (UNS R55111) rod (see 6.5.3) and bar (see 6.5.1) for use in critical seawater applications. This specification also covers hot worked and beta annealed plus alpha-beta annealed Ti-5111 (UNS R55111) billet (see 6.5.2) in sizes up to and including 8.375 inches thick for use in critical seawater applications.

1.2 Classification. Rod, bar, and billet are of the following forms and finishes, as specified (see 6.2).

1.2.1 Forms. Titanium alloy comes in the following forms:

a. Rod
b. Bar, round
c. Bar, hexagonal
d. Bar, octagonal
e. Bar, square
f. Bar, rectangular
g. Billet

1.2.2 Finishes. Titanium alloy comes in the following finishes:

a. Finish I – Ground or machined and pickled
b. Finish II – Centerless ground

Comments, suggestions, or questions on this document should be addressed to: Commander, Naval Sea Systems Command, ATTN: SEA 05S, 1333 Isaac Hull Avenue, SE, Stop 5160, Washington Navy Yard DC 20376-5160 or emailed to CommandStandards@navy mil, with the subject line "Document Comment". Since contact information can change, you may want to verify the currency of this address information using the ASSIST Online database at https://assist.dla.mil.

2. APPLICABLE DOCUMENTS

2.1 General. The documents listed in this section are specified in sections 3 and 4 of this specification. This section does not include documents cited in other sections of this specification or recommended for additional information or as examples. While every effort has been made to ensure the completeness of this list, document users are cautioned that they must meet all specified requirements of documents cited in sections 3 and 4 of this specification, whether or not they are listed.

2.2 Non-Government publications. The following documents form a part of this document to the extent specified herein. Unless otherwise specified, the issues of these documents are those cited in the solicitation or contract.

ASTM INTERNATIONAL

ASTM B348	-	Standard Specification for Titanium and Titanium Alloy Bars and Billets
ASTM B600	-	Standard Guide for Descaling and Cleaning Titanium and Titanium Alloy Surfaces
ASTM E3	-	Standard Guide for Preparation of Metallographic Specimens
ASTM E8/E8M	-	Standard Test Methods for Tension Testing of Metallic Materials
ASTM E18	-	Standard Test Methods for Rockwell Hardness of Metallic Materials
ASTM E23	-	Standard Test Method for Notched Bar Impact Testing of Metallic Materials
ASTM E29	-	Standard Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications
ASTM E399	-	Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness K_{Ic} of Metallic Materials
ASTM E539	-	Standard Test Method for Analysis of Titanium Alloys by X-Ray Fluorescence Spectrometry
ASTM E604	-	Standard Test Method for Dynamic Tear Testing of Metallic Materials
ASTM E1409	-	Standard Test Method for Determination of Oxygen and Nitrogen in Titanium and Titanium Alloys by the Inert Gas Fusion Technique
ASTM E1447	-	Standard Test Method for Determination of Hydrogen in Titanium and Titanium Alloys by the Inert Gas Fusion Thermal Conductivity/Infrared Detection Method
ASTM E1820	-	Standard Test Method for Measurement of Fracture Toughness
ASTM E1823	-	Standard Terminology Relating to Fatigue and Fracture Testing
ASTM E1941	-	Standard Test Method for Determination of Carbon in Refractory and Reactive Metals and Their Alloys by Combustion Analysis
ASTM E2371	-	Standard Test Method for Analysis of Titanium and Titanium Alloys by Atomic Emission Plasma Spectrometry

(Copies of these documents are available online at www.astm.org.)

SAE INTERNATIONAL

SAE-AMS-2380	-	Approval and Control of Premium-Quality Titanium Alloys
SAE-AMS-2631	-	Ultrasonic Inspection, Titanium and Titanium Alloy Bar, Billet and Plate

SAE-AMS-2643	-	Structural Examination of Titanium Alloys, Chemical Etch Inspection Procedure
SAE-AMS-2750	-	Pyrometry
SAE-AMS-4930	-	Titanium Alloy Bars, Wire, Forgings, and Rings, 6Al – 4V, Extra Low Interstitial, Annealed
SAE-AMS-H-81200	-	Heat Treatment of Titanium and Titanium Alloys

(Copies of these documents are online at www.sae.org.)

2.3 Order of precedence. Unless otherwise noted herein or in the contract, in the event of a conflict between the text of this document and the references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

3. REQUIREMENTS

3.1 First article. Unless otherwise specified (see 6.2), a sample shall be subjected to first article inspection in accordance with 4.2 and test results shall be submitted as specified (see 6.3). The following information shall accompany the test results:

a. For ingot:

(1) Ingot size and handling procedures.

(2) Aim chemistries and an internal chemical composition range including aim and range percentages for major alloying elements and maximum percentages for the remaining elements.

(3) Cropping procedure to ensure that all finished material will meet specification requirements.

b. For stock for forging and extrusion:

(1) Forging and hot working procedures, including the minimum and maximum processing temperatures and percent reduction for each step.

(2) The method for beta transus temperature determination.

c. For forged rod, bar, and billet:

(1) Forging and hot working procedures, including the minimum and maximum processing temperatures and percent reduction for each step.

(2) The method for beta transus temperature determination.

(3) Details of fan placement and positioning of the forging.

The above shall govern the manufacturer of all future materials unless otherwise approved by NAVSEA.

