



AEROSPACE MATERIAL SPECIFICATION

Society of Automotive Engineers, Inc.
400 COMMONWEALTH DRIVE, WARRENDALE, PA 15096

AMS 49 91

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Revised

TITANIUM ALLOY CASTINGS, INVESTMENT 6.0A1 - 4.0V Annealed

1. SCOPE:

- 1.1 Form: This specification covers a titanium alloy in the form of four quality-grades of investment castings.
- 1.2 Application: Primarily for parts of intricate design requiring a combination of good strength-to-weight ratio, creep and fatigue properties, and corrosion resistance up to 750° F (400° C).

2. APPLICABLE DOCUMENTS: The following publications form a part of this specification to the extent specified herein. The latest issue of Aerospace Material Specifications (AMS) shall apply. The applicable issue of other documents shall be as specified in AMS 2350.

- 2.1 SAE Publications: Available from Society of Automotive Engineers, Inc., 400 Commonwealth Drive, Warrendale, PA 15096.

2.1.1 Aerospace Material Specifications:

- AMS 2350 - Standards and Test Methods
- AMS 2635 - Radiographic Inspection
- AMS 2645 - Fluorescent Penetrant Inspection
- AMS 2804 - Identification, Castings

- 2.2 ASTM Publications: Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103.

- ASTM E8 - Tension Testing of Metallic Materials
- ASTM E18 - Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials
- ASTM E120 - Chemical Analysis of Titanium and Titanium Alloys
- ASTM E384 - Microhardness of Materials

- 2.3 U.S. Government Publications: Available from Commanding Officer, Naval Publications and Forms Center, 5801 Tabor Avenue, Philadelphia, PA 19120.

2.3.1 Federal Standards:

- Federal Test Method Standard No. 151 - Metals; Test Methods

2.3.2 Military Standards:

- MIL-STD-794 - Parts and Equipment, Procedures for Packaging and Packing of

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3. TECHNICAL REQUIREMENTS:

- 3.1 Composition: Shall conform to the following percentages by weight, determined by wet chemical methods in accordance with ASTM E120, by spectrographic methods in accordance with Federal Test Method Standard No. 151, Method 112, or by other analytical methods approved by purchaser:

	min	max
Aluminum	5.50	6.75
Vanadium	3.50	4.50
Iron	--	0.30
Oxygen	--	0.20
Carbon	--	0.10
Nitrogen	--	0.05 (500 ppm)
Hydrogen	--	0.015 (150 ppm)
Yttrium	--	0.005 (50 ppm)
Residual Elements, each (3.1.1)	--	0.10
Residual Elements, total (3.1.1)	--	0.40
Titanium	remainder	

- 3.1.1 Determination not required for routine acceptance.

- 3.2 Condition: Annealed.

- 3.3 Casting:

- 3.3.1 The metal for castings shall be melted and poured under vacuum without loss of vacuum between melting and pouring.

- 3.3.2 Castings shall be poured either from remelted metal from a master heat or directly from a master heat. In either case, metal for casting shall be qualified as in 3.4.

- 3.3.2.1 A master heat is refined metal of a single furnace charge, multiple melted using consumable electrode practice with at least the final melting cycle under vacuum, melted and cast into ingot or pig under vacuum, or is metal blended as in 3.3.2.2. Gates, sprues, risers, and rejected castings shall be used only in preparation of master heats; they shall not be remelted directly, without refining, for pouring of castings.

- 3.3.2.2 Unless prohibited by purchaser, metal from two or more master heats may be blended provided that the composition of each master heat to be blended is within the limits of 3.1 and that the total weight of metal blended does not exceed 10,000 lb (4500 kg). When two or more master heats are blended, the resultant blend shall be considered a master heat.

- 3.4 Master Heat Qualification: Each master heat shall be qualified by evaluation of chemical analysis and tensile test specimens conforming to 3.4.1 and 3.4.2, respectively. A master heat may be considered conditionally qualified if vendor's test results show conformance to all applicable requirements of this specification. However, except when purchaser waives confirmatory testing, final qualification shall be based on purchaser's test results. Conditional qualification of a master heat shall not be construed as a guarantee of acceptance of castings poured therefrom.

