



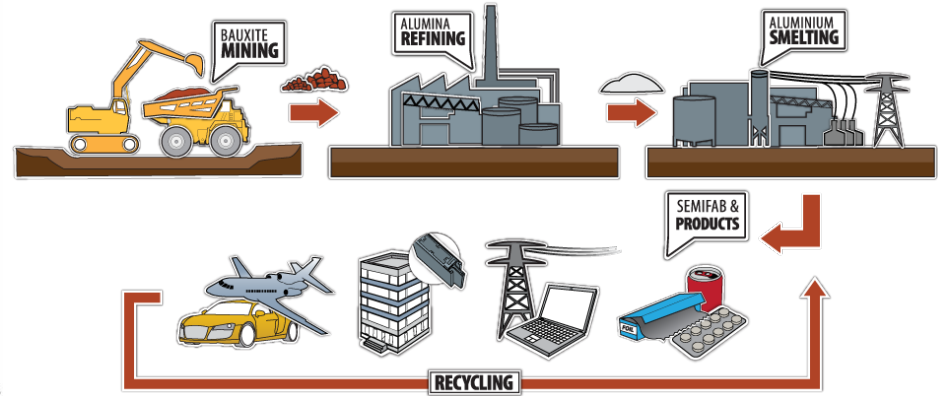
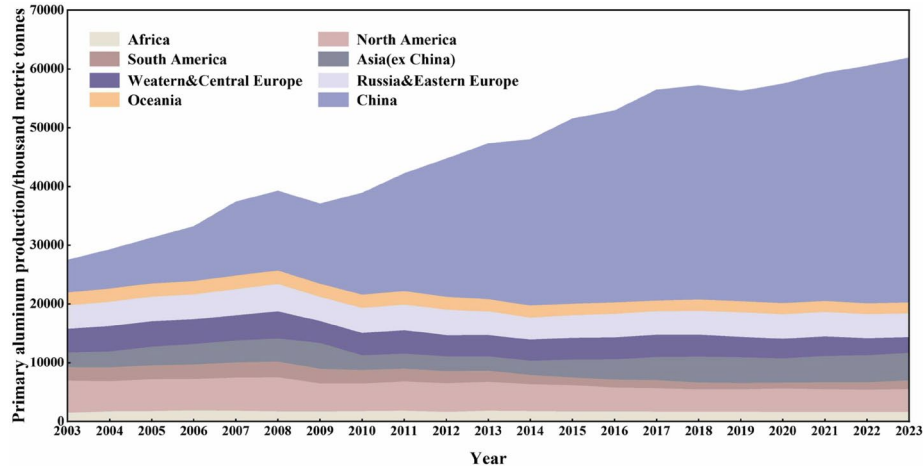
FS 2025/26

MSE-422 – Advanced Metallurgy

12-Metals processing – primary Al metallurgy

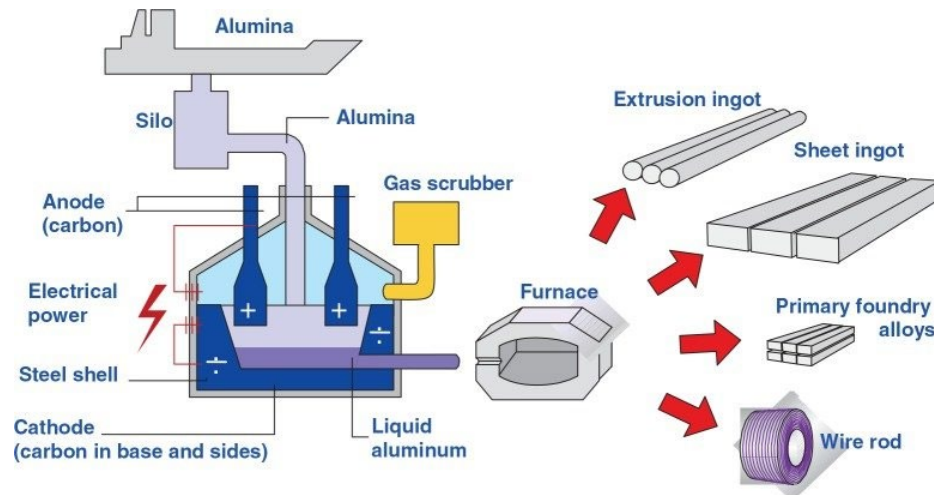
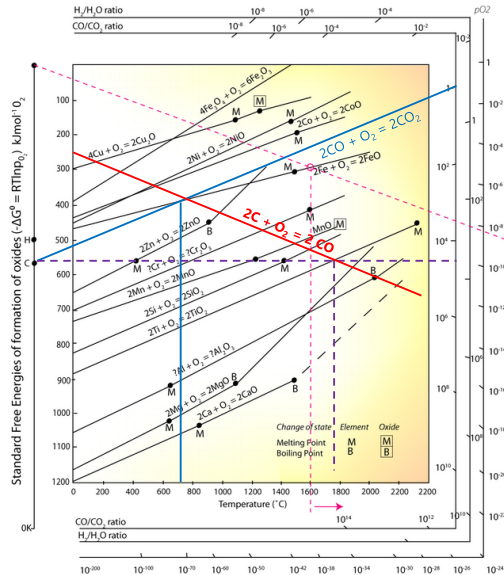
Christian Leinenbach

