Designation: A541/A541M – 05 (Reapproved 2020)

Standard Specification for Quenched and Tempered Carbon and Alloy Steel Forgings for Pressure Vessel Components[1]

This standard is issued under the fixed designation A541/A541M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This specification[2] covers requirements for quenched and tempered carbon and alloy steel forgings for pressure vessel components.

1.2 All grades are considered weldable under proper conditions. Welding technique is of fundamental importance, and it is presupposed that welding procedure and inspection will be in accordance with approved methods for the grade of material used.

NOTE 1—Grades 1 and 1A have different chemistries but the same mechanical requirements.

NOTE 2—Designations have been changed as follows:

Current	Formerly
Grade 1	Class 1
Grade 1A	Class 1A
Grade 1C	Class 4
Grade 2 Class 1	Class 2
Grade 2 Class 2	Class 2A
Grade 3 Class 1	Class 3
Grade 3 Class 2	Class 3A
Grade 4N Class 1	Class 7
Grade 4N Class 2	Class 7A
Grade 4N Class 3	Class 7B
Grade 5 Class 1	Class 8
Grade 5 Class 2	Class 8A
Grade 11 Class 4	Class 11C
Grade 22 Class 3	Class 22B
Grade 22 Class 4	Class 22C
Grade 22 Class 5	Class 22D
Grade 22V	Class 22V
Grade 3V	Class 3V

1.3 The values stated in either inch-pound units or SI (metric) units are to be regarded separately as standard. Within the text and tables, the SI units are shown in brackets. The values stated in each system are not necessarily exact equivalents; therefore, to ensure conformance with the standard, each system shall be used independently of the other, and values from the two systems shall not be combined.

1.4 Unless the order specifies the applicable "M" specification designation, the material shall be furnished to the inch-pound units.

1.5 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[3]

A275/A275M Practice for Magnetic Particle Examination of Steel Forgings

A370 Test Methods and Definitions for Mechanical Testing of Steel Products

A388/A388M Practice for Ultrasonic Examination of Steel Forgings

A788/A788M Specification for Steel Forgings, General Requirements

E208 Test Method for Conducting Drop-Weight Test to Determine Nil-Ductility Transition Temperature of Ferritic Steels

2.2 *ASME Code:*[4]

ASME Boiler and Pressure Vessel Code

3. Ordering Information and General Requirements

3.1 In addition to the ordering information required by Specification A788/A788M, the purchaser shall include with the inquiry and order a detailed drawing that locates areas of significant loading in the forging (when required); the method of selecting test locations (see 6.2); purchase option (if any) in accordance with 9.1, and any supplementary requirements desired.

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[1] This specification is under the jurisdiction of ASTM Committee A01 on Steel, Stainless Steel and Related Alloys, and is the direct responsibility of Subcommittee A01.06 on Steel Forgings and Billets.

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[2] For ASME Boiler and Pressure Vessel Code applications, see related Specification SA-541/SA-541M in Section II of that Code.

[3] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[4] Available from American Society of Mechanical Engineers (ASME), ASME International Headquarters, Two Park Ave., New York, NY 10016-5990, http://www.asme.org.

3.2 Material supplied to this specification shall conform to the requirements of Specification A788/A788M, which outlines additional ordering information, manufacturing requirements, testing and retesting methods and procedures, marking, certification, product analysis variations, and additional supplementary requirements.

3.3 If the requirements of this specification are in conflict with the requirements of Specification A788/A788M, the requirements of this specification shall prevail.

4. Chemical Composition

4.1 *Heat Analysis*—The heat analysis obtained from sampling in accordance with Specification A788/A788M shall comply with Table 1 except that the additional features of Supplementary Requirements S8, S9, S10, S12, and S15 shall also apply as individually specified in the ordering information.

4.2 *Product Analysis*—The manufacturer shall use the product analysis provision of Specification A788/A788M to obtain a product analysis from a forging representing each heat or multiple heat. The permissible variations of Table 1 of Specification A788/A788M do not apply to carbon, phosphorus, silicon, and sulphur for all classes, vanadium for Grade 1C, and columbium and calcium for Grades 22V and 3VCb. Boron is not subject to product analysis. The purchaser may also make this determination in accordance with Specification A788/A788M.