- 3.4.1 Chemical Analysis Specimens: Shall be of any convenient size, shape, and form for vendor's tests; when chemical analysis specimens are required by purchaser, specimens shall be cast to a size, shape, and form agreed upon by purchaser and vendor.

3.4.2 Tensile Test Specimens: Shall be cast from remelted metal from each master heat except when castings are poured directly from a master heat, in which case the specimens shall also be poured directly from the master heat. Specimens shall be of standard proportions in accordance with ASTM E8 with 0.250 in. (6.25 mm) diameter at the reduced parallel gage section. Specimens shall be cast to size or shall be cast oversize and subsequently machined to 0.250 in. (6.25 mm) diameter. Tensile test specimens shall be free of oxygen-rich or carbon-rich layer, such as alpha case, or other surface contamination (See 3.6.3).

3.5 Heat Treatment: Castings and separately-cast tensile test specimens shall be annealed by heating in argon atmosphere or vacuum to a temperature within the range 1300° - 1550° F (705° - 845° C), holding at the selected temperature within + 25° F (+ 15° C) for 2 - 4 hr, cooling in the furnace to below 1000° F (540° C), and cooling in air to room temperature.

3.6 Properties: Castings, specimens cut from attached coupons, and representative tensile test specimens produced in accordance with 3.4.2 shall conform to the following requirements; conformance to the requirements of 3.6.1.1 may be used for acceptance except when purchaser specifies that the requirements of 3.6.1.2 shall apply:

3.6.1 Tensile Properties: Shall be as specified in 3.6.1.1 or 3.6.1.2, determined in accordance with ASTM E8 with the rate of strain maintained at 0.003 - 0.007 in. per in. per min. (0.003 - 0.007 (mm/mm)/min.) through the yield strength and then increased so as to produce failure in approximately one additional minute. When a dispute occurs between purchaser and vendor over the yield strength values, a referee test shall be performed on a machine having a strain rate pacer, using a rate of 0.005 in. per in. per min. (0.005 (mm/mm)/min.) through the yield strength and a minimum cross head speed of 0.10 in. (2.5 mm) per min. above the yield strength.

3.6.1.1 Separately-Cast Specimens or Specimens Cut From Attached Coupons:

Tensile Strength, min	130,000 psi (896 MPa)
Yield Strength at 0.2% Offset, min	120,000 psi (827 MPa)
Elongation in 4D, min	6%

3.6.1.2 Specimens Cut From Castings:

3.6.1.2.1 Designated Areas:

Tensile Strength, min	130,000 psi (896 MPa)
Yield Strength at 0.2% Offset, min	120,000 psi (827 MPa)
Elongation in 4D, min	6%

3.6.1.2.2 Non-Designated Areas:

Tensile Strength, min	127,000 psi (876 MPa)
Yield Strength at 0.2% Offset, min	110,000 psi (758 MPa)
Elongation in 4D, min	4.5%

3.6.2 Hardness of Castings: Shall be not higher than 39 HRC or equivalent, determined in accordance with ASTM E18.

3.6.3 Surface Contamination: Castings shall be free of any oxygen-rich or carbon-rich layer, such as alpha case, or other surface contamination, determined by microhardness measurements in accordance with ASTM E384 in conjunction with standard metallographic techniques.

3.7 Quality:

3.7.1 Castings, as received by purchaser, shall be uniform in quality and condition, sound, and free from foreign materials and from internal and external imperfections detrimental to usage of the castings.

3.7.1.1 Castings shall have smooth surfaces and shall be well cleaned. Metallic shot or grit shall not be used for final cleaning, unless otherwise permitted by purchaser.

3.7.1.2 Detrimental imperfections include negative surface conditions, such as voids or depressions, and subsurface conditions, such as less-dense or more-dense foreign material, gas holes, and shrinkage, and shall be controlled as follows; definitions of discontinuities referenced herein are shown in 8.1:

3.7.1.2.1 Permissible Negative Surface Discontinuities: Shall be not greater than specified in Table I for the area grade of the casting as specified on the drawing:

TABLE I

Area Grade	Maximum Number of Discontinuities (See 8.1)	Maximum Discrete Discontinuity Length		Maximum Cluster Length (3.7.1.2.1.1) Inch
		Linear	Nonlinear	
A	4 discrete discontinuities in a 1-in. square	None Allowed	0.015	None Allowed
B	4 discrete discontinuities in a 1-in. square	None Allowed	0.020	--
	One cluster in a 2-in. square	None Allowed	0.010	0.125
C	8 discrete discontinuities in a 1-in. square	0.020, One max	0.030	--
	One cluster in a 2-in. square	0.010	0.030	0.375
D	8 discrete discontinuities in a 1-in. square	0.045, Two max	0.040	--

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TABLE I (SI)

Area Grade	Maximum Number of Discontinuities (See 8.1)	Maximum Discrete Discontinuity Length		Maximum Cluster Length (3.7.1.2.1.1) Millimetres
		Millimetres		
		Linear	Nonlinear	
A	4 discrete discontinuities in a 25-mm square	None Allowed	0.40	None Allowed
B	4 discrete discontinuities in a 25-mm square	None Allowed	0.50	--
	One cluster in a 50-mm square	None Allowed	0.25 (3.7.1.2.1.2)	3.2
C	8 discrete discontinuities in a 25-mm square	0.50, One max	0.75	--
	One cluster in a 50-mm square	0.25	0.75 (3.7.1.2.1.2)	9.5
D	8 discrete discontinuities in a 25-mm square	1.15, Two max	1.00	--

3.7.1.2.1.1 Clusters shall be nonlinear. An area of shrinkage appearing on a finished surface may be considered a cluster.

3.7.1.2.1.2 One discrete nonlinear discontinuity is permitted within the cluster.

3.7.1.2.2 Positive (Raised) Material on Cast Surfaces: Excess material on cast surfaces shall be permissible as follows:

3.7.1.2.2.1 Nodules: Three nodules, 0.020 in. (0.50 mm) and under in height above the parent surface and 0.020 in. (0.50 mm) and under in length, are permissible in a 1-in. (25-mm) square or one nodule, 0.020 in. (0.50 mm) and under in height and 0.150 in. (3.8 mm) and under in length, is permissible in a 2-in. (50-mm) square.

3.7.1.2.2.2 Parting Lines and Gating Material: Positive material in the form of parting lines, gates, risers, or material due to wax welds less than 0.015 in. (0.40 mm) in height above the parent surface is permissible.

3.7.1.2.2.3 Areas to be Finished: Positive material up to 0.060 in. (1.50 mm) in height above the parent surface is permissible in areas to be finished.

3.7.1.2.3 Negative Depressed Discontinuities on Cast or Finished Surfaces:

3.7.1.2.3.1 Unlimited Discontinuities:

3.7.1.2.3.1.1 Discontinuities which will be removed by final finishing operations are permissible.

3.7.1.2.3.1.2 In Grade C or D areas, unlimited discrete discontinuities 0.020 in. (0.50 mm) and under in length and separated by at least 0.100 in. (2.50 mm) are permissible if the subsurface portions of these discontinuities are in accordance with limitations specified in 3.7.2.

3.7.1.2.3.2 Other Surface Conditions: Flowlines on a cast surface, which indicate the direction of metal flow, are permissible in accordance with 3.7.1.2.3.2.1 through 3.7.1.2.3.2.6.

3.7.1.2.3.2.1 Flowlines shall have well-rounded contours.

3.7.1.2.3.2.2 The width of the flowline shall be equal to, or greater than, twice the depth of the flowline below the parent surface.

3.7.1.2.3.2.3 Flowlines shall not be associated with cold shuts or misruns.

3.7.1.2.3.2.4 In Grade A areas, flowlines are permissible provided the flowlines do not extend below the parent surface.

3.7.1.2.3.2.5 In Grade B, C, and D areas, flowlines 0.005 in. (0.13 mm) and under in depth below the parent surface are permissible without length or number restriction.

3.7.1.2.3.2.6 In Grade C and D areas, flowlines 0.010 in. (0.25 mm) and under in depth below the parent surface are permissible provided that not more than two such flowlines exist in a 1-in. (25-mm) square and that the flowlines are 0.250 in. (6.25 mm) and under in length.

3.7.2 Castings shall be produced under radiographic control. This control shall consist of radiographic examination of castings in accordance with AMS 2635 until proper foundry technique, which will produce castings free from harmful internal imperfections, is established for each part number and of production castings as necessary to ensure maintenance of satisfactory quality as defined in Tables II and III.