Aluminium and the AI making process



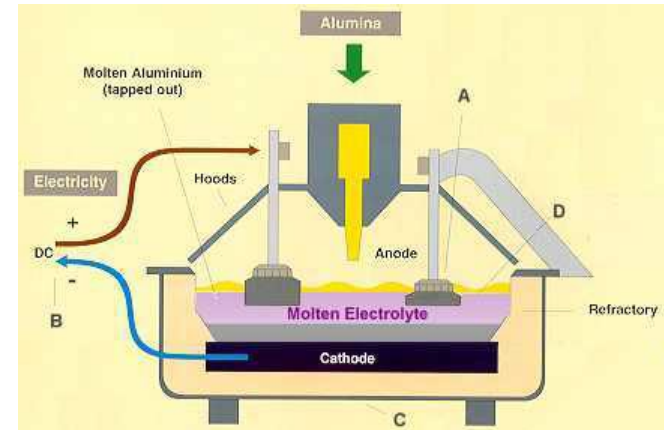
Reduction of Alumina

- Al_2O_3 has a melting point of 2050°C and is thermodynamically very stable, thus a reduction is very difficult
- The common process for the production of Al from Al_2O_3 is the Hall-Héroult electrolysis process

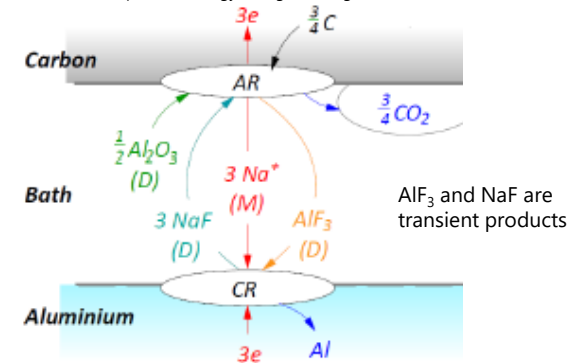


Reduction of Alumina

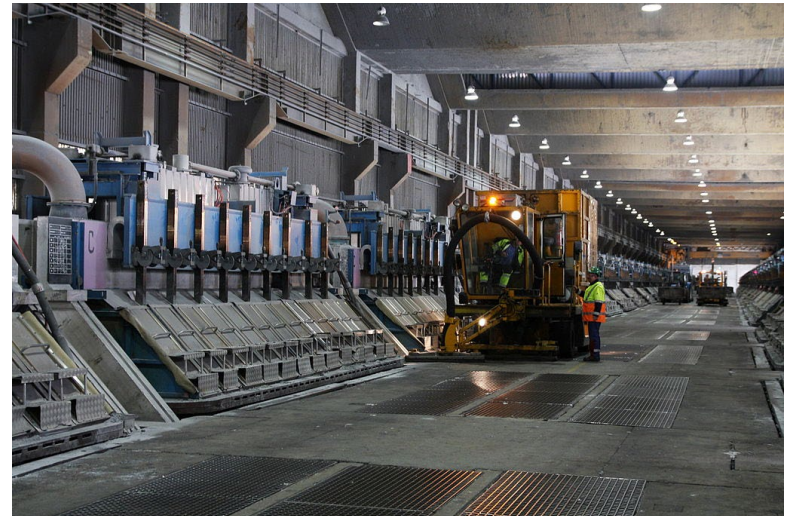
- Fused salt electrolysis (Hall-Heroult process)
 - Cathode (permanent), anode (graphite, consumed)
 - electrolyte is a eutectic of 81.5% cryolite Na_3AlF_6 and 18.5% Al_2O_3
- Reactions
 - Electrolysis: $\text{Al}_2\text{O}_3 = 2 \text{Al}^{3+} + 3 \text{O}^{2-}$
 $\text{Al}^{3+} + 3 \text{e}^- = \text{Al}$
 - Reaction with anode $\text{C} + 2 \text{O}^{2-} = \text{CO}_2 + 4 \text{e}^-$
 - Overall reaction: $2 \text{Al}_2\text{O}_3 + 3 \text{C} = 4 \text{Al} + 3 \text{CO}_2$
 (1.5 ton CO_2 per ton Al – carbon reduces voltage)
- Current efficiency is 80-95%
 - some losses due to Al dissolved in electrolyte, transferred to anode where it is reoxidized : $2\text{Al} + 3 \text{CO}_2 = \text{Al}_2\text{O}_3 + 3 \text{CO}$
 - Also ohmic resistance in electrolyte



