

ALUMINIUM CAST-HOUSE TECHNOLOGIES, PRACTICES AND QUALITY ASSURANCE FOR AEROSPACE APPLICATIONS

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ABSTRACT

Aerospace-grade aluminium billets demand the highest standards of chemical homogeneity, low hydrogen, minimal non-metallic inclusions, and full metallurgical traceability – far stricter than commodity products. The cast-house (melting furnace, melt treatment, casting bay, homogenisation, and post-cast inspection) is the decisive stage at which these are either met or irreversibly compromised. This article systematically examines key technologies, operating practices, and QA frameworks in modern aerospace aluminium cast-houses, covering: melting (furnace selection, atmosphere control, contamination prevention); melt treatment (rotary/in-line degassing, Al-Ti-B grain refinement, multi-stage CFF) against H₂ and inclusion targets; DC casting (solidification control and as-cast microstructure); homogenisation regimes for 2xxx, 6xxx, and 7xxx alloys with microstructural outcomes; and comprehensive QA (melt sampling, PoDFA, ultrasonic inspection, and certification to AS9100D, AMS 2770, AMS 2630, ASTM E2375).

KEYWORD

Aluminium cast-house, aerospace alloys, DC casting, degassing, grain refinement, melt quality, PoDFA, AS9100, AMS 2770, quality assurance

INTRODUCTION

The commercial aviation industry consumed ~5.8 million metric tonnes of aluminium alloys in 2023, the second-largest end-use segment (Kaufman, 2004). Structural components (wing spars, fuselage frames, bulkheads, landing-gear forgings) require strong, light, and demonstrably defect-free material with fully auditable quality records. This positions the cast-house at the centre of the aerospace supply chain, since all downstream properties depend on ingot quality (Kumar et al., 2022).

Key aerospace alloy families are 2xxx (Al-Cu), 6xxx (Al-Mg-Si), and 7xxx (Al-Zn-Mg-Cu). The 7xxx series (e.g., AA7050, AA7150, AA7075) is the most demanding due to its high solute content, wide solidification range, and extreme sensitivity to hydrogen porosity sensitivity (Li et al., 2023). The 2xxx series (e.g., AA2024, AA2219) requires tight control of impurities (Fe, Si, Bi, Pb) that form detrimental low-melting eutectics, reducing fracture toughness. The 6xxx series requires precise Mg/Si ratio control for extrudability and corrosion resistance. Aerospace cast-houses differ from commodity ones in three respects: (i) much tighter elemental purity and composition control; (ii) dissolved hydrogen and non-metallic inclusions one to two orders of magnitude lower; (iii) complete documentation, traceability, and auditability under AS9100D (Granillo-Macías et al., 2020). These drive specialised furnaces, multi-stage melt treatment, real-time instrumentation, and 100% ultrasonic inspection.

Although individual steps are covered in the literature, no recent integrated review of the full aerospace cast-house exists. This article addresses the gap by systematically covering every stage—from charge preparation to certified dispatch—with governing standards and quality targets (Jensdóttir, 2009). The process flow is shown in Figure 1.