5. Heat Treatment for Mechanical Properties

5.1 After complete austenitization, the forgings shall be quenched in a suitable liquid medium by spraying or immersion. For Grade 22V forgings, the minimum austenitizing temperature shall be 1650 °F [900 °C]. Quenching shall be followed by tempering at a subcritical temperature and holding at this temperature for a minimum time of ½ h/in. [25 mm] of maximum section thickness. Minimum tempering temperatures shall be:

Grade	°F [°C]
1, 1A, 2 Class 2, 3 Class 2	1150 [620]
2, 3 Class 1, 22 Class 3	1200 [650]
1C, 11 Class 4, 22 Class 4, 4N Class 1, 4N Class 2, 5 Class 1, 5 Class 2	1100 [595]
22 Class 15	1050 [565]
4N Class 3	1125 [605]
3V, 3VCb	1250 [675]
22V	1250 [675]

5.2 For Classes 1, 1A, 2, 2A, 3, or 3A, a multiple stage austenitizing procedure may be used whereby the forging is first fully austenitized and liquid quenched, followed by reheating within the intercritical temperature range to partially reaustenitize, and again liquid quenched. On completion of the austenitizing/quenching cycles, the forgings shall be tempered at a subcritical temperature as described in 5.1.

6. Mechanical Properties

6.1 *General Requirements*—The forgings shall conform to the requirements of Table 2. The forgings shall also conform to the requirements of Table 3 unless either Supplementary Requirement S6 or S13 is specified, in which case the requirements of those sections shall apply. The largest obtainable tension test specimen as specified in Fig. 4 of Test Methods and Definitions A370 shall be used. Impact specimens shall be Charpy V-notch, as shown in Fig. 10 of Test Methods and Definitions A370. The usage of subsize impact specimens due to material limitations must have prior purchaser approval.

6.2 *Sampling*—The longitudinal axis and mid-length of tension and impact test specimens shall be positioned in accordance with one of the following methods as specified by the purchaser:

6.2.1 *Method 1*—This method shall always be used when the maximum quenched thickness does not exceed 2 in. [50 mm]. Specimens shall be located in the production forging or test forging (as described in Method 4) at mid-thickness and at least 2 in. from other quenched surfaces.

TABLE 1 Chemical Requirements Composition, %

	Grade 1	Grade 1A	Grade 2	Grade 3	Grade 1C	Grade 11 Class 4	Grade 22 Classes 4 and 5	Grade 4N	Grade 5	Grade 3V	Grade 22 Class 3	Grade 22V	Grade 3VCb
Carbon	0.35 max	0.30 max	0.27 max	0.25 max	0.18 max	0.10–0.20	0.05–0.15	0.23 max	0.23 max	0.10–0.15	0.11–0.15	0.11–0.15	0.10-0.15
Manganese	0.40–0.90	0.70–1.35	0.50–0.90	1.20–1.50	1.30 max	0.30–0.80	0.30–0.60	0.20–0.40	0.20–0.40	0.30–0.60	0.30–0.60	0.30–0.60	0.30-0.60
Phosphorus	0.025 max	0.025 max	0.025 max	0.025 max	0.025 max	0.025 max	0.025 max	0.025 max	0.025 max	0.020 max	0.015 max	0.015 max	0.020 max
Sulfur	0.025 max	0.025 max	0.025 max	0.025 max	0.025 max	0.025 max	0.025 max	0.025 max	0.025 max	0.020 max	0.015 max	0.010 max	0.010 max
Silicon[A]	0.35 max	0.40 max	0.35 max	0.35 max	0.35 max	0.50–1.00	0.50 max	0.30 max	0.30 max	0.10 max	0.50 max	0.10 max	0.10 max
Nickel	0.40 max	0.40 max	0.50–1.00	0.40–1.00	0.25 max	0.50 max	0.50 max	2.8–3.9	2.8–3.9	. . .	0.25 max	0.25 max	0.25 max
Chromium	0.25 max	0.25 max	0.25–0.45	0.25 max	0.15 max	1.00–1.50	2.00–2.50	1.25–2.00	1.25–2.00	2.8–3.3	2.00–2.50	2.00–2.50	2.7-3.3
Molybdenum	0.10 max	0.10 max	0.55–0.70	0.45–0.60	0.05 max	0.45–0.65	0.90–1.10	0.40–0.60	0.40–0.60	0.90–1.10	0.90–1.10	0.90–1.10	0.90-1.10
Vanadium	0.05 max	0.05 max	0.05 max	0.05 max	0.02–0.12	0.05 max	0.05 max	0.03 max	0.08 max	0.20–0.30	0.02 max	0.25–0.35	0.20-0.30
Titanium	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	0.015–0.035	. . .	0.030 max	0.015 max
Boron	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	0.001–0.003	. . .	0.0020 max	. . .
Copper	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	0.20 max	0.25 max
Columbium	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	0.07 max	0.015-0.070
Calcium	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	0.015 max[B]	0.0005-0.0150

[A] When vacuum carbon-deoxidation is required for the classes included in Supplementary Requirement S10, the silicon content shall be 0.10 % max.
[B] For Grade 22V, rare earth metals (REM) may be added in place of calcium, subject to agreement between the producer and the purchaser. In that case the total amount of REM shall be determined and reported.