3.2 Material processing. The manufacturer shall document the material processing and heat treatment facilities and procedures used to produce the products for first article testing (see 6.3), and these same material processing and heat treatment facilities and procedures shall be used in the production of all product supplied to this specification. The manufacturing procedures used shall be controlled procedures and are subject to audit by NAVSEA or its authorized representative.

3.2.1 Ingot production. Ti-5111 ingot shall be produced in accordance with SAE-AMS-2380, Grade 2.

3.2.2 Forging and rolling. Ingot to billet reductions and rolling or forging to final product shall be accomplished in accordance with a specified schedule of reductions, temperatures, reheats, and final condition (amount of work, nominal microstructure, and shape) so that the completed product will meet required properties.

3.2.3 Chemical composition. The heat analysis and the final product hydrogen analysis shall conform to the requirements in table I.

3.2.4 Heat treatment. Heat treatment facilities, equipment, and procedures shall be in accordance with SAE-AMS-H-81200 and as specified herein.

3.2.4.1 Heat treatment information. The manufacturer shall include heat treatment information as part of the certification of conformance (see 4.8) and shall include the heat treatments given to each product, including stress relief. For batch-type furnaces, the heat treatment information shall include all the information presented on figures 1 and 2.

3.2.4.2 Working zone temperature uniformity. Working zone temperature uniformity shall be determined in accordance with SAE-AMS-2750.

3.2.4.3 Contact thermocouples. Unless otherwise specified (see 6.2), for batch-type furnaces a minimum of three thermocouples shall be attached to the furnace load. The hot junctions (or the caps of sheathed thermocouples) shall be in contact with the items.

3.2.4.4 Heat treatment procedures. Rod, bar, and billet produced to this specification shall be hot worked with the final reductions performed below the beta transus, followed by a beta anneal and an alpha-beta anneal to provide the required properties. Heat treatments, if required for straightening or stress relief, shall be performed in a vacuum and documented in the test results.

TABLE I. Chemical composition requirements. 1/

Element	Requirements, percent (maximum unless a range is indicated)	Product (check) analysis variations, under minimum or over maximum, of the specified limit of the element, percent 2/
Nitrogen, max.	0.03	+0.02
Carbon, max.	0.08	+0.02
Hydrogen, max. 3/	0.015	+0.002
Iron, max.	0.25	+0.15
Oxygen, max.	0.11	+0.02
Aluminum	4.5 – 5.5	±0.40
Vanadium	0.6 – 1.4	±0.15
Tin	0.6 – 1.4	±0.15
Molybdenum	0.6 – 1.2	±0.10
Zirconium	0.6 – 1.4	±0.10
Silicon	0.06 – 0.14	±0.02
Yttrium, max.	0.005	---------
Residuals, max. each	0.1	+0.02
Residuals, max. total	0.4	---------
Titanium	balance	---------

NOTES:

1/ Heat (i.e., ingot) analysis.

2/ Product (check) analysis variations are allowed only on a check analysis done upon receipt inspection of the product supplied to this specification.

3/ Final product hydrogen analysis shall be determined after all chemical and thermal processing is complete (see 4.5.1.1 through 4.5.3).

3.3 Dimensional tolerances. Dimensions and variations in dimensions of rods, bars, and billets shall be in accordance with ASTM B348, as applicable.

3.4 Identification marking. Each rod, bar, or billet in a lot shall be marked in accordance with SAE-AMS-4930.

3.5 Workmanship. Rod, bar, and billet surfaces shall be cleaned after heat treatment in accordance with ASTM B600. After cleaning and prior to any subsequent processing involving temperatures over 500 °F (260 °C), material shall be handled in a manner to preclude surface contamination. Material shall be free of defects harmful to its intended use, such as seams, cracks, scale, and fins.

3.6 Performance characteristics.

3.6.1 Soundness. Material shall be of uniform quality and shall conform to the inspection requirements of table IV.

3.6.2 Mechanical properties. Rod, bar, and billet produced to this specification shall meet the mechanical property requirements in tables II and III and specified in 3.6.4 and 3.6.5 after all heat treatments, including stress relief. Except for first article and conformance testing, where zero tolerance is required, the following tolerances may be applied to product supplied to this specification to determine acceptability as part of the final acceptance or verification procedures.

a. Minimum measured yield strength shall be not less than 98 percent of the minimum specified value.

b. Maximum measured yield strength shall be not more than 102 percent of the maximum specified value.

c. Minimum measured tensile elongation shall be not less than 98 percent of the minimum specified value.

d. Minimum measured average fracture toughness or impact toughness energy shall be not less than 98 percent of minimum specified values.

TABLE II. Tensile property requirements.

Property	Value [1/]
Tensile strength, ksi, minimum	100
Yield strength (0.2% offset), ksi	90 – 110
Elongation (% in 4D), minimum	10
Reduction of area, %, minimum	15
NOTE: [1/] Average.	

TABLE III. Impact toughness requirements.

Diameter (inches)	Toughness at +28 °F	
	Charpy V-notch [1/], minimum	5/8 Inch dynamic tear [2/], minimum
<2.00	27 ft-lbs	Not required
≥2.00 to ≤8.375	Not required	220 ft-lbs
NOTES: [1/] Average with no individual value more than 3 ft-lbs below the specified minimum. [2/] Average with no individual value more than 10 ft-lbs below the specified minimum.		