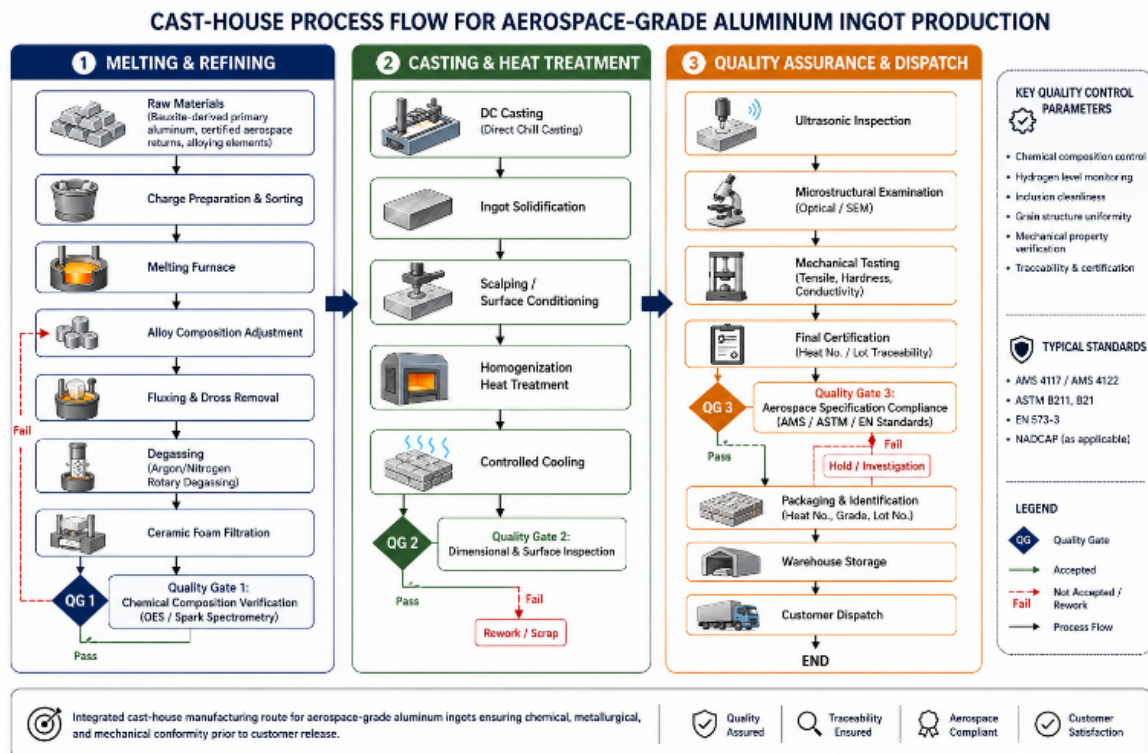


Figure 1: Cast-house process flow for aerospace-grade aluminium ingot production, showing the three principal stages – melting & refining, casting & heat treatment, and quality assurance & dispatch – with key process steps and quality gates.

FURNACE TECHNOLOGIES AND MELTING PRACTICE

The choice of melting furnace for aerospace aluminum production is governed by a hierarchy of requirements: (i) minimisation of hydrogen pick-up and oxide inclusion generation; (ii) precise temperature control within $\pm 5^\circ\text{C}$ throughout the melt volume; (iii) suitability for the alloy family and charge form; and (iv) energy efficiency and environmental compliance (Whiteley, 2011). Figure 2 compares the primary furnace technologies on thermal efficiency and melt loss metrics.

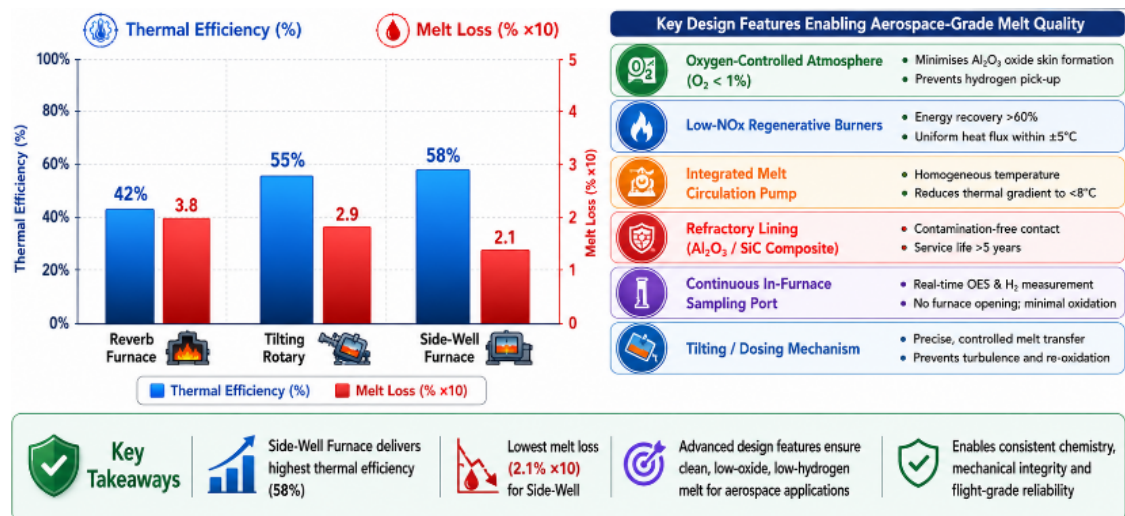


Figure 2: Comparison of primary furnace technologies on thermal efficiency and melt loss, with key design features enabling aerospace-grade melt quality.

Reverberatory furnaces remain widely used for aluminum melting due to high throughput, but their low efficiency (40–45%) and high melt loss (3.5–4.0%) limit aerospace suitability. Side-well furnaces reduce oxidation and hydrogen pickup; tower furnaces achieve the highest efficiency (up to 85%) with melt losses <1.5%. Induction furnaces are preferred for final alloying of high purity 7xxx alloys, providing clean and contactless stirring. Tilting rotary furnaces are used mainly for secondary charges due to contamination risks.

