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Aluminum and Aluminum Alloys for Passenger Equipment Carbody Construction

Abstract: This standard provides a guide for the selection of appropriate aluminum alloys used in the fabrication of passenger railroad carbody structures and equipment. In addition to basic information on the grades of aluminum alloys and their designations, this standard also includes precautions for selecting, welding and handling the aluminum alloys.

Keywords: aluminum, aluminum alloys, railcar construction

Summary: This standard covers heat-treatable and work-hardenable aluminum alloys in sheet, plate, extrusion, forging, casting and bar form for use in mechanically or weld-assembled structural elements of passenger rail vehicles. Of the 150 or more alloys recognized by the Aluminum Association, some are more suitable for specific applications than others. Alloys to be avoided for specific applications are listed. The end user should ascertain the commercial availability of the proposed alloys in their specific commodity format. The fact that an alloy is registered does not necessarily guarantee its availability. Aluminum products and test methods may be fully described in traditional English units or in SI units, in ASTM, EN, JIS and Aluminum Association standards and data documentation.

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Scope

This standard applies to aluminum and aluminum alloys used in passenger equipment and carbody construction and was developed to help ensure the quality of aluminum and aluminum alloys used in the fabrication of passenger equipment carbodies.

This standard is limited to the application of aluminum alloys for construction of passenger rail equipment carbodies. This standard makes specific recommendations for alloys that are suitable for this application and provides specific cautions against the use of unsuitable alloys.

This standard is based on conservative industry practices and reference other industry/trade association standards that are currently valid.

Standards from other jurisdictions—i.e., EN, JIS—are deemed acceptable; however, these alloys should be used in conjunction with their respective design standards—i.e., no mixing between different national standards. Also, availability of alloys and/or replacement alloys that can be procured in North America, especially for repairs, should be a consideration.

In case of conflict between this standard and a referenced specification, the more stringent requirement shall prevail, including any national standards that may apply.

Introduction

This introduction is not part of APTA PR-CS-S-015-99, Rev. 2, "Aluminum and Aluminum Alloys for Passenger Equipment Carbody Construction."

This standard applies to all:

1. Railroads that operate intercity or commuter passenger train service on the general railroad system of transportation; and
2. Railroads that provide commuter or other short-haul rail passenger train service in a metropolitan or suburban area, including public authorities operating passenger train service.

This standard does not apply to:

1. Rapid transit operations in an urban area that are not connected to the general railroad system of transportation;
2. Tourist, scenic, historic, or excursion operations, whether on or off the general railroad system of transportation;
3. Operation of private cars, including business/office cars and circus trains; or
4. Railroads that operate only on track inside an installation that is not part of the general railroad system of transportation.

Aluminum and Aluminum Alloys for Passenger Equipment Carbody Construction

1. Alloy specifications

1.1 Standards for purchasing raw material

The chemical and physical properties of recognized alloys are listed in the ASTM, EN and JIS standards, and the Aluminum Association publications cited in the references section at the end of this document. Use of the ASTM standards is preferred for ordering raw material in mill run quantities, because these standards include information that facilitates procurement in North America. Examples are guides to product marking quality control, testing, source inspection and certification, and guides for rejection and retesting.

The relevant standards are listed below.

1.1.1 ASTM standards

ASTM B209/B209M, “Specification for Aluminum and Aluminum-Alloy Sheet and Plate”
ASTM B211/B211M, “Specification for Aluminum-Alloy Bars, Rod and Wire”
ASTM B221/B221M, “Specification for Aluminum-Alloy, Extruded Bars, Rods, Wires, Shapes and Tubes”
ASTM B26, “Specification for Aluminum-Alloy Sand Castings”
ASTM B308, “Standard Specification for Aluminum-Alloy 6061-T6 Standard Structural Profiles”

1.1.2 EN standards

EN 485-2, “Aluminium and aluminium alloys - Sheet strip and plate”
EN 755-2, “Aluminium and aluminium alloys - Extruded rod/bar, tube and profiles”
EN 1999-1-3, “Eurocode 9: Design of aluminum structures”
EN 13981-1, “Aluminium and aluminium alloys - Products for structural railway applications”
Technical conditions for inspection and delivery - Part 1 Extruded products
EN 13981-2, “Aluminium and aluminium alloys —Products for structural railway applications”
Technical conditions for inspection and delivery - Part 2: Plates and sheets
EN 15085-3, “Railway Application – Welding of railway vehicles and components”
Part 3: Design requirements
EN 17149-1, “Railway Applications – Strength assessment of railway vehicle structures”
Part 1: General
EN 17149-3, “Railway Applications – Strength assessment of railway vehicle structures”
Part 3: Fatigue strength assessment based on cumulative damage
EN ISO 25239-2 “Friction Stir Welding – Aluminium Part 2: Design of weld joints”