3.6.3 Fracture toughness properties. Fracture toughness testing is required for first article testing; fracture toughness is required for conformance testing only when specified (see 6.2). Rod, bar, and billet shall display a minimum average value for fracture toughness, J_{Ic}, of 520 in-lbs/in^2 (K_{Ic} of 95 ksi-in$^{1/2}$) at +70 °F. No individual value shall be less than 450 in-lbs/in^2 (K_{Ic} of 89 ksi-in$^{1/2}$).

3.6.4 Hardness properties. Rod, bar, and billet shall display an average Rockwell C hardness (HRC) value of 20 HRC to 35 HRC based on results of five tests.

3.6.5 Macrostructure and microstructure. The macrostructure of the rod, bar, or billet shall be examined after final heat treatment and shall conform to the macrostructure requirements of SAE-AMS-4930 for forgings. Further, the microstructure of the rod, bar, or billet shall consist of fully transformed structure free of prior beta grain boundaries or other evidence of prior processing above the beta transus.

3.6.6 Alpha case. The surface of the rod, bar, or billet material shall be free of alpha case.

TABLE IV. Ultrasonic inspection requirements. [1/]

Product thickness, diameter or distance between flats, inches [2/]	**Ultrasonic classification** [2/]	
	Surface Finish I (see 1.2 and 6.2)	**Surface Finish II (see 1.2 and 6.2)**
0.500 – 1.500, incl.	A1	AA
Over 1.500 – 8.375, incl.	A1	A1

NOTES:

1/ Surface area to be scanned shall be in accordance with SAE-AMS-2631, except that the minimum size for round and flat-faced products shall be 0.5 inch in diameter or distance between flats.

2/ Acceptance classes shall be in accordance with SAE-AMS-2631, as specified for Grade 1 material.

4. VERIFICATION

4.1 Classification of inspections. The inspection requirements specified herein are classified as follows:

a. First article inspection (see 4.2).

b. Conformance inspection (see 4.3).

4.2 First article inspection. First article inspection shall include all the examinations and tests specified in 4.4 through 4.6, as summarized in table V. First article testing shall include testing of rod, bar, and billet representing both the smallest and largest diameter, or thickness, expected to be produced by the mill. In addition to bracketing the sizes expected in future production, rod, bar, and billet subjected to first article inspection shall be from a production lot(s) and represent the same form to be supplied under this specification.

4.3 Conformance inspection. Conformance inspection shall include the examinations and tests specified in 4.4 through 4.6, as summarized in table V.

TABLE V. Summary of required tests.

Item	First article inspection	Conformance inspection	Requirement	Method
Chemical composition	X	X	3.2.3	4.5
Dimensional tolerances	X	X	3.3	4.4.2
Identification marking	X	X	3.4	4.4.2
Workmanship	X	X	3.5	4.4.2
Soundness (NDT)	X	X	3.6.1	4.4.3
Tensile properties	X	X	3.6.2, table II	4.6.2
Impact toughness	X	X	3.6.2, table III	4.6.3, 4.6.4
Fracture toughness	X	1/	3.6.3	4.6.5
Hardness	X	X	3.6.4	4.6.6
Macrostructure	X	X	3.6.5	4.4.4.2
Microstructure	X	X	3.6.5	4.4.5.2
Alpha case	X	X	3.6.6	4.4.6.2

NOTE:
1/ When specified (see 6.2).

4.4 Examinations.

4.4.1 Lot. A lot shall be all products from the same ingot, of the same size (i.e., cross-section and nominal length equal to or shorter than the tested length), form, shape (i.e., straight or coiled form), and heat treated in the same furnace charge (or, in the case of continuously processed lots, as part of the same continuous production run).

4.4.2 Visual examination.

4.4.2.1 Sampling. Sample size shall be in accordance with table VI.

4.4.2.2 Inspection. Each sample representing the lot shall be visually inspected after acid dip pickling (see 3.5). Linear defects greater than 1/16 inch revealed by visual examination shall be removed by grinding or other suitable means.

4.4.2.3 Rejection criteria. Failure of a sample representing the lot to meet the requirements in 3.3 to 3.5 shall be cause for rejection.

TABLE VI. Sample size for visual and dimensional examinations.

Number in lot	Number sampled
1 – 8	All
9 – 15	8
16 – 90	8
91 – 150	12
151 – 280	19
281 – 500	21
501 – 1200	27
1201 – 3200	35
3201 or more	38

4.4.3 Ultrasonic inspection.

4.4.3.1 Sampling. Each rod, bar, or billet in the lot 0.5 inch or greater in diameter or thickness shall be inspected.

4.4.3.2 Procedure. Each rod, bar, or billet in a lot shall be ultrasonically inspected 100 percent by volume in accordance with SAE-AMS-2631.

4.4.3.3 Rejection criteria. Rod, bar, or billet that fails to meet the requirements in table IV shall be rejected.

4.4.4 Macrostructure examination.

4.4.4.1 Sampling. Two rods, bars, or billets shall be selected at random from each lot. Where there is only one piece in the lot, only one rod, bar, or billet is required.

4.4.4.2 Procedure. One full cross-section from each sample representing the lot shall be subjected to macroscopic examination. Each specimen selected for macrostructure examination shall be prepared and examined in accordance with SAE-AMS-2380 for forgings.