Atmosphere control is critical: O₂ is kept below 1% to minimize oxides and hydrogen absorption. Modern furnaces use regenerative burners, electromagnetic stirring, and continuous H₂ monitoring to maintain levels <0.10 mL/100 g Al before casting. Charge preparation employs qualified P1020A primary aluminum with strict inspection. Materials are preheated (≥150°C for 2 h) to remove moisture, while alloying additions use master alloys for uniform dissolution and composition control.

MELT TREATMENT: DEGASSING, GRAIN REFINEMENT, AND FILTRATION

Dissolved hydrogen is the primary source of microporosity in cast aluminum alloys and the most critical melt quality parameter for aerospace applications. The aerospace limit of <0.08 mL H₂/100g Al (AMS 2770) compares with a typical as-melted level of 0.20–0.35 mL/100g Al, requiring a removal efficiency of 65–75% (Neff et al., 2018). Figure 3 illustrates degassing and filtration technologies with their respective removal efficiencies.

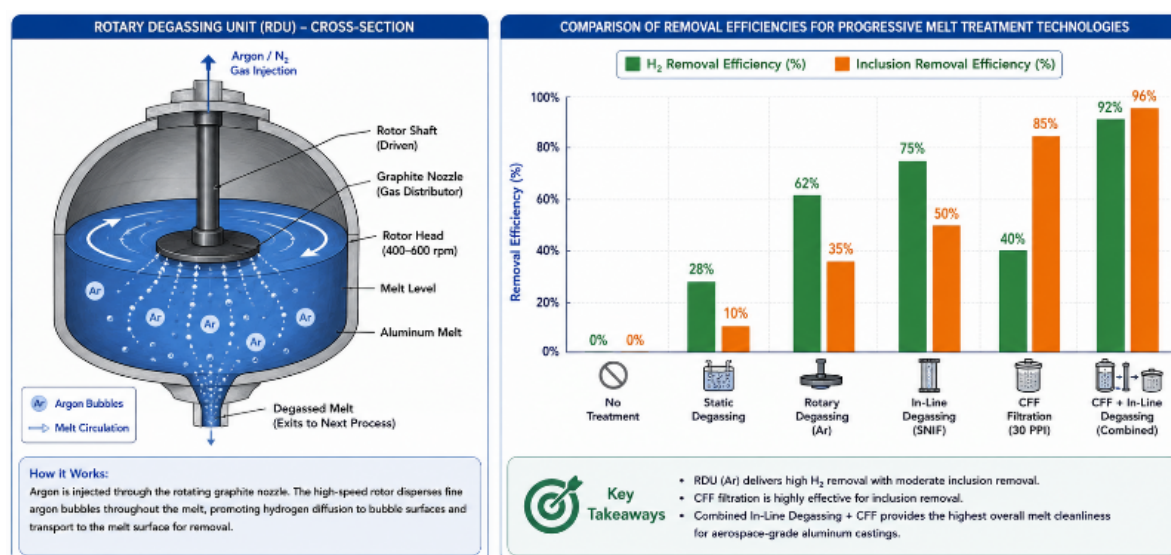


Figure 3: Rotary degassing unit (RDU) cross-section schematic (left) and comparison of H₂ removal and inclusion removal efficiencies for progressive melt treatment technologies (right), from no treatment through combined in-line degassing and CFF filtration.

The rotary degassing unit (RDU) is the industry standard for in-furnace H₂ removal. A graphite rotor at 400–600 rpm disperses argon or N₂ into fine bubbles; H₂ diffuses into them via partial pressure differential and is purged to the atmosphere. Modern RDUs achieve 60–70% removal in one 20–30 min cycle. For large-diameter 7xxx aerospace billets, in-line units (SNIF, Alpur, Hycast) between the furnace and the mould provide a second stage, achieving a combined efficiency of 85–92% with RDU. Grain refinement is essential in aerospace DC casting for fine equiaxed grains that minimise hot tearing, improve isotropy, and enhance ultrasonic inspect ability. Al-5Ti-1B master alloy is standard (0.5–2.0 kg/t, min. 0.8 kg/t), verified by macro-etch; it promotes heterogeneous nucleation of α-Al on TiB₂ particles with Al₃Ti phase (Sun et al., 2004).