1.1.3 JIS standards

JIS H 4000, "Aluminium and aluminium alloy sheets, strips and plates"
JIS H 4040, "Aluminium and aluminium alloy bars and wires"
JIS H 4080, "Aluminium and aluminium alloy extruded tubes and cold-drawn tubes"
JIS H 4100, "Aluminium and aluminium alloy extruded profiles"
JIS H 5202, "Aluminium alloy castings"
JIS H 5302, "Aluminium alloy die castings"

1.2 Alloy designations

The basic wrought commercial alloys are defined by ANSI H35.1 with a four-digit designation in which the first digit indicates the principal alloy components. Cast alloys have a similar three-digit designation. See **Table 1**.

TABLE 1
Aluminum Association Numerical Designations for Wrought and Cast Alloys

Principal Alloy Materials	Wrought Alloys	Cast Alloys
Aluminum, essentially pure	1xxx	
Copper	2xxx	2xx.x
Manganese	3xxx	
Silicon	4xxx	3xx.x, 4xx.x
Magnesium	5xxx	5xx.x
Silicon/manganese	6xxx	
Zinc	7xxx	7xx.x

The mechanical properties of the aluminum alloys are further defined by a letter/number suffix designating the temper of the alloy. Complete details of this system are contained in ANSI H35.1, "Alloy and Temper Designation Systems for Aluminum." The basic classifications are listed in **Table 2**.

TABLE 2
Basic ANSI Classifications for Treated Aluminum[1]

Designation	Type of Treatment
F	As fabricated
O	Annealed
H	Strain-hardened/cold-worked
W	Solution heat-treated
T	Heat-treated to tempers other than F, O or H

1. From ANSI H35.1, "Alloy and Temper Designation Systems for Aluminum"

All the designations other than "F" may or must be followed by one or more numbers that give additional information about the specific treatments.

The temper designation is an integral part of the ordering information for all aluminum alloys.

2. Mechanical data/applications

2.1 Recommended alloys

1xxx is too soft for structural applications.

2xxx is susceptible to corrosion in saline environments. It is not recommended for use in the railcar transportation industry.

3xxx is suitable for secondary structure, e.g., roof skins.

4xxx is used for welding electrodes and in architectural anodizing applications.

5xxx is the most versatile alloy for sheet and plate. These 5000 series alloys are available in different amounts of cold-work hardening, as denoted by the suffix "H" temper. Cold working increases the strength but the trade-off is a reduction in ductility. The alloys in this series lose proportionally the least amount of strength in the welded condition. This series is difficult to extrude and generally is not available in the extruded form.

6xxx is a heat treatable alloy series available in a number of ranges of mechanical strengths. The two basic tempers are the T4 (naturally aged) and T6 (artificially aged) tempers. 6xxx alloys are available in nearly every commodity, including extrusions. 6061-T6 products outsell all other alloys combined. It has good corrosion resistance and can be easily welded, albeit with a considerable decrease in strength. This loss of strength can be recovered by re–heat treating, on smaller parts.

The 7xxx series are generally considered to be aircraft alloys. They are substantially more expensive than 6000 group alloys; however, the 7xxx alloys can be heat treated to the highest strength of all the aluminum alloys. Due to its higher costs, some alloys susceptible to stress corrosion cracking (SCC), and lack of weldability, the use of 7xxx series is typically limited in railway structures.

Alloys used for castings are typically the 2xx, 3xx and 4xx series. The 2xx aluminum-copper alloys have the highest strength, but often poor corrosion resistance. The 3xx aluminum-silicon-magnesium (i.e., A356.0, 357.0, 360.0) and 4xx aluminum-silicon (i.e., 413.0) alloys are also structural and have the best corrosion resistance.

2.2 Static design

The allowable stress for static design shall be either per:

- AWS D1.2/D1.2M, "Structural Welding Code – Aluminum", or
- EN 1999-1-1, "Eurocode 9: Design of aluminum structures – General Structural Rules", or
- DVS 1608, "Design and strength assessment of welded structures from aluminium alloys in railway applications."