3.7.2.1 Shrinkage: Shall be in accordance with Table II. Depth of such shrinkage shall be as agreed upon by purchaser and vendor.

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TABLE II

Area Grade	Maximum Number in 1-in. Square	Minimum Separation (3.7.2.1.1) Inch	Feature Thickness Inch	Maximum Shrinkage Length, Inch		
				Up to 0.250, incl	to 0.500, incl	Over 0.500
A	3	0.500	Up to 0.500, incl	0.050	0.070	0.120
B	3	0.200	Over 0.500	0.050	0.070	0.120
C	5	0.100	Up to 0.500, incl	0.120	0.160	0.200
D	7	0.100	Over 0.500	0.120	0.160	0.200

TABLE II (SI)

Area Grade	Maximum Number in 25-mm Square	Minimum Separation (3.7.2.1.1) Millimetres	Feature Thickness Millimetres	Maximum Shrinkage Length, Millimetres		
				Up to 6.50, incl	to 12.50, incl	Over 12.50
A	3	12.50	Up to 12.50, incl	1.25	1.75	3.00
B	3	5.00	Over 12.50	1.25	1.75	3.00
C	5	2.50	Up to 12.50, incl	3.00	4.00	5.00
D	7	2.50	Over 12.50	3.00	4.00	5.00

3.7.2.1.1 Discrete areas of shrinkage separated by less than the amount shown in Table II shall be considered as one discrete discontinuity.

- 3.7.2.2 Gas Holes and More-Dense or Less-Dense Foreign Material: Shall be in accordance with Table III. Depth of less-dense foreign material discontinuities shall be as agreed upon by purchaser and vendor.

TABLE III

Area Grade	Maximum Number in a 1-in. (25-mm) Square	Minimum Separation (3.7.2.2.1)	Maximum Length (3.7.2.2.2)
A	3	0.250 in. (6.25 mm)	1/8 section thickness
B	6	3 times the largest dimension of the larger discontinuity	1/4 section thickness for 0.060 in. (1.50 mm) and under wall 3/8 section thickness for wall over 0.060 in. (1.50 mm)
C	9	2 times the largest dimension of the larger discontinuity	1/2 section thickness
D	12	2 times the largest dimension of the larger discontinuity	1/2 section thickness

- 3.7.2.2.1 Discrete gas holes and foreign material discontinuities separated by less than the amount shown in Table III shall be considered as one discrete discontinuity.
- 3.7.2.2.2 The maximum discontinuity lengths in Table III are based on the feature section thickness for which high-low limit dimensions are shown on, or can be determined from, the detail drawing. If the detail drawing indicates that a feature will be finished, but the final thickness cannot be determined from the dimensions shown on the detail drawing, the maximum discontinuity length permitted is one-half that shown in Table III with no change in number and separation requirements.
- 3.7.2.3 Combinations of Different Types of Defects in the Same Area: Discrete discontinuities permitted by Tables II and III may exist in the same area provided that all requirements of 3.7.2.1 and 3.7.2.2 are met, that the total number of discrete discontinuities is not greater than permitted by Table II, and that the minimum spacing between Table II and Table III defects is not less than permitted by Table II.
- 3.7.2.4 Background Discontinuities: Size and number of background discontinuities shall not exceed, and the spacing shall be not less than, that indicated by any of the reference charts (Fig. No. 1) specified in Table IV. The depth of background discontinuities shall be as agreed upon by purchaser and vendor.

TABLE IV

Area Grade	Standard Chart Number (See Fig. 1)	Table II Discontinuities Permissible	Table III Discontinuities Permissible	Spacing Between Table II, Table III, and Background Discontinuities
A	No Background Discontinuities Permitted	Yes	Yes	--
B	1	Yes	Yes	None Required
B	2	Yes	Yes	Per Table II
B	3	Yes	Yes	None Required
B	4	One discrete	No	None Required
C & D	4	Yes	Yes	Per Table II
C & D	5	Yes	Yes	None Required
C & D	6	Yes	Yes	Per Table II

3.7.2.5 Other Indications: Indications due to grain orientation, diffraction pattern, variations in material density, or ghost lines are permissible in all areas.