Ceramic foam filtration (CFF) is the final inclusion barrier. Aerospace lines use two-stage CFF: 30 PPI pre-filter (>80 μm coarse inclusions) followed by 50–80 PPI final filter (sub-30 μm oxides

and TiB_2 agglomerates). Performance is measured by Prefill or PoDFA, targeting $<0.06 \text{ mm}^2/\text{kg}$ inclusion index.

DIRECT-CHILL (DC) CASTING: SOLIDIFICATION CONTROL

Direct-chill (DC) casting is the universal process for producing aerospace aluminum ingots and extrusion billets. Treated melt is poured continuously into a water-cooled open-ended mould from which the partially solidified ingot is progressively withdrawn at a controlled casting speed (Figure 4). Two cooling stages govern solidification: primary cooling by the mould wall (typically 5–15% of total heat extraction) and secondary cooling by water jets impinging directly on the ingot surface immediately below the mould exit.

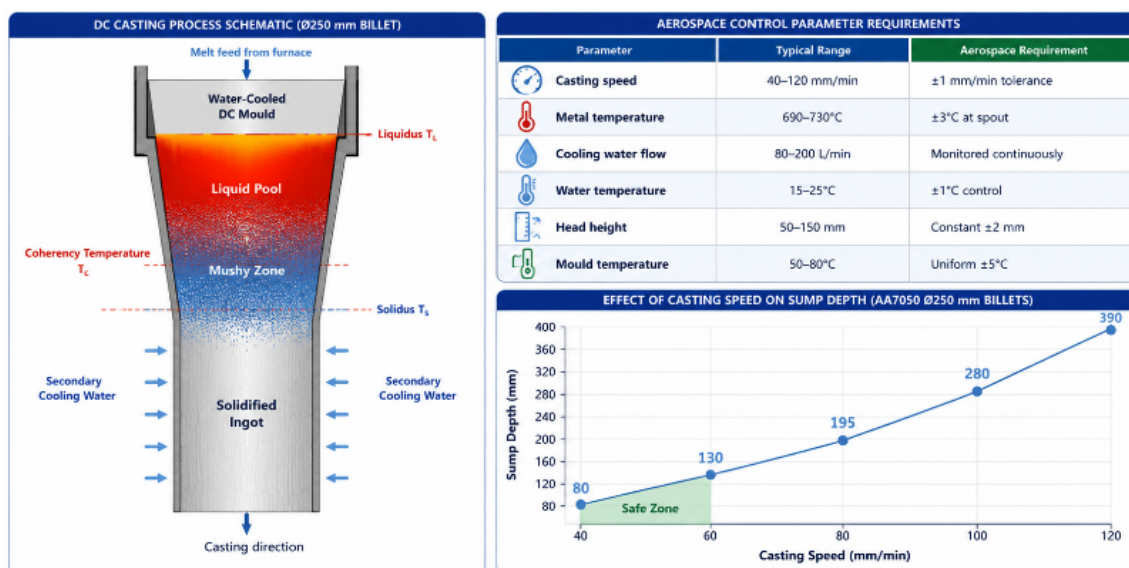


Figure 4: DC casting process schematic showing the liquid pool, mushy zone, and solidification isotherms (left), aerospace control parameter requirements and the effect of casting speed on sump depth for AA7050 Ø250 mm billets (right).

Casting speed is the most influential variable, controlling sump depth, solidification front shape, and thermal gradient at the front. For aerospace billets, shallow flat sumps are preferred to minimise centreline segregation and residual thermal stresses. Typical speeds for 7xxx billets (Ø300–600 mm) are 40–80 mm/min. Spout temperature is maintained within $\pm 3^\circ\text{C}$ of target (usually 25–50°C above liquidus) to control mushy zone and prevent premature freezing. Electromagnetic casting (EMC) is increasingly used for 7xxx billets: it enables contactless melt confinement, eliminates cold-shut defects, and reduces sub-surface segregation band depth by 30–50% vs. standard DC casting (Schneider, 2016).

As-cast microstructure is cored dendritic with segregation—cores enriched in Al and primary solutes, interdendritic regions enriched in Fe, Si, and eutectic-forming elements. SDAS ranges 30–80 μm depending on alloy and local solidification rate; finer SDAS improves fatigue life and fracture toughness [10]. Hydrogen micro-porosity forms at dendrite boundaries if H_2 exceeds solidus solubility ($\sim 0.034 \text{ mL}/100\text{g Al}$). These sub-0.5 mm pores (below conventional UT resolution) act as fatigue crack initiators and are the primary target of Section 3 melt treatments.