4.4.4.3 Rejection criteria. Failure to meet the macrostructure requirements of 3.6.5 shall not be cause for rejection of a lot, provided that the rod, bar, or billet conform to all the other requirements in this specification.

4.4.5 Microstructure examination.

4.4.5.1 Sampling. Samples shall be selected in accordance with 4.4.4.1.

4.4.5.2 Procedure. One specimen shall be removed from the center and one specimen from the surface of a full cross-section of each sample representing the lot for microstructure examination. Each specimen shall be prepared in accordance with ASTM E3 and SAE-AMS-2643 in such a manner as to enable examination of the cross-section of each sample. The polished and etched specimens selected for microstructure examination shall be examined at not lower than 400× magnification for conformance to the microstructure requirements in 3.6.5.

4.4.5.3 Rejection criteria. Failure to meet the microstructure requirements of 3.6.5 shall be cause for rejection of the lot.

4.4.6 Alpha case examination. Each specimen removed from the surface and prepared and evaluated for microstructure examination in accordance with 4.4.5.2 shall be examined at a magnification not lower than 100× for conformance to 3.6.6. Examination of the microstructure for surface contamination (e.g., alpha case) shall be made at a magnification not lower than 100× for conformance to 3.6.6.

4.4.6.1 Sampling. Samples shall be selected in accordance with 4.4.4.1.

4.4.6.2 Procedure. Each specimen removed from the surface and prepared and evaluated for microscopic examination in 4.4.5.2 shall be examined at a magnification not lower than 100×.

4.4.6.3 Rejection criteria. Failure of one specimen to meet the alpha case requirement in 3.6.6 shall be cause for rejection of the lot.

4.5 Chemical composition.

4.5.1 Heat analysis.

4.5.1.1 Lot. For a heat analysis, a lot shall consist of all products from the same ingot.

4.5.1.2 Sampling. Two representative samples shall be obtained from each lot. One sample shall be taken from the head of the ingot, and the other sample shall be taken from the toe of the ingot.

4.5.1.3 Test procedure. The test method(s) used to determine chemical composition and conformance with table I shall be correlated with National Institute of Standards and Technology standard reference materials, when available, to ensure the validity of the test method that is used as a control in chemical analysis or for calibration in instrumental methods of analysis. The accuracy and precision of the chemical analysis test method(s) shall be accurate over the range for which the particular element is being analyzed. Carbon content shall be determined in accordance with ASTM E1941. Oxygen and nitrogen content shall be determined in accordance with ASTM E1409. Other elements shall be determined in accordance with ASTM E539, ASTM E2371, or equivalent procedures and equipment. Unless otherwise specified (see 6.2), the beta transus temperature shall be determined by testing in accordance with SAE-AMS-2380. When a product check analysis is conducted upon receipt inspection of material supplied to this specification, the composition shall conform to the requirements in table I, subject to the permissible product check analysis variations indicated therein.

4.5.2 Final product hydrogen analysis.

4.5.2.1 Lot. For final product hydrogen analysis, a lot shall consist of all products from the same ingot, of the same size (i.e., cross-section and nominal length equal to or shorter than the tested length), form, shape (i.e., straight or coiled form), and heat treated in the same furnace charge (or, in the case of continuously processed lots, as part of the same continuous production run).

4.5.2.2 Sampling. Sampling for final product hydrogen analysis shall be in accordance with table VII.

4.5.2.3 Test procedure. Final product hydrogen content shall be determined in accordance with ASTM E1447 at opposite ends of each rod, bar, or billet representing the lot. Final product hydrogen analysis shall be performed after all chemical and thermal processing of the lot is complete to determine conformance with the hydrogen content required by table I.

4.5.3 Rejection criteria. Results of chemical analysis that fail to meet the requirements in table I shall be cause for rejection.

4.6 Mechanical property tests.

4.6.1 Lot. A lot shall consist of all products from the same ingot, of the same size (i.e., cross-section and nominal length equal to or shorter than the tested length), form, shape (i.e., straight or coiled form), and heat treated in the same furnace charge (or, in the case of continuously processed lots, as part of the same continuous production run).

TABLE VII. Sampling for final product hydrogen analysis.

Lot size	Sample size
1 – 3	All
3 – 8	3
9 – 15	4
16 – 25	5
26 – 40	7
41 – 65	10
66 – 110	15
Over 110	1/

NOTE:
1/ Fifteen plus additional samples as required above for equivalent quantities over 110.

4.6.2 Tensile tests.

4.6.2.1 Sampling. Two sample rods, bars, or billets shall be selected at random from each lot. Where there is only one rod, bar, or billet in the lot, only one sample is required.

4.6.2.2 Test procedure. One tensile specimen shall be taken from each end of each sample representing the lot. Tensile testing shall be performed on each specimen in accordance with ASTM E8/E8M. The largest standard round test specimen in ASTM E8/E8M obtainable from the sample being tested shall be used. For samples up to and including 1.5 inches in diameter or thickness, the long axis of the test specimens shall coincide with the long axis of each sample. For samples above 1.5 inches, up to 5 inches in diameter or thickness, the long axis of the test specimens shall coincide with the mid-radius or quarter-thickness of each sample. For samples 5 inches and greater in diameter or thickness, the long axis of the test specimens shall be perpendicular to and intersect the long axis of each sample.

4.6.2.3 Rejection criteria. Failure of the results from any sample representing the lot to meet the requirements specified in table II shall be cause for rejection. Failure to meet the tolerances specified in 3.6.2 when properties are measured by the purchaser shall also be cause for rejection.