TABLE 2 Tensile Requirements

	Grade 1 and 1A	Grades 2 Class 1, 3 Class 1, 1C and 11 Class 4	Grade 2 Class 2 and Grade 3 Class 2	Grade 22 Class 4	Grade 22 Class 5	Grade 4N Class 1 and Grade 5 Class 1	Grades 4N Class 2 and 5 Class 2	Grade 4N Class 3	Grades 3V and 22V	Grade 22 Class 3	Grade 3VCb
Tensile strength, ksi [MPa]	70–95 [485–655]	80–105 [550–725]	90–115 [620–795]	105–130 [725–895]	115–140 [795–965]	105–130 [725–895]	115–140 [795–965]	90–115 [620–795]	85–110 [585–760]	85–110 [585–760]	85–110 [585-760]
Yield strength (0.2 % offset), min, ksi [MPa]	36 [250]	50 [345]	65 [450]	85 [585]	100 [690]	85 [585]	100 [690]	70 [485]	60 [415]	55 [380]	60 [415]
Elongation in 2 in. or 50 mm, min, %	20	18	16	16	15	18	16	20	18	18	18
Reduction of area, min, %	38	38	35	45	40	48	45	48	45	45	45

TABLE 3 Charpy V-Notch Impact Requirements at 40 °F (4 °C) (Except for 2A)[A, B]

	Grades 1, 1A, and 11 Class 4	Grade 2 Class 2 and 3 Class 2	Grade 2 Class 1, 3 Class 1 and 1C	Grade 22 Class 5	Grades 22 CL 4 4N Classes 1, 2, 3 5 Classes 1, 2	Grades 3V and 3VCb, Grade 22, Class 3 and Grade 22V
Minimum average value of set of three specimens, ft·lbf (J)[C]	15 [20]	35 [47][D]	30 [41]	25 [34]	35 [47]	40 [54][E]
Minimum value of one specimen, ft·lbf (J)	10 [14]	30 [41][D]	25 [34]	20 [27]	30 [41]	35 [47][E]

[A] These Charpy values are for tests made on standard 10 mm square specimens. If sub-size impact specimens are used, the required minimum ft·lbf values shall be determined by multiplying the ft·lbf values in Table 3 by 5/6 for 7.5 mm by 10 mm specimens, and by 2/3 for 5 mm by 10 mm specimens.
[B] These values apply for tests at lower temperatures if Supplementary Requirement S6 is specified in the order.
[C] Not more than one specimen from a set may be below this value.
[D] Tested at 70 °F [21 °C].
[E] Tested at 0 °F [–18 °C].

6.2.2 *Method 2—t* by 2*t*, where *t* is the distance from the area of significant loading (see 3.1) to the nearest quenched surface. However, the specimens shall not be nearer to one quenched surface than ¾ in. [20 mm] and to the second quenched surface than 1½ in. [40 mm]. When this method of testing is employed, forgings are usually manufactured in accordance with a purchaser-approved drawing showing pre-quenched dimensions and the location of mechanical test specimens.

6.2.3 *Method 3—¼ T* by *T*, where *T* is the maximum thickness of the forging as heat treated. Where this method of testing is employed, the following limitations for as-treated thickness shall apply, unless otherwise agreed upon:

Grade	in. [1 mm], max
1 and 1A	3 [75]
2 Class 2 and 3 Class 2	6 [150]
2 Class 1 and 3 Class 1	8 [200]
1C	4 [100]
11 Class 4	5 [125]
22 Class 4, 4N Class 2, 5 Class 2	6 [150]
22 Class 5	8 [200]
4N Class 1, 5 Class 1, 4N Class 3, 3V, 3VCb, 22V, and 22 Class 3	10 [250]

6.2.4 *Method 4*—Test specimens shall be taken from a representative separate test forging or bar made from the same heat of steel, which shall receive substantially the same reduction and type of hot working as the production forgings that it represents, except that a longitudinally forged bar may be used to represent a rolled ring of similar cross section. It shall be of the same nominal thickness as the as-quenched production forgings and shall be heat treated in the same furnace charge and under the same conditions as the production forgings. Test specimens shall be removed using the ¼ *T* by *T* procedure referenced in Method 3 with the same limitation on forging thickness as in 6.2.3. This method shall be limited to forgings with a rough machined weight of not more than 1000 lb [450 kg].