Mechanical properties for cast products shall be agreed upon between purchaser and supplier.

2.3 Fatigue design

The allowable stress for fatigue design shall be either per:

- AWS D1.2, "Structural Welding Code – Aluminum," which refers to American Welding Society and Aluminum Design Manual; or
- EN 1999-1-3, "Eurocode 9: Design of aluminum structures - Part 1-3: Structures susceptible to fatigue.", or
- DVS 1608, "Design and strength assessment of welded structures from aluminium alloys in railway applications."

Other standards are acceptable as agreed upon between purchaser and supplier.

2.4 Extrusion seams

Extrusion seams are present in the hollow extruded product (closed section). They are formed in the dies, when the aluminum billet is split into separate flows by the legs supporting the mandrel, and are rejoined in the welding chambers. Extrusion seams are formed along the entire extruded length, and they are part of the hollow extrusions.

The mechanical properties of the extrusion seams shall be uniform and close to those of the parent metal. Extrusion seams shall be metallurgically sound and free from metal separations or nonmetallic inclusions, which can affect the required mechanical properties. The extrusion seams shall be tested using methods such as metallographic tests, transverse tensile tests, deformation tests such as bend tests, drift expansion tests, resonance tests or ultrasonic tests. If a transverse tensile test is performed, the minimum values shall be agreed between supplier and purchaser. However, the elongation shall exceed 4% for all thicknesses, alloys and tempers.

2.5 Charge welds

The charge welds are formed in the extruded product, at the transition between two consecutively extruded billets, at the billet change. The mechanical properties in the transition length are inferior in comparison with the remainder of the extruded length. The charge weld formed by the billet changes is not permitted within one cut length of the extruded product. The transition zone between two consecutively extruded billets shall be discarded.

2.6 Material strength and FEA modeling considerations

2.6.1 Rate dependence

For loading rates spanning static to crash applications, aluminum alloys do not have strong strain rate sensitivity like some steels do.

5xxx series generally have a negative rate sensitivity for low to moderate rates (10^{-3} to 10^{2} s^{-1}) and positive sensitivity for higher rates (10^{3} and above).

6xxx series alloys do not exhibit significant rate dependence.

7xxx series alloys have a moderately increasing strength amplification from about 101 s-1.

Also, there is no significant forming direction dependence for rate sensitivity. Given its small or negligible influence on alloy strength, strain rate effects can be neglected for railcar structural analysis applications.

2.6.2 Other considerations

- Heat-affected zone: extent of effect, allowable properties, for regions away from welds and adjacent to welds.
- Anisotropy of formed shapes.
- For static/elastic strength analysis, models should be based on minimum acceptable properties for the alloys. For crashworthiness analysis that considers material plasticity, true stress-true strain curves derived from material tests should be implemented and based on nominal alloy properties. (see references)

3. Product tolerances

Physical tolerances for extruded product shall be per:

- ANSI H35.2, "Standard Dimensional Tolerance for Aluminum Mill Products";
- EN 755-9, "Aluminium and aluminium alloys — Extruded rod/bar, tube and profiles - Part 9: Profiles, tolerances on dimensions and form"; or
- JIS tolerances specified within each standard (see Section 1.1.3)

4. Procurement specifications

The purchaser may specify the applicability of any of the relevant portions of the ASTM, EN or JIS specifications that are cited in Section 1 of this document.

Consideration should be placed on the procurement of selected alloys within North America, or alternative alloys that can be used for repairs.

5. Welding

5.1 Arc welding, resistance welding

Welding processes, weld and welder qualification, quality assurance and inspection, and workmanship practices shall be per:

- AWS D1.2, "Structural Welding Code, Aluminum"; and/or
- AWS D15.1, "Railroad Welding Specification – Cars and Locomotives"; or
- EN 15085, "Railway applications – Welding of railway vehicles and components."

5.2 Friction stir welding

Friction stir welding is authorized in the railroad application and shall be per either:

- AWS D17.3, "Specification for Friction Stir Welding of Aluminum Alloys for Aerospace Application"; or
- ISO 25239, "Friction Stir Welding – Aluminum."

The mechanical properties of the friction stir welding joint shall be agreed between supplier and purchaser before placing the order.

5.3 Adhesive bonding

Bonding to other materials—i.e., steel and composites—is a function of the adhesive material, often polyurethanes. Preparation and application of adhesives is critical to obtain full mechanical properties.