4.6.3 Charpy V-notch (CVN) tests.

4.6.3.1 Sampling. When required (see table III), two sample rods, bars, or billets shall be selected at random from each lot. Where there is only one rod, bar, or billet in the lot, only one sample is required.

4.6.3.2 Test procedure. Three CVN specimens shall be prepared and tested from each sample representing the lot. Specimens shall be in the L-T or L-R (rounds only) orientation in accordance with ASTM E1823. Specimens shall be prepared and tested in accordance with ASTM E23. All specimens shall be removed from the same end of each sample representing the lot. For samples less than or equal to 1.5 inches in diameter or thickness, the long axis of the test specimens shall coincide with the long axis of each sample. For samples greater than 1.5 inches and less than to 2.0 inches in diameter or thickness, the long axis of the test specimens shall coincide with the mid-radius or quarter-thickness of each sample.

4.6.3.3 Rejection criteria. Failure of the results from any sample representing the lot to meet the requirements specified in table III shall be cause for rejection. Failure to meet the tolerances specified in 3.6.2 when properties are measured upon receipt inspection of product supplied to this specification shall also be cause for rejection.

4.6.4 Dynamic tear tests.

4.6.4.1 Sampling. When required (see table III), two sample rods, bars, or billets shall be selected at random from each lot. Where there is only one rod, bar, or billet in the lot, only one sample is required.

4.6.4.2 Test procedure. One specimen shall be removed from each end of each sample representing the lot. Specimens shall be in the L-T or L-R (rounds only) orientation in accordance with ASTM E1823. Specimens shall be prepared and tested in accordance with ASTM E604. Unless otherwise specified (see 6.2), the long axis of the specimens shall coincide with the long axis of each sample. Where section size permits, specimens may be in the R-C orientation in accordance with ASTM E1823.

4.6.4.3 Rejection criteria. Failure of the results from any sample representing the lot to meet the requirements specified in table III shall be cause for rejection. Failure to meet the tolerances specified in 3.6.2 when properties are measured upon receipt inspection of product supplied to this specification shall also be cause for rejection.

4.6.5 Fracture toughness tests. When required (see 6.2), fracture toughness testing shall be performed.

4.6.5.1 Sampling. When specified (see 6.2), two sample rods, bars, or billets shall be selected at random from each lot. Where there is only one rod, bar, or billet in the lot, only one sample is required.

4.6.5.2 Test procedure. One specimen shall be removed from each end of each sample representing the lot. Specimens shall be in the L-T or L-R (rounds only) orientation in accordance with ASTM E1823. The long axis of the specimens shall coincide with the long axis of the sample. Fracture toughness specimens shall be as thick as possible, except that specimen thickness need not exceed 1.5 inches. The preferred fracture toughness quantity is J_{Ic} as determined in accordance with ASTM E1820 as modified below.

4.6.5.2.1 K_{JIc} and K_{Ic}. K_{JIc} is defined by ASTM E1820 and K_{Ic} is defined by ASTM E399. K_{JIc} and K_{Ic} values can be evaluated, but should only be used in fully elastic applications. If K_Q (a tentative value of K_{Ic}) is evaluated, but does not meet the validation requirements of ASTM E399 to be designated as K_{Ic}, then ASTM E1820 shall be used to evaluate J_{Ic}.

4.6.5.2.2 Modifications to the testing procedure of ASTM E1820. The following guidelines shall be adhered to during the performance of fracture toughness tests conducted in accordance with ASTM E1820 to eliminate, when possible, unstable specimen behavior:

a. The stiffest available load train should be employed in the test.

b. The displacement between unloading cycles shall be limited to less than 0.0005 inch.

c. Use relatively large a/W ratio specimens, that is, $0.65 < a/W < 0.70$.

It would be ideal if tests conducted according to ASTM E1820 were valid, and if such is the case, the toughness values measured are applicable to structural applications of this metal. However, tests of this material are often interrupted by ductile instabilities characterized by sudden load drops accompanied by increases in the crack mouth opening displacement and valid J_{Ic} results according to ASTM E1820 cannot be obtained. Alternative acceptance criteria are provided here for these circumstances.

4.6.5.2.3 Alternate acceptance criteria for ASTM E1820. The acceptance criteria of ASTM E1820 shall be modified by the criteria described herein. If crack growth instability (defined by the inability of the test machine to impose an elastic unloading at predetermined crack opening displacement [COD] increments) occurs during the test which causes the qualification requirements of ASTM E1820 not to be met, then the following procedure shall be followed:

a. Prepare the specimens, pre-crack the specimens, and conduct the resistance curve procedure in accordance with ASTM E1820. Determine the series of J-Δa data pairs obtained from the series of partial un-loadings following the procedure of ASTM E1820.

b. Disregard the requirements addressing final crack size and crack straightness requirements in ASTM E1820. The accuracy requirement on the initial compliance prediction of the optical crack length measurement shall be met.

c. Plot J versus crack extension (Δa) on axes as defined in ASTM E1820 using in-lb/in^2 and inch units respectively. Do not include any J-Δa data pairs beyond the first instability. Plot the construction line defined by $J=M\sigma_Y\Delta a$, with M = 2.0 and then draw an exclusion line parallel to the construction line intersecting the abscissa at 0.006 inch. Draw a second exclusion line parallel to the construction line intersecting the abscissa at 0.06 inch. Plot an offset line parallel to the construction and exclusion lines at an offset value of 0.008 inch.