http://www.energymanagertraining.com/aluminium/Al_how.htm



The Hall-Héroult process

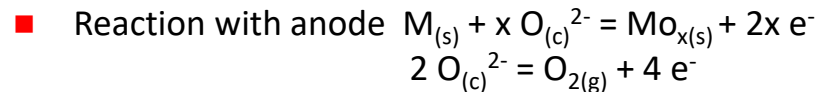


[/www.youtube.com/watch?v=4a1ptfTtXA/](https://www.youtube.com/watch?v=4a1ptfTtXA/)

- Compared with other metallurgical processes, the Hall-Héroult process has a low productivity and consumes significant amounts of energy (13-15 kWh/kg_{Al})
- The production of each kg of Al consumes between 0.4 and 0.5 kg carbon in the form of anodes → Al production contributes to 2-5% of the world man-made CO₂ equivalent emissions
- The process also generates greenhouse gasses such as CF₄ and C₂F₆ or perfluorocarbons (PFCs) from the carbon electrode and reactions with liquid cryolite
- Possibilities for improving the environmental efficiency
 - Use of inert anodes instead of C
 - Alternative Al production methods
 - Al recycling

- Inert (i.e. non-reactive) anodes as a replacement of graphite have been investigated for >30years
- Their successful adoption to the electrolysis cell is expected to eliminate the emission of CO₂
- Among the anode materials (cermets, ceramics and metals), metallic anodes are preferred as they possess high electrical conductivity, mechanical robustness, easy fabrication, good thermal resistance and ease in electrically connecting to current leads
- The metallic anode is protected by an oxide scale which grows once the anode is immersed into the melt, which is supposed to improve the anode's chemical resistance.

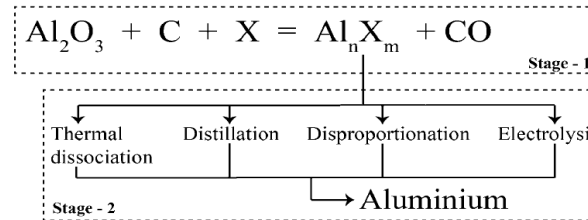
- Reactions:



- Materials investigated
 - Fe(50-80)-Ni(50-20) alloys
 - Fe(55-60)-Ni(35-40)-Al(5) alloys
 - Cu(45-65)-Fe-Ni (Ni/Fe = 1.33) alloys
 - Cu(85-90)-Al(10-15) alloys
 - Cermets
- All materials form complex oxide layer structures at the surface upon exposure to liquid cryolite
- Pronounced corrosion of anodes; pre-oxidizing the anode materials can improve the corrosion resistance.
- The use of low-temperature electrolytes can improve the stability of the anode oxide scale
- No industry has successfully launched an inert anode for the Al electrolysis yet.

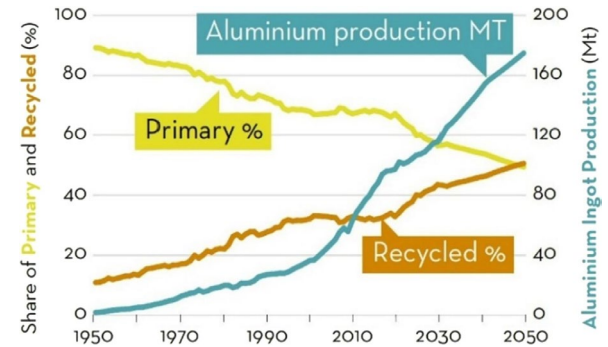
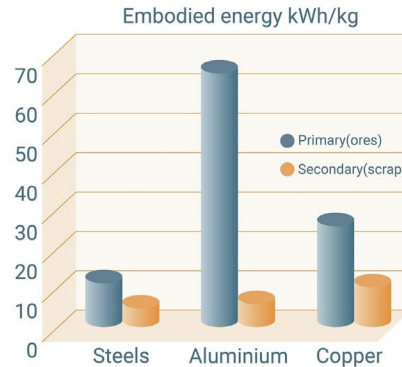
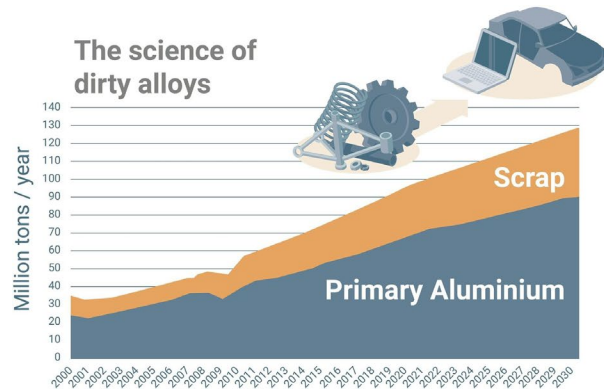
Alternative Al production methods