6.3 *Metal Buffers*—The required distances from quenched surfaces may be obtained with metal buffers instead of integral extensions. Buffer material may be carbon or low-alloy steel, and shall be joined to the forging with a partial penetration weld that seals the buffered surface. Specimens shall be located at least ½ in. [13 mm] from the buffered surface of the forging. Buffers shall be removed and the welded areas subjected to magnetic particle test to ensure freedom from cracks unless the welded areas are completely removed by subsequent machining.

6.4 Samples shall be removed from forgings after the quenching and tempering heat treatments. This sample material shall be subjected to a simulated post-weld heat treatment if Supplementary Requirement S1 is specified.

6.5 *Orientation*—For upset disk forgings, the longitudinal axis of all test specimens shall be oriented in the tangential direction. For all other forgings, the longitudinal axis of the specimens shall be oriented in the direction of maximum working of the forging unless Supplementary Requirements S11 or S14 are imposed.

6.6 *Number of Tests:*

6.6.1 *Forgings under 500 lb [230 kg] As Treated*—For duplicate forgings weighing less than 500 lb [230 kg] as treated, one tension test and one impact test (three specimens) shall be made to represent each heat in each heat-treatment charge. When heat treatment is performed in continuous-type

furnaces with suitable temperature control and equipped with recording pyrometers so that complete heat-treatment records are available, a heat-treatment charge shall be considered as any continuous run not exceeding an 8-h duration.

6.6.2 *Forgings Weighing 500 to 10 000 lb [230 to 4500 kg] As-Heat Treated*—One tension and one impact test (3 specimens) shall be made for each forging.

6.6.3 Each forging weighing over 10 000 lb [4500 kg] shall require two tension tests and two impact tests, located at opposite ends if the length is 1½ times the diameter or more, or 180° apart otherwise.

7. Repair Welding

7.1 Repair welding of forgings may be permitted, but only at the option of the purchaser.

7.2 If repair welding is performed, welders and weld procedures shall be qualified in accordance with Section IX of the ASME Boiler and Pressure Vessel Code.

8. Workmanship and Quality Level Requirements

8.1 Dimensional and visual inspections shall be conducted by the manufacturer. Forgings shall be free of cracks, thermal ruptures, or other imperfections.

9. Certification and Reports

9.1 In addition to items required to be reported by Specification A788/A788M, the following items shall also be reported:

9.1.1 Product chemical analysis.

9.1.2 The method used for locating test specimens.

9.1.3 Sketches included in the report of non-destructive examinations.

9.1.4 Details of the heat treatment cycle, as listed in Specification A788/A788M.

10. Product Marking

10.1 The purchaser may specify additional identification marking and the location of the marking. If stamps are used, they shall be round-nosed or "interrupted-dot" die stamps having a minimum radius of 1/32 in. [0.8 mm].

11. Keywords

11.1 chromium-molybdenum steel; nickel-chromium-molybdenum alloy steel; pressure vessel service; quenched and tempered steel; steel forgings—alloy; steel forgings—carbon

SUPPLEMENTARY REQUIREMENTS

One or more of the following supplementary requirements shall apply only when specified by the purchaser in the inquiry or order. Details of these supplementary requirements shall be agreed upon by the manufacturer and the purchaser.

S1. Simulated Post-Weld Heat Treatment of Mechanical Test Samples

S1.1 All test coupons shall be subjected to single or multiple heat treatments at subcritical temperatures prior to testing. Such treatments are intended to simulate post-weld or other treatments to which the forgings will be subjected during subsequent fabrication. The purchaser shall furnish the manufacturer with details of the desired heat treatment for the test coupons, including temperatures, times, and cooling rates.

S2. Ultrasonic Inspection

S2.1 Forgings shall be ultrasonically examined in accordance with the procedures of Practice A388/A388M.

S2.1.1 *Longitudinal Wave Test:*

S2.1.1.1 Unless otherwise specified, the back reflection method of tuning shall be used in accordance with the Procedure Section (the paragraph regarding Back–Reflection Technique) of Practice A388/A388M.