d. If the first instability, defined by a sudden load drop and increase in crack opening displacement, occurs before the J-R curve crosses the 0.008-inch offset line, then:

(1) Determine J_{Qc} in accordance with the annex in ASTM E1820 for fracture instability toughness determination using J. Qualify J_{Qc} using the qualification requirements of ASTM E1820 as revised here. If all qualification requirements are met, then $J_{init} = J_Q$ and

$$K_{init} = \sqrt{\frac{J_{init} \times E}{1 - v^2}}$$

(2) For this case, J_{init} represents the ductile initiation fracture toughness and K_{init} represents the linear elastic initiation fracture stress intensity. If J_{Qc} does not meet the validity criteria as set by ASTM E1820 and exempted above, a retest is necessary, possibly using a larger specimen.

e. If the first instability occurs beyond the 0.008-inch offset line and prior to the 0.060-inch offset exclusion line as defined in the annex in ASTM E1820 for J_{Ic} and K_{JIc} evaluation, then:

(1) Disregard the fracture instability instructions related to proceeding to annexes in ASTM E1820.

(2) Perform data analysis in accordance with the method in ASTM E1820 for J_{Ic} and K_{JIc} evaluation using M = 2.0 to determine an interim J_Q value.

(3) Disregard the following requirements in the ASTM E1820 method for J_{Ic} and K_{JIc} evaluation:

(a) At least one J–Δa point shall lie between the 0.006-inch exclusion line and a parallel line with an offset of 0.02 inch from the construction line.

(b) At least one J−Δa point shall lie between this 0.02-inch offset line and the 0.06-inch exclusion line.

(c) At least five data points shall remain between Δa_{min}, Δa_{limit}, and J_{limit}.

(d) Data point spacing shall meet the requirements of (a) above.

(e) If these data points are different from those used to evaluate J_Q, obtain a new value of J_Q based only on data in accordance with ASTM E1820.

(4) Disregard the requirements in the ASTM E1820 method for J_{Ic} and K_{JIc} evaluation regarding the number of points used to determine a_{oq}, except that the correlation coefficient of the a_{oq} fit, using only the J-Δa data pairs up to the first instability, shall be greater than 0.96.

(5) If there is not enough data to support calculation of the power law regression line and the correlation coefficient of the a_{oq} fit, as detailed in ASTM E1820 method for J_{Ic} and K_{JIc} evaluation, is greater than 0.96, then the intersection between the 0.008-inch offset line and a linearly interpolated line between the immediate J-Δa data points straddling the 0.008-inch offset may be used as a J_Q value.

(6) If all ASTM E1820 method for J_{Ic} and K_{JIc} evaluation validity criteria are met other than as exempted above, then $J_{init} = J_Q$ and:

$$K_{init} = \sqrt{\frac{J_{init} \times E}{1 - v^2}}$$

(7) For this case J_{init} represents the ductile initiation fracture toughness and K_{init} represents the linear elastic initiation fracture stress intensity. If J_Q does not meet the validity criteria as set by ASTM E1820 and exempted above, a retest is necessary, possibly using a larger specimen.

f. If the first instability occurs beyond the 0.060-inch offset exclusion line as defined in ASTM E1820 method for J_{Ic} and K_{JIc} evaluation, then:

(1) Perform data analysis using the above evaluation method in ASTM E1820 and using M = 2.0 to determine J_Q (i.e., disregard fracture instability instructions related to proceeding to annexes in ASTM E1820).

(2) If all ASTM E1820 method for J_{Ic} and K_{JIc} evaluation validity criteria are met other than as exempted above, then $J_{Ic} = J_Q$ and

$$K_{init} = \sqrt{\frac{J_{init} \times E}{1 - v^2}}$$

(3) For this case J_{init} represents the ductile initiation fracture toughness and K_{init} represents the linear elastic initiation fracture stress intensity. If J_Q does not meet the validity criteria as set by ASTM E1820 and exempted above, a retest is necessary, possibly using a larger specimen.

4.6.5.3 Rejection criteria. Failure of the results from any sample representing the lot to meet the requirements specified in 3.6.3 shall be cause for rejection. Failure to meet the tolerances specified in 3.6.2 when properties upon receipt inspection of product supplied to this specification shall also be cause for rejection.

4.6.6 Hardness tests.

4.6.6.1 Sampling. Two sample rods, bars, or billets shall be selected at random from each lot. Where there is only one rod, bar, or billet in the lot, only one sample is required.

4.6.6.2 Test procedure. Rockwell hardness shall be determined on each sample representing the lot in accordance with ASTM E18. For samples less than or equal to 0.5 inches in diameter or thickness, five hardness readings shall be taken on the surface of each sample representing the lot. For samples greater than 0.5 inches in diameter or thickness, five hardness readings shall be taken at mid-radius or quarter-thickness on a flat cross-section of each sample representing the lot.

4.6.6.3 Rejection criteria. Failure of the results from any sample representing the lot to meet the requirements in 3.6.4 shall be cause for rejection.