Structural bonding to aluminum alloys shall be demonstrated through mechanical testing with static and fatigue properties defined.

5.4 Mechanical connections

All the recommended aluminum alloys can be joined by rivets or bolts, typically on 6061-T6 or 6053-T61 alloy.

If steel rivets or bolts are used, see the recommendations in Section 6.

Design guidelines for mechanical connections shall be per:

Aluminum Association, "Aluminum Design Manual", or
EN 1999-1-1, "Eurocode 9: Design of aluminum structures – General Structural Rules"

NOTE: Rivets should be driven cold if possible, to avoid coarsening of the grain structure with hot rivets.

6. Corrosion prevention

6.1 Atmospheric corrosion

Aluminum alloys, particularly the 5xxx and 6xx series, have good resistance to atmospheric corrosion. However, corrosion can occur in locations where standing water can accumulate, particularly at crevices. Standing water can be minimized using surface gradients and drainage holes, sealing crevices, and ensuring adequate ventilation.

If agreed to between the purchaser and carbuilder, surfaces shall be protected from corrosion using wax-based or epoxy coatings. Aluminum surfaces shall then be treated with a self-etching primer prior to coating, such as zinc phosphate. Panel edges should have a chamfer or radius to prevent edge failure. Coatings on exterior surfaces should be resistant to environmental conditions such as UV radiation, ozone and salt fog.

Aluminum surfaces should not be exposed to harsh chemicals during service (chemical transport) or cleaning to avoid staining and pitting corrosion. In particular, contact should be avoided with strongly alkaline solutions such as lye (sodium hydroxide).

6.2 Galvanic corrosion

Galvanic corrosion occurs when metals of different electrode potentials are in electrical contact. Aluminum has an anodic potential compared with carbon steel, and these materials must be electrically isolated when in contact. Galvanic corrosion is an issue that shall be addressed on the exterior and interior of the car, due to varying climatic conditions.

Examples of satisfactory electrical isolation techniques include the following:

- solid materials such as mica paper or elastomeric sheets
- sealant beads or tape such as butyl rubber
- thick epoxy coatings

Aluminum fasteners are preferred for joining aluminum sheets, but if agreed to with the purchaser and builder, coated (e.g., galvanized, dipped in sealant) steel fasteners can also be used. Fasteners used to connect aluminum and steel must be electrically isolated by coating or sheathing to avoid galvanic corrosion.

Galvanic corrosion can be especially problematic when dissimilar metal surfaces are wetted with conductive liquids such as salts. Car bodies that are designed for marine environments should be given special attention regarding electrical isolation of steel and aluminum, and exposed parts should be regularly washed to avoid build-up of salts.

6.3 Stress corrosion cracking

SCC occurs in a susceptible microstructure under tensile loading exposed to a corrosive environment.

6000 series aluminum alloys have good resistance to SCC.

Some higher strength (strain-hardened) 5000 series alloys and 7000 series alloys can be susceptible to SCC in high concentrations of sodium chloride (NaCl). If these alloys are to be used in railcar construction, the design should shield them from chloride exposure, such as marine environments.

7. Finishes

Coatings may be applied for corrosion prevention and/or appearance.

Application of coatings shall be formulated for use on aluminum and shall be applied as per the coating's supplier instructions, including surface preparation and environmental conditions during application.

Sound-deadening materials shall be compatible for use with aluminum and noncorroding.

Aluminum can also be exposed, typically with a brush or satin finish using abrasive belts, flap and nylon wheels. Care shall be taken to not introduce any ferritic particles into the surface, which could cause local corrosion and/or staining.

8. References

References including supplementary references to other topics relating to aluminum design and construction:

Aluminum Association
    "Aluminum Design Manual"
    "Aluminum Standards and Data"

Alcoa, Technical Report No. 524,"Specifications covering use of aluminum in passenger carrying railway vehicles."