- The Direct carbothermal reaction (DCR) aims at
 - $\text{Al}_2\text{O}_3(\text{s}) + 3\text{C}(\text{s}) = 2\text{Al}(\text{s}) + 3\text{CO}(\text{g})$
 - $\text{Al}_2\text{O}_3(\text{s}) + 3\text{CH}_4(\text{g}) = 2\text{Al}(\text{s}) + 3\text{CO}(\text{g}) + 6\text{H}_2(\text{g})$
 - These two reactions are thermodynamically favored above 2057°C and 1497°C, respectively
- Indirect carbothermal reaction (IDCR) involves two or more steps where in the first step (stage 1) alumina or Al ores are converted to intermediate Al compounds. The intermediate Al compounds are then further reduced to Al in subsequent steps (stage 2)
 - Carbochlorination route
 - Extraction of Al from Al trichloride
 - Extraction of Al from Al sulphides
 - Extraction of Al from Al nitride
- DCR has not been commercialised because of problems with extreme operating conditions and yield
- stage indirect carbothermic reduction using Cl, S and N sources to form intermediates have been investigated but still require significant developments



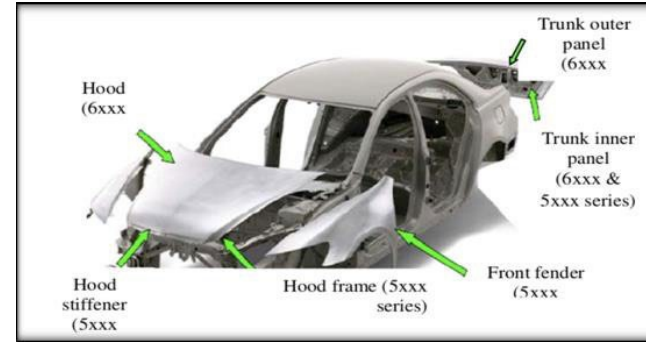
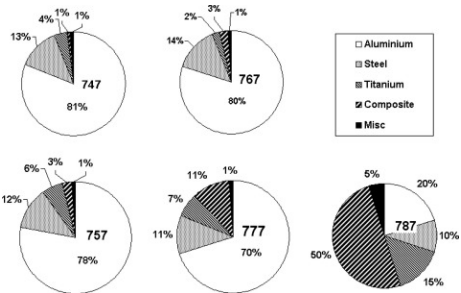
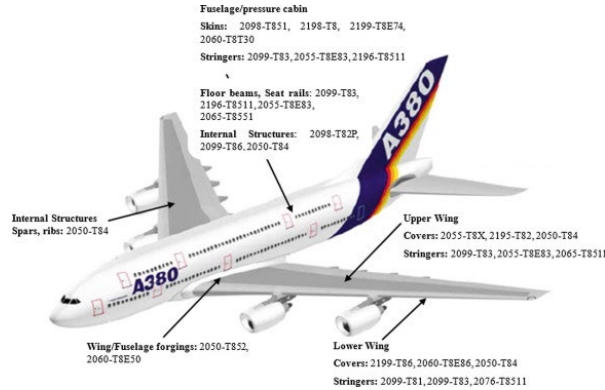
Al recycling

- Al has a high recycling potential and the amount of recycled Al has continuously increased over the years
- Aluminium is an infinitely recyclable material, and it takes up to 95 percent less energy to recycle it than to produce primary aluminum, which also limits emissions, including greenhouse gases.
- Today, about 75 percent of all aluminum produced in history, nearly a billion tons, is still in use.