4.7 Replacement and retest.

4.7.1 Replacement of a test specimen. If any test specimen shows defective machining or develops flaws as the result of machining which cause inaccurate test results, it may be discarded and a replacement test specimen substituted. If the percentage of elongation of any tension test specimen is less than that specified and any part of the fracture is outside of the middle two-thirds of the gage length or in a punched or scribed mark within the reduced section, a retest shall be allowed.

4.7.2 Retests. If mechanical property test results from one of the samples representing a lot fail to meet the acceptance criteria, the manufacturer may: (a) reprocess and conduct verification according to section 4; or (b) conduct two additional sets of tests on the same sample that failed to meet specified requirements. The results for both retest sets shall meet the specified requirements for acceptance of the lot. Results of mechanical property tests on specimens from coiled rod or bar that do not meet the specified requirements or the results of fracture toughness tests that fail to meet the validity requirements of ASTM E1820 may be submitted as specified (see 6.2).

4.8 Certificate of conformance. Unless otherwise specified (see 6.2), a certificate of conformance shall be prepared for each lot of material offered for acceptance. A certification for conformance for each lot shall provide requirements and test results, including results that required retesting, for all specified chemical and mechanical tests. Results of nondestructive tests and other inspections or tests shall be recorded on the certificate. In addition, the manufacturer shall report the melt processes used and the melting source of the material if the manufacturer is not the melter. The certificate shall state that each lot has been produced using manufacturing facilities and processes demonstrated in first article testing and sampled, tested, and inspected in accordance with the specification requirements herein, and shall be signed and dated by a responsible representative of the manufacturer.

4.9 Rounding of test results. For purposes of determining compliance with the limits in this specification, an observed value or a calculated value shall be rounded in accordance with the rounding methods of ASTM E29.

5. PACKAGING

5.1 Packaging. For acquisition purposes, the packaging requirements shall be as specified in the contract or order (see 6.2). When packaging of materiel is to be performed by DoD or in-house contractor personnel, these personnel need to contact the responsible packaging activity to ascertain packaging requirements. Packaging requirements are maintained by the Inventory Control Point's packaging activities within the Military Service or Defense Agency, or within the military service's system commands. Packaging data retrieval is available from the managing Military Department's or Defense Agency's automated packaging files, CD-ROM products, or by contacting the responsible packaging activity.

6. NOTES

(This section contains information of a general or explanatory nature that may be helpful, but is not mandatory.)

6.1 Intended use. This specification covers requirements for Ti-5111 alloy titanium rod, bar, and billet intended for use in critical seawater applications, including those affecting safety of nuclear submarine systems (SUBSAFE), where high strength, fracture toughness, and seawater corrosion resistance is required at low to moderate temperatures. Ti-5111, a near-alpha alloy, is well suited for marine applications where strength and high toughness are required. The dynamic toughness (a measure of load and plastic energy dissipation necessary for crack initiation and propagation) of Ti-5111 is nearly three times that of Ti-6Al-4V ELI.

6.2 Acquisition requirements. Acquisition documents should specify the following:

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

b. Form and finish to be supplied (see 1.2 and table IV).

c. When first article testing is not required (see 3.1).

d. When and how results should be submitted to NAVSEA for review and approval (see 3.1 and 6.3).

e. When less than three thermocouples may be attached to the furnace load in batch-type furnaces (see 3.2.4.3).

f. When fracture toughness testing is required as part of conformance inspection (see 3.6.3, table V, and 4.6.5.1).

g. When sample size greater than 0.001 ounce may be used for hydrogen analysis (see 4.5.2.2).

h. When the beta transus temperature can be determined other than in accordance with SAE-AMS-2380 (see 4.5.1.3).

i. When the long axis of the dynamic tear test specimens is not required to be coincident with the long axis of the sample (see 4.6.4.2).

j. When results of mechanical property tests on specimens from coiled rod or bar that do not meet the specified requirements or the results of fracture toughness tests that fail to meet the validity requirements of ASTM E1820 should be submitted to NAVSEA for review and approval (see 4.7.2).

k. When a certificate of conformance is not required with each lot offered for acceptance (see 4.8).

l. Packaging requirements (see 5.1 and 6.6).

6.3 First article inspection. When first article inspection is required, the contracting officer of the Command or Agency should provide specific guidance to manufacturers whether the item should be a first article sample or a sample selected from first production items (see 3.1), and the number of items to be tested as specified in the individual test procedures listed in section 4. The contracting officer should also include specific instructions on acquisition documents regarding arrangements for examinations, approval of first article inspection test results, other requirements in 3.1, and disposition of first articles. The contracting officer should advise the manufacturers that NAVSEA approval is required on first article inspection test results. Invitations for bids should stipulate that the Government reserves the right to waive the requirement for first article inspection testing to those bidders offering a product that has previous first article inspection tests results approved by NAVSEA to this specification, and that for such bidders offering such products, who wish to, Government approval is presently appropriate for the pending contract. Bidders should not submit alternate bids unless specifically requested to do so in the solicitation.

6.3.1 Exemption from first article inspection. Manufacturers that supply evidence of having met the requirements of 4.2 may obtain a letter of confirmation from NAVSEA excusing them from future first article inspections. This does not exempt suppliers from the requirements in 4.8.

6.3.2 New manufacturers. Prior to delivery, manufacturers that have not previously produced products under this specification should demonstrate to the Commander, Naval Sea Systems Command, Ship Integrity and Performance Engineering Group (NAVSEA 05P), that their facilities produce products conforming to the requirements of this specification.