HOMOGENISATION HEAT TREATMENT

DC-cast ingots are unsuitable for downstream thermomechanical processing as-cast due to dendritic segregation, non-equilibrium eutectic phases, and super-saturated dispersoid-forming elements (Mn, Cr, Zr). Homogenisation—a prolonged sub-solidus anneal—is mandatory for all aerospace aluminum semi-products and serves four key functions: (i) dissolution of coarse non-

equilibrium intermetallics (Al_2CuMg , MgZn_2 , $\text{Al}_7\text{Cu}_2\text{Fe}$); (ii) homogenisation of elemental profiles via solid-state diffusion; (iii) precipitation/coarsening of dispersoids (Al_3Zr , Al_6Mn) to inhibit grain growth; (iv) reduction of residual casting stresses for safe handling.

Temperature and time are alloy-specific to balance goals against incipient melting risk. AA7050/AA7150 use two-step homogenisation ($460^\circ\text{C}/4\text{h} + 477^\circ\text{C}/24\text{h}$) to dissolve low-melting eutectics before higher-temperature diffusion [8]. AA2024 uses single-step at $488\text{--}495^\circ\text{C}$ for 16–24 h to dissolve S-phase (Al_2CuMg) and θ -phase (Al_2Cu). AA6061 is treated at 530°C for 6–10 h, mainly dissolving Mg_2Si eutectic.

Cooling rates of $200\text{--}400^\circ\text{C}/\text{h}$ are typical to prevent coarse re-precipitation while avoiding thermal cracking in large billets [9]. Furnace uniformity is critical: AMS 2770 and AMS-H-6088 require $\pm 8^\circ\text{C}$ throughout the load, verified by thermocouple surveys. Deviations risk under-homogenisation (retained segregation) in cold zones or incipient melting/blistering in hot zones (Dons, 2001).

QUALITY ASSURANCE FRAMEWORK FOR AEROSPACE ALUMINUM INGOTS

The QA framework for aerospace aluminum ingots integrates real-time process monitoring, post-process inspection, and documented certification to meet AS9100D, customer quality plans, and material specifications. It comprises seven interconnected domains. OES sampling is done at each furnace tap; aerospace alloys use ICP-OES on solidified billet slices for greater accuracy on trace elements (Bi, Pb, Sn <10 ppm). Results must meet AMS QQ-A-200 or customer material data sheet before casting [3]. Continuous in-line H_2 monitoring (e.g., Foseco Alspek H, ABB) acts as a real-time quality gate. Bifilm index is measured via reduced pressure test (Alu-Quak) at least once per aerospace cast. Both H_2 and Bifilm must meet limits before casting; non-conforming melts are re-treated (Jia et al., 2026).

PoDFA quantifies inclusions (mm^2/kg) as the most sensitive cleanliness measure: a 30 g sample is pressure-filtered through a ceramic disc, with residue analysed by SEM-EDS. Aerospace requires <0.06 mm^2/kg to support Class AA UT inspection. 100% immersion UT of homogenised billets is mandatory. Phased array UT (PAUT) is standard, providing higher sensitivity, faster inspection, and full volumetric digital records. Acceptance is Class AA per AMS 2630: no indications >1.0 mm FBH equivalent. All records are archived in the billet Certificate of Conformance (CoC) for AS9100D audits (Ranganayakulu et al., 2017).

CONCLUSION

This article has examined cast-house technologies, practices, and QA frameworks for aerospace-grade aluminum ingots and billets. Principal conclusions: Tower and side-well furnaces with low-oxygen atmospheres and regenerative low- NO_x burners are state-of-the-art for aerospace melting, achieving 70–85% efficiency and melt losses $<1.5\%$. Multi-stage melt treatment (in-furnace RDU + in-line degassing + two-stage CFF) is necessary and sufficient for aerospace targets: H_2 <0.08 mL/100g Al and PoDFA <0.06 mm^2/kg . DC casting control (especially speed and secondary cooling) critically determines sump geometry, SDAS, and centreline segregation; optimal parameters are alloy- and diameter-specific. Homogenisation is indispensable for dissolving non-equilibrium eutectics, compositional homogenisation, and controlled dispersoid precipitation required for downstream processing. The aerospace QA framework (AS9100D with AMS 2770, AMS 2630, and ASTM E2375) ensures multi-domain inspection, certification, and full pedigree traceability. Emerging technologies – electromagnetic casting, real-time LIBS, and digital twin control – offer major potential to tighten process control, reduce scrap, and improve as-cast quality.

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