3.7.2.6 Other Discontinuities: Discontinuities which will be removed by final finishing operations are not restricted.

3.7.3 Blending: Blending of cast surfaces is permissible as specified in Table V and 3.7.3.1, 3.7.3.2, and 3.7.3.3.

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TABLE V

Area Grade	Minimum Specified Feature Thickness		Blend Depth Limit (3.7.3.1) Below Minimum Specified Thickness	
	Inch	(Millimetres)	Inch	(Millimetre)
A and B	Up to 0.100, excl	(Up to 2.50, excl)	Not below minimum specified thickness	
	0.100 and Over	(2.50 and Over)	0.005	(0.13)
C and D	Up to 0.100, excl	(Up to 2.50, excl)	0.010	(0.25)
	0.100 and Over	(2.50 and Over)	0.020	(0.50)

- 3.7.3.1 Areas blended below minimum specified thickness shall be not greater than 1 sq in. (645 mm²) in area.
- 3.7.3.2 Blended areas shall be smooth with no internal or external radius less than 1/4 in. (6 mm) except that an internal blended radius equal to the minimum internal radius specified on the drawing is permissible on the curved surface represented by that radius.
- 3.7.3.3 Blended areas shall be separated by distances equal to, or greater than, the length of the largest adjacent blended area or 1 in. (25 mm), whichever is less. Blended areas separated by less than this distance shall be considered as one blended area.
- 3.7.4 Discontinuities for which specific limits are not defined herein, such as hot tears, cracks, cold shuts, and misruns, are not acceptable. Any type of discontinuity appearing on opposite sides of a wall, and which is interconnected, is not acceptable.
- 3.7.5 When specified, castings shall be subjected to fluorescent penetrant inspection in accordance with AMS 2645. Standards for acceptance shall be as agreed upon by purchaser and vendor.
- 3.7.6 Castings shall not be repaired by peening, plugging, welding, or other methods without written permission from purchaser.
 - 3.7.6.1 When permitted in writing by purchaser, defects in castings may be removed and the castings repaired by welding provided the weld repair area has tensile properties equivalent to or greater than specified minimum tensile strength of the parent metal; other properties shall be comparable to those of the parent metal. Repair welds shall be subjected to the same inspection procedures and acceptance standards required of the castings. Weld repair areas shall be suitably marked to facilitate inspection. Repair welding shall be performed prior to any heat treatment and non-destructive testing specified herein.

4. QUALITY ASSURANCE PROVISIONS:

- 4.1 Responsibility for Inspection: The vendor of castings shall supply all samples for vendor's tests and shall be responsible for performing all required tests. Results of such tests shall be reported to the purchaser as required by 4.5. Purchaser reserves the right to sample and to perform such confirmatory testing as he deems necessary to ensure that the castings conform to the requirements of this specification.
- 4.2 Classification of Tests:

- 4.2.1 Acceptance Tests: Except as specified in 4.2.1.1, tests to determine conformance to all technical requirements of this specification are classified as acceptance tests and shall be performed to represent each lot of castings.
- 4.2.1.1 Tensile properties of specimens cut from castings shall be determined only when specified by purchaser or when representative separately-cast specimens or specimens cut from attached coupons are not available. Tensile properties of separately-cast specimens or specimens from attached coupons need not be determined when tensile properties of specimens cut from castings are determined.
- 4.2.2 Preproduction Tests: Tests to determine conformance to all technical requirements of this specification are classified as preproduction tests and shall be performed on the first-article shipment of a casting to a purchaser, when a change in material or processing requires reapproval as in 4.4.2, and when purchaser deems confirmatory testing to be required.
- 4.2.2.1 For direct U.S. Military procurement, substantiating test data and, when requested, preproduction test material shall be submitted to the cognizant agency as directed by the procuring activity, the contracting officer, or the request for procurement.
- 4.3 Sampling: Shall be in accordance with the following; a lot shall be all castings from one master heat poured at one time, annealed in one furnace load, and presented for vendor's inspection at one time:
- 4.3.1 Two chemical analysis specimens in accordance with 3.4.1 and/or a casting from each master heat except that for hydrogen determinations one sample from each lot, obtained after thermal and chemical processing is completed.
- 4.3.2 Three separately-cast tensile test specimens in accordance with 3.4.2 from each master heat except when tensile test specimens are permitted to be obtained from attached coupons as in 4.3.3.
- 4.3.3 One attached coupon when specified or permitted by purchaser, obtained from each of three castings selected at random from each lot. Coupons shall be of a size and shape and located on castings as specified on the part drawing or as agreed upon by purchaser and vendor. Specimens conforming to ASTM E8 with 0.250 in. (6.25 mm) at the reduced parallel gage section shall be machined from each coupon.
- 4.3.4 Two preproduction castings in accordance with 4.4.1 of each part number.
- 4.3.5 One or more castings from each master heat when tensile properties of specimens cut from castings are required. Specimens shall conform to ASTM E8 and shall be either 0.250 in. (6.25 mm) diameter at the reduced parallel gage section, sub-size specimens proportional to the standard, or standard sheet-type specimens. For determining conformance to the requirements of 3.6.1.2, if specimen locations are not specified on the drawing or by purchaser, not less than four tensile specimens, two from the thickest section and two from the thinnest section, shall be cut from a casting or castings from each master heat.
- 4.3.6 For determining conformance to quality requirements, sampling shall be as agreed upon by purchaser and vendor.
- 4.4 Approval:
- 4.4.1 Sample castings from new or reworked master patterns and the casting procedure shall be approved by purchaser before castings for production use are supplied, unless such approval be waived.