/Raabe et al., Progress in Materials Science 128 (2022) 100947/

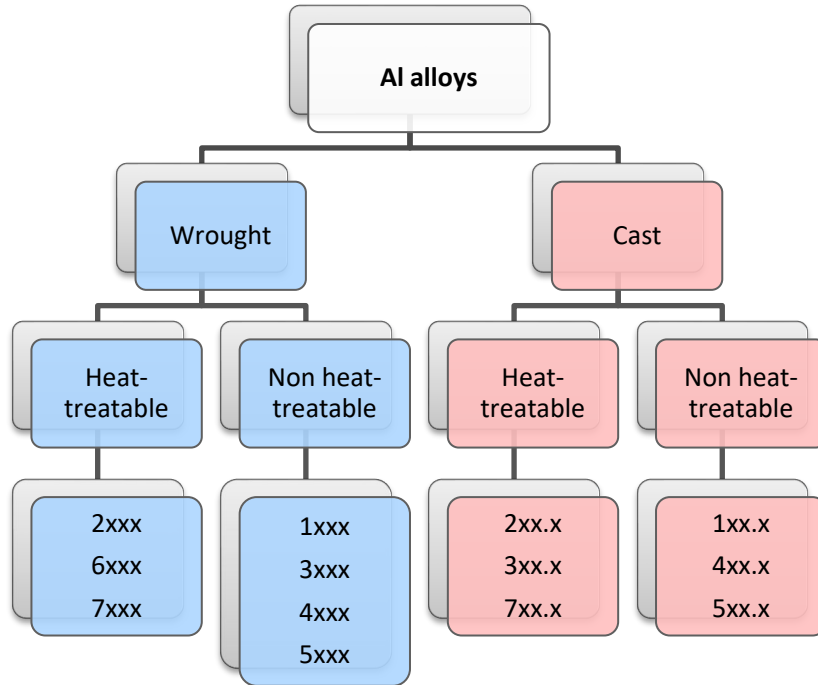
Applications of Al alloys – aircrafts and cars



Body & Inner Panel	Body Closures	Heat Exchangers	Heat Shields	Misc. Engine
2008, 5030, 5052, 5182, 5454, 6009, 6016, 6111	2008, 2036, 6009, 6016, 6010, 6383, 6061, 6111	6060, 6061, 6063, 6106, 5049, 7072, 1145, 4047, 4004, 4045, 4343, 3003, 8079, 6006, 1200, 1050, 1100	1056, 3003, 5052, 5182	226, AlSn20Cu, AlZn5B4
Cradles & Frames	Wheels	Steering System	Fuel System	Engine/Cylinders
5182	356, 6081, 6061	6082, 7108, 7021	6063, 3103, 5049, 5754	380, 319, Al-Si
Collision	Brake System	Suspension Parts	Trans	Pistons
6013, 7021, 7029	359 or 360+SIC	AlSi7Mg, 6013, 6082	380.2	4032

/T. Dursun, C. Soutis, Mater. Des. 56 (2014) 862-871/

Classification of Al alloys



Wrought Al alloys	
Alloy series	Main alloying elements
1xxx	Pure Al (>99%)
2xxx	Al-Cu
3xxx	Al-Mn
4xxx	Al-Si
5xxx	Al-Mg
6xxx	Al-Mg-Si
7xxx	Al-Zn
8xxx	Al + others

Cast Al alloys	
Alloy series	Main alloying elements
1xx.x	Pure Al (>99%)
2xx.x	Al-Cu
3xx.x	Al-Si-(Cu,Mg)
4xx.x	Al-Si
5xx.x	Al-Mg
6xx.x	unused
7xx.x	Al-Zn
8xx.x	Al-Sn
9xx.x	Al + others

Classification of Al alloys - examples

Cast

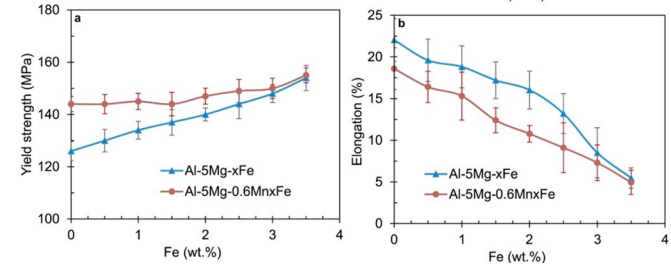
- 1xx.x (nearly pure, specialty use)
 - 105.0 – Al-($\geq 99.5\%$)
- 2xx.x (Al–Cu-based)
 - 222.0 – Al-(9.2–10.7)Cu-(0.15–0.35)Mg-(≤ 2.0)Si
- 3xx.x (Al–Si–Cu/Mg)
 - 333.0 – Al-(8.0–10.0)Si-(3.0–4.0)Cu-(0.05–0.5)Mg
- 4xx.x (Al–Si, low Cu/Mg)
 - 443.0 – Al-(4.5–6.0)Si-(0.6)Cu-(0.05)Mg
- 5xx.x (Al–Mg)
 - 514.0 – Al-(3.5–4.5)Mg-(≤ 0.35)Si
- 7xx.x (Al–Zn)
 - 713.0 – Al-(7.0–8.0)Zn-(0.2–0.5)Mg-(0.4–1.0)