S2.1.1.2 In addition to the reportable conditions of the Recording Section of Practice A388/A388M, indications exceeding the resultant back reflection shall be recorded.

S2.1.1.3 The following conditions are subject to rejection:

Complete loss of back reflection accompanied by an indication of a discontinuity. For this purpose, a back reflection less than 5 % of full screen height shall be considered complete loss of back reflection.

An indication equal in amplitude to that of the back reflection established in an indication-free portion of the forging.

S2.1.2 *Angle Beam Test:*

S2.1.2.1 Calibration notches, calibration reference, and method of scanning shall be in accordance with the Procedure Section (the paragraph regarding Angle–Beam Examination) of Practice A388/A388M.

S2.1.2.2 A forging that contains a discontinuity that results in an indication exceeding the amplitude of the reference line is subject to rejection.

S2.1.3 The report of the ultrasonic examination shall be in compliance with the Report Section of Practice A388/A388M.

S2.1.4 Additional nondestructive examination or trepanning may be employed to resolve questions of interpretation of ultrasonic indications. The manufacturer shall accept responsibility for injurious conditions that will not be removed in final machining.

S3. Magnetic Particle Examination

S3.1 Each forging shall be inspected by magnetic particle methods described in Practice A275/A275M. Acceptance and rejection standards shall be mutually agreed upon by the purchaser and manufacturer.

S4. Charpy V-Notch Impact Transition Curve

S4.1 Sufficient impact tests shall be made from the forging test material to establish a temperature-absorbed energy curve. The test temperature range shall be wide enough to establish the upper and lower shelf foot pound energies, with sufficient testing at intermediate temperatures to permit plotting a reasonably smooth curve.

S5. Additional Charpy Data

S5.1 The percent shear fracture and mils or millimetres of lateral expansion, defined in Test Methods and Definitions A370, shall be reported for each Charpy specimen tested.

S6. Charpy Impact Tests

S6.1 Charpy impact tests shall be made in accordance with the provisions of Section 6 of this specification except that the test temperature shall be lower than that specified in Table 3.

S7. Drop-Weight Test

S7.1 Drop-weight tests shall be conducted in accordance with the requirements of Test Method E208. The fracture plane of the specimens shall coincide with the location required for other mechanical test specimens as specified by the purchaser in accordance with 6.2. However, since the drop-weight specimen can be taken in any orientation, the fracture plane of the specimen when tested to Method 2 (6.2.2) shall be a minimum distance of 7⁄16 in. [11 mm] from the nearest quenched surface, and 1½ in. [40 mm] from any second surface. The purchaser may specify either duplicate no-break performance when tested 10° warmer than a specified temperature or request a determination of the nil-ductility temperature.

S8. Restrictive Chemistry for Grades 4N and 5

S8.1 Phosphorus and sulfur limits for Grades 4N and 5 may be specified 0.020 %, max.

S9. Additional Vanadium

S9.1 For Grade 5 forgings, 0.05 to 0.15 % vanadium may be specified.

S10. Special Steels

S10.1 Vacuum treated steel shall be specified.

S10.2 When Grades 2, 3, 4N, and 5 are vacuum carbon deoxidized, the silicon content shall be 0.10 % maximum.

S10.3 The test report shall indicate that the steel was vacuum carbon deoxidized.

S11. Rings and Hollow Cylindrically Shaped Parts

S11.1 Tests shall be removed in the tangential (circumferential) direction regardless of direction of maximum working.

S12. Restrictive Chemistry

S12.1 The following restricted phosphorus and copper limits may be specified as follows:

P 0.012 % max heat, 0.015 % max product; Cu 0.10 % max
P 0.015 % max heat, 0.018 % max product; Cu 0.15 % max

S13. Alternative Fracture Toughness Requirements

S13.1 The fracture toughness requirements (drop-weight or Charpy impact tests, or both) for materials of the ASME Boiler and Pressure Vessel Code, Section III, Article NB2300, NC2300, ND2300, NE2300, NF2300 or NG2300, as specified, shall be used instead of the Charpy impact test requirements of this specification.

S14. Alternative Test Specimen Orientation

S14.1 The longitudinal axis of all test specimens shall be oriented in a direction transverse to the direction of maximum working of the forging.

S15. Restricted Sulfur Content

S15.1 The sulfur content shall be limited to 0.015 % maximum heat and 0.018 % maximum product.