4.4.2 Vendor shall establish separately for tensile test specimens used for master heat qualification and for production of sample castings of each part number parameters for the control factors of processing which will produce tensile test specimens meeting master heat qualification requirements and acceptable castings; these shall constitute the approved casting procedures and shall be used for producing subsequent master heat qualification specimens and production castings. If necessary to make any change in parameters for the control factors of processing, vendor shall submit for re-approval a statement of the proposed changes in processing and, when requested, sample test specimens, castings, or both. Production castings incorporating the revised operations shall not be shipped prior to receipt of reapproval.

4.4.2.1 Control factors for producing test specimens and castings include, but are not limited to, the following:

- Size of furnace crucible
- Master heat metal source
- Furnace atmosphere and pressure
- Mold refractory formulation
- Mold back-up material
- Gating practices
- Mold preheat and pouring temperatures (variations of $\pm 25^{\circ}\text{F}$ ($\pm 15^{\circ}\text{C}$) from established limits are permissible)
- Solidification and cooling procedures
- Hot isostatic processing (HIP) cycles, if used
- Annealing heat treatment cycles
- Cleaning operations
- Weld repair of castings when permitted by purchaser
- Methods of routine inspection

4.4.2.1.1 Any of the above control factors of processing for which parameters are considered proprietary by the vendor may be assigned a code designation. Each variation in such parameters shall be assigned a modified code designation.

4.5 Reports:

4.5.1 The vendor of castings shall furnish with each shipment three copies of a report showing the results of tests for chemical composition of at least one casting, or of specimens as in 3.4.1 cast in a mold with parts, from each master heat represented and the results of tests for tensile properties of separately-cast specimens, specimens cut from attached coupons when permitted, or of specimens cut from castings representing each master heat, and the results of tests for hardness of castings from each lot, and stating that the castings conform to the quality requirements of this specification. This report shall include the purchase order number, master heat number and/or code symbol, AMS 4991, part number, and quantity from each master heat.

4.5.2 The vendor of finished or semi-finished parts shall furnish with each shipment three copies of a report showing the purchase order number, AMS 4991, contractor or other direct supplier of castings, part number, and quantity. When castings for making parts are produced or purchased by the parts vendor, that vendor shall inspect castings from each master heat represented to determine conformance to the requirements of this specification, and shall include in the report a statement that the castings conform, or shall include copies of laboratory reports showing the results of tests to determine conformance.

4.6 Resampling and Retesting: If any specimen used in the above tests fails to meet the specified requirements, disposition of the castings may be based on the results of testing three additional specimens for each original nonconforming specimen. Failure of any retest specimen to meet the specified requirements shall be cause for rejection of the master heat in the case of qualification test specimens or of the castings in that shipment in the case of tests on castings, on specimens cut from castings, or on specimens cut from attached coupons, and no additional testing shall be permitted. Results of all tests shall be reported.