Wrought

- 1xxx (pure Al)
 - 1050 – 99.5Al
- 2xxx (Al–Cu)
 - 2024 – Al-(3.8–4.9)Cu-(0.3–0.8)Mn-(1.0–1.6)Mg
- 3xxx (Al–Mn)
 - 3103 – Al-(1.0–1.5)Mn-(0.3–0.6)Si
- 4xxx (Al–Si)
 - 4015 – Al-(1.4–2.2)Si-(0.6–1.2)Mn
- 5xxx (Al–Mg)
 - 5754 – Al-(2.6–3.6)Mg
- 6xxx (Al–Mg–Si)
 - 6061 – Al-(0.8–1.2)Mg-(0.4–0.8)Si
- 7xxx (Al–Un)
 - 7075 – Al-(5.1–6.1)Zn-(2.1–2.9)Mg-(1.2–2.0)Cu

Al recycling – challenges

- **Technical & material barriers**
 - Oxide formation: Rapid oxidation during melting leads to metal loss - 1–3% of molten Al can be lost to oxidation during remelting.
 - Contamination: mixed alloys, coatings, and other elements (Fe, Cu) lower recycle quality.
 - Downcycling risk: impurity accumulation limits high-end reuse (e.g., aerospace, electronics) – most recycled Al ends up in low-spec applications like castings due to quality degradation
- **Process limitations**
 - Automotive shredded scrap (“Twitch”) contains painted, mixed, and composite forms requiring advanced separation
 - Sorting technologies: Inadequate AI-based or sensor-based systems can misidentify alloys
 - Export of scrap: Developing countries often lack infrastructure for sustainable Al recycling
- **Quality standards**
 - OEMs demand tight specs; recycled aluminum often cannot meet them