6.3.3 Forwarding test results. When a contract does not exist, first article test results may be submitted directly to NAVSEA. The first article inspection test results should be verified by the Defense Contract Management Agency (DCMA) or by the American Bureau of Shipping (ABS) representative. The report should be forwarded to the Commander, Naval Sea Systems Command, Ship Integrity and Performance Engineering Group (NAVSEA 05P), via DCMA.

6.3.4 Manufacturing and testing. The manufacture of the first article, the laying out of test specimens, and the testing should be witnessed by an ABS or DCMA representative.

6.4 Alternate ultrasonic inspection procedure. Consideration may be given to alternate ultrasonic inspection procedures. These procedures must be reviewed by the Command or Agency concerned.

6.5 Definitions.

6.5.1 Bar. A hot rolled or forged semi-finished round, hexagonal, octagonal, or square solid section product whose cross-sectional area is equal to or less than 16 square inches.

6.5.2 Billet. A solid semi-finished section hot rolled or forged from an ingot, with a cross-sectional area greater than 16 square inches whose width is less than five times its thickness.

6.5.3 Rod. A round bar greater than or equal to 0.312 inch in diameter.

6.6 Suggested packaging. Products should be packed in accordance with the requirements of ASTM A700, as referenced for stainless steel.

6.7 Subject term (key word) listing.

Corrosion-resistant

High strength

High toughness

A. Procedure: _____ Revision: _____ Date: _____

B. Heat Treater:

C. Item Material Specification: _____ Revision: _____ Amend.: _____

Interim Change: _____

D. Material Composition: _____ Type: _____ Condition: _____ Grade: _____

Class: _____

E. Pre-Heat Treatment Burn Out:

Time: _____ Temperature: _____

F. Time and Temperature:

Heat Treatment	Aim Temperature	Tolerance*	Holding Time	Cooling Method and Rate**
Beta Anneal				
Alpha-Beta Anneal				
Stress Relieving				
Other (specify)				

*Include temperature tolerance if the tolerance is other than ±25 °F.

**Specify how items are cooled and include cooling rate.

G. Working Zone Atmosphere:

1. Type of Atmosphere: _____
2. Dew point (maximum): _____ °F or °C
3. Temperature above which the dew point must be controlled if other than 600 °F: _____
4. Flow rate: _____ cubic feet per hour
5. Vacuum – maximum pressure: _____ torr (mm Hg) or _____ microns Hg
6. Type of inert gas backfill (if used): _____ Backfill dew point (maximum) _____ °F or °C

NOTES:

1. Enter “NA” when an item does not apply.
2. A single heat treatment procedure may cover more than one heat treatment process, provided that the required information for each process is clearly distinguished.

FIGURE 1. Heat treatment procedure information.

A. Heat Treater: _____

B. Items Heat Treated: _____

C. Lot Numbers or Serial Numbers: _____

D. Heat Treatment Procedure Used (including revision and date of revision): _____

E. Date of Heat Treatment: _____

F. Time/Temperature Data (the original temperature chart or the original manually recorded data). Include a standard time interval, such as one hour, or the starting time and chart speed marked on the chart.

G. Specific Furnace(s) Used: _____

H. Method of Thermocouple Attachment (batch furnace only): _____

I. Furnace Information:

1. Furnace type(s):

Batch furnace _____

Vacuum furnace – Integral quench: _____ Yes _____ No _____

2. Method of Preventing Flame Impingement: _____

J. Temperature Measurement and Control Information:

1. Thermocouple information:

a. How many thermocouples were used? Contact: _____ Non-contact: _____

b. Describe the location of each thermocouple (may provide a sketch): _____

2. How was working zone temperature recorded? Automatically: _____ Manually: _____ (Monitoring interval) _____

3. How was working zone temperature controlled? Automatically: _____ Manually: _____ (Monitoring interval) _____

4. If manual temperature control was used, how was the temperature adjusted (may reference a written standard practice):

5. If thermocouples were not used, briefly describe the type, number, and location of the temperature measuring devices used to indicate, record, and control temperature:

6. Distance between the thermocouples and the load in an oscillating furnace: inches

FIGURE 2. Information to be documented on the heat treatment record.

K. Furnace Loading Information:

1. General description of item distribution in the load (not required when a thermocouple is attached to each item in the load). NOTE: A sketch or reference to a written standard practice is acceptable.

a. Approximate weight or size of batch furnace load: Pounds: _____ or no. of pieces: _____ and size: _____

b. Approximate continuous furnace production rate: _____ lbs/hr.

2. General description of the supporting method used. NOTE: A sketch or reference to a written standard practice is acceptable.

L. Location of Test Coupons (when used) in relation to items and attached thermocouples (when used). NOTE: A sketch or reference to a written standard practice is acceptable.

M. Furnace Survey Information:

1. Was this heat treatment used in conjunction with a temperature survey? Yes No

FIGURE 2. Information to be documented on the heat treatment record – Continued.

Custodians:
Army – MI
Navy – SH
Air Force – 99

Review Activities:
Army – MR
Navy – AS
Air Force – 16, 84
DLA – IS
GSA – FAS

Preparing Activity:
Navy – SH
(Project 9530-2009-008)

NOTE: The activities listed above were interested in this document as of the date of this document. Since organizations and responsibilities can change, you should verify the currency of the information above using the ASSIST Online database at https://assist.dla.mil.