American National Standards Institute (ANSI)
    H35.1, "Alloy and Temper Designation Systems for Aluminum"
    H35.2, "Standard Dimensional Tolerance for Aluminum Mill Products"

American Society of Civil Engineers (ASCE)
    "Suggested Specification for Structures of Aluminum Alloys 6061T6 and 6062T6"

American Society for Testing and Materials (ASTM)
    ASTM B209/B209M, "Specification for Aluminum and Aluminum-Alloy Sheet and Plate"
    ASTM B211/B211M, "Specification for Aluminum-Alloy Bars, Rod and Wire"
    ASTM B221/B221M, "Specification for Aluminum-Alloy, Extruded Bars, Rods, Wires, Shapes and Tubes"

ASTM B26, “Specification for Aluminum-Alloy Sand Castings”
ASTM B308, “Standard Specification for Aluminum-Alloy 6061-T6 Standard Structural Profiles”

American Welding Society (AWS)
AWS D1.2/D1.2M, “Structural Welding Code – Aluminum”
AWS D15.1, “Railroad Welding Specification – Cars and Locomotives”
AWS D17.3, “Specification for Friction Stir Welding of Aluminum Alloys for Aerospace Application”

Deutscher Verband Für Schweissen (DVS)
DVS 1608, “Design and strength assessment of welded structures from aluminium alloys in railway applications.”

Europäische Norm Standards (EN)
EN 485-2, “Aluminium and aluminium alloys - Sheet strip and plate”
EN 755-2, “Aluminium and aluminium alloys - Extruded rod/bar, tube and profiles”
EN 755-9, “Aluminium and aluminium alloys — Extruded rod/bar, tube and profiles - Part 9: Profiles, tolerances on dimensions and form”
EN 1999-1-1, “Eurocode 9: Design of aluminum structures – General Structural Rules”
EN 1999-1-3, “Eurocode 9: Design of aluminum structures - Structures susceptible to fatigue.”
EN 13981-1, “Aluminium and aluminium alloys - Products for structural railway applications” - Technical conditions for inspection and delivery - Part 1 Extruded products
EN 13981-2, “Aluminium and aluminium alloys —Products for structural railway applications” - Technical conditions for inspection and delivery - Part 2: Plates and sheets
EN 15085-3, “Railway Application – Welding of railway vehicles and components” Part 3: Design requirements
EN 17149-1, “Railway Applications – Strength assessment of railway vehicle structures” Part 1: General
EN 17149-3, “Railway Applications – Strength assessment of railway vehicle structures”
Part 3: Fatigue strength assessment based on cumulative damage
EN ISO 25239-2 “Friction Stir Welding – Aluminium Part 2: Design of weld joints”

International Standards Organization (ISO)
ISO 25239, “Friction Stir Welding – Aluminum.”

Japanese Industrial Standards
JIS H 4000, “Aluminium and aluminium alloy sheets, strips and plates”
JIS H 4040, “Aluminium and aluminium alloy bars and wires”
JIS H 4080, “Aluminium and aluminium alloy extruded tubes and cold-drawn tubes”
JIS H 4100, “Aluminium and aluminium alloy extruded profiles”
JIS H 5202, “Aluminium alloy castings”
JIS H 5302, “Aluminium alloy die castings”

References related to Section 2.6 of this document:

Higashi, K., et al, “Strain Rate Dependence on Mechanical Properties in Some Commercial Aluminum Alloys,” Journal de Physique IV Colloque 01 (1991) pg. C3-341-C3-346.

Chen, Y., et al, "Stress-Strain Behaviour of Aluminum Alloys at a Wide Range of Strain Rates," International Journal of Solids and Structures 46 (2009) pg. 3825-3835.

References for Section 2.6.2 regarding true stress-strain curves

McClintock and Argon, Mechanical Behaviour of Materials, Addison-Wesley ISSN 0515-3972

Zhang et al, International Journal of Solids and Struct. 36 (1999) pp 3497-3516

ASM Metals Handbook, Volume 08, Mechanical Testing and Evaluation

Abbreviations and acronyms

ANSI American National Standards Institute
ASTM ASTM International (formerly American Society for Testing and Materials)
EN Europäische Norm (European Norm)
FEA finite element analysis
JIS Japanese Industrial Standards
NaCl sodium chloride
NATSA North American Transportation Services Association
SCC stress corrosion cracking

Summary of document changes

- Summary: Added EN, JIS to third paragraph
- Working group: Updated list of contributors
- Scope (incorporated previous Scope and Introduction): Updated text to include EN, JIS standards
- Section 1.1.1: Added metric suffix, full titles to standards
- Added new sections 1.1.2 and 1.1.3
- Created new Section 2.1 from previous Section 2
- Section 2.1: Added casting alloys (last paragraph)
- Added sections 2.2 through 2.6
- Section 3: Added EN and JIS references
- Section 4: Added paragraph 2
- Rewrote Section 5 and added sections 5.1 through 5.4
- Added new Section 6 and sections 6.1 through 6.3
- Added new Section 7, "Finishes"

Document history

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