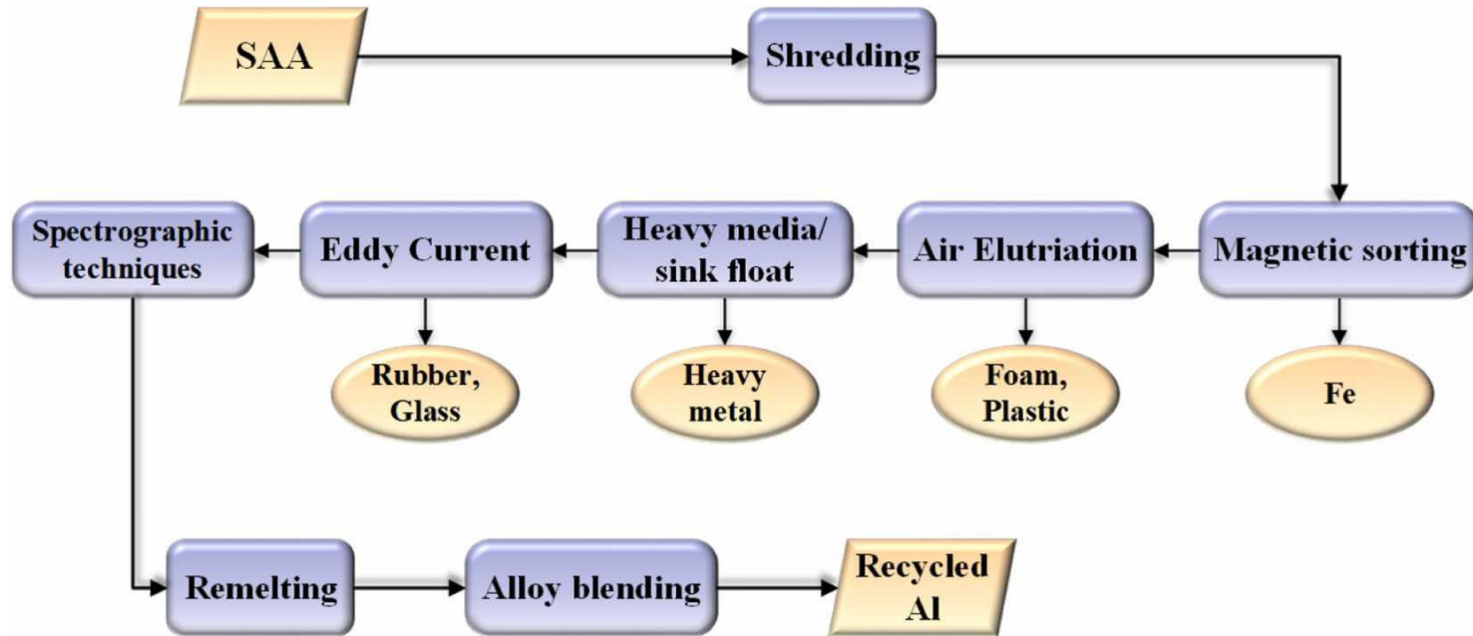


Alloys	ALLOYING ELEMENTS			
	Major	Minor (common)	Minor (less common)	Critical limits
1xxx	Al	Si, Fe	-	Mg, Mn, Zn, Cu, Ti
2xxx	Al, Cu	Mg, Mn	Si, Fe, Zr, Li, Ni, Cr, Zn, Pb, Bi	Fe, Si (some alloys)
3xxx	Al, Mn	Mg, Cu	Fe, Si	Cu (some alloys)
4xxx	Al, Si	Mg	Mn	Mn, Mg (some alloys)
5xxx	Al, Mg	Mn	Cr, Zr, Cu, Zn	Si, Cu (most alloys)
6xxx	Al, Mg, Si	Cu, Mn, Cr	Fe, V, Zn, Bi, Pb	Fe, Cu, Mn (some alloys)
7xxx	Al, Zn, Mg	Cu, Mn, Cr, Zr	-	Si, Fe
8xxx	Al	Fe, Si, Cu	Sn, Ni	Mg

Compositional restrictions: tough challenging moderate

/Raabe et al., Progress in Materials Science 128 (2022) 100947/

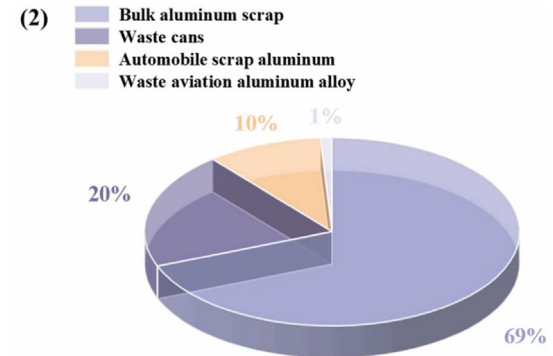
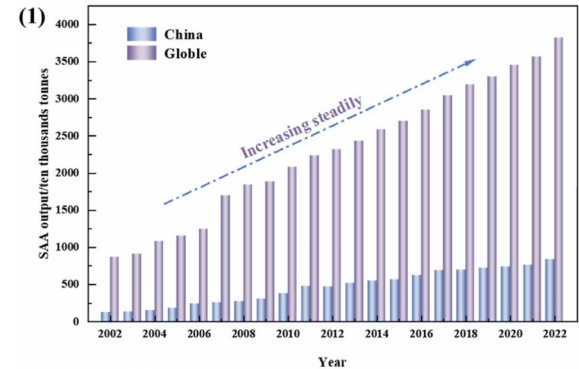
Al recycling – procedure



/Gao et al., Process Safety and Environmental Protection 202,A, (2025) 107588/

Recycling of Al beverage cans

- Recycling Process of Aluminum Beverage Cans
 - Separated from municipal waste (e.g. via eddy current separators)
 - Shredded into small pieces to reduce volume and aid processing
 - Cleaned mechanically and/or chemically
 - Compacted into blocks to minimize oxidation during melting
 - Melted at $\sim 750\text{ }^{\circ}\text{C}$ ($\pm 100\text{ }^{\circ}\text{C}$) in a furnace
 - Slag removed; hydrogen degassed using chlorine/nitrogen gases
 - Spectroscopic analysis used to adjust alloy composition
 - Alloying elements (e.g. Cu, Zn, Si, Mg) added as needed
 - Molten aluminum cast into ingots, billets, rods, powder, or transported for direct use

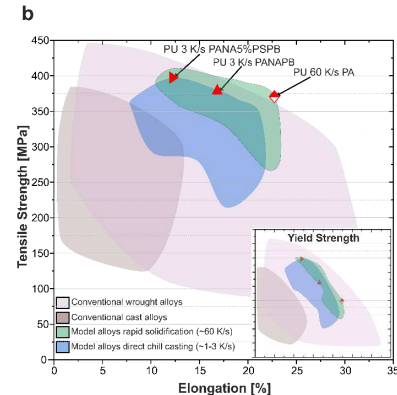
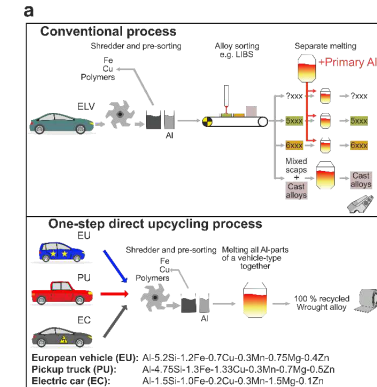


/Gao et al., Process Safety and Environmental Protection 202,A, (2025) 107588/

- The design of Al alloys for recycling involves developing compositions that can tolerate common impurities (like Fe and Si) found in scrap while maintaining desired performance characteristics.
- Design of alloys with broader compositional windows and higher Fe/Si tolerance to enable high scrap content.
- Use targeted additions (e.g., Ca) and heat treatments to control Fe–Si intermetallics and reduce their negative effects.
- Apply processes like friction extrusion or AM to handle mixed “dirty” scrap without extensive remelting.
- Reduce the number of alloy grades in use to improve scrap segregation and enable closed-loop recycling.
- Engineer alloys where impurity-driven intermetallics contribute to beneficial heterostructures and improved mechanical properties

Research trends - upcycling of Al alloys

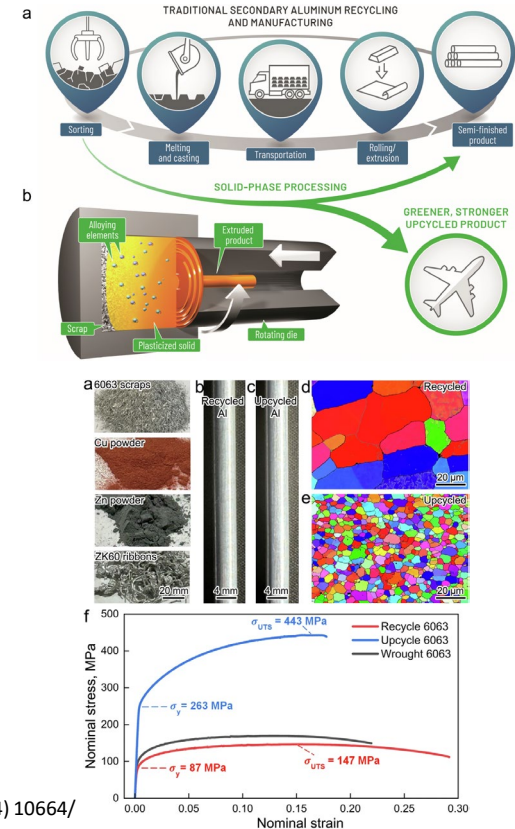
- Upcycling = upgrading low-grade mixed Al scrap into higher-value alloys through metallurgical design, not simple remelting
- Avoids downcycling: instead of producing low-performance cast alloys, upcycling aims for structural or automotive-grade materials
- Works with mixed scrap streams: cast/wrought scrap mixtures can be reused without full sorting by controlling impurities
- Impurities become useful: elements such as Si, Fe, Cu, Mg can be tolerated or exploited (heterostructures, grain refinement, controlled precipitates) rather than removed.
- Processing is crucial: control of cooling rate to refine intermetallics, homogenization + deformation to break and distribute phases etc..
- Outcome: upcycled alloys can reach high strength and ductility, enabling low-emission, circular aluminium flows without relying on primary Al dilution or complex sorting.



/Pogatscher et al, <https://doi.org/10.21203/rs.3.rs-7059967/v1/>

Research trends - upcycling of Al alloys

- Solid-phase alloying (friction extrusion) used for melting-free upcycling of 6063 scrap into high-performance alloys
- Direct addition and dispersion of Cu, Zn and Mg produce a 7075-like composition and strength
- Severe deformation creates a fine-grained microstructure and nanocluster strengthening (GP zones, $\eta'/\text{Mg}(\text{CuZn})_2$)
- Oxides and heterogeneous scrap features are broken and homogenized, avoiding defects typical of remelting routes
- Process yields >200% strength increase and offers a low-energy, low-CO₂ pathway to high-value Al products



/Wang et al. Nature Communications 15 (2024) 10664/