TECHNICAL REPORT

« Market Development for secondary Casting Alloys beyond Motor Blocks - Study on casting alloy market and recycling »

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IRTM2P Institut de Recherche Technologique Matériaux Métallurgie et Procédés

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Summary

Key words: Recycling, Casting alloys, aluminium, market, recycling technologies, value chain

This report aims at providing a broad view on the current value chain (market and end of life) for aluminium casting alloys in Europe. It gives global figures for casting aluminium production and demand in Europe, and presents the major types of casting alloys and their respective applications. Main actors and sectors associated to casting alloys are described, together with their respective roles and technologies along the value chain. Finally, a focus is made on the different aluminium scraps available and their expective volumes.
The second part of the report focuses on the potential evolutions associated to casting alloy market as well as to the technologies, and their potential consequences. Finally possible adaptations of the actors are listed, whether they could benefit or endure the expected evolutions.

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Comments

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1 General context and objectives of the study

Casting alloy market in Europe, and also more generally worldwide, is driven by the demand for the automotive industry, and more specifically, the production of Internal Combustion Engines (ICE). Furthermore, ICE market is currently the major consumer of secondary casting alloys, and incidentally the major consumer of mixed and shredded aluminium scraps. Current trend in automotive, strengthened by EU regulations, will see a significant increase in the share of electromobility and thus, a reduction of Internal Combustion Engines (ICE). These evolutions, which are to happen over 10 to 15 years, are happening faster than anticipated, due to the COVID-19 crisis. Losing ICEs as a scrap “sink” is an issue as today no other product uses the same type and amount of secondary casting alloy. According to several academic studies, if the recycling practices in the aluminium industry do not change, these evolutions could result in the production of significant volumes of “scrap surplus”, a scrap quality that would not be suited for the production of new products. To anticipate this issue, it is therefore important to understand how the cast aluminium market works, its players, the different types of aluminium, and the technologies used to identify possible alternatives, solutions or opportunities.

This study has three main objectives:

- Provide information on current scrap market and recycling value chain for casting alloys and its future evolutions (trends), if possible, data which could be implemented in MFA models.
- Identify possible opportunities for secondary cast (new sectors, new applications in current sectors, new alloys, new technologies) as well as optimization potential (innovative sorting technologies, incremental evolution…).
- Gather technical specifications for current/new casting alloys which could absorb increased contents of mixed/cast scrap (higher content of Si, Fe, Cu..), and assess the volumes related.

This study focuses on Europe and for the time period 2020-2030. All sectors are investigated, although a strong focus is made on automotive industry.

The work performed here consisted in 2 main steps:

- Description of current cast market and cast recycling chain in Europe. The global value chain from the production to the end of life, will be investigated. The aim is to understand what are the main types of cast aluminium products, which forms and alloys, who are the main actors of the value chain and which technologies are used. A special focus will be the fate of casting alloys.
- Identify major expected evolutions and trends of the value chain. A literature review and discussions with the main actors will help identify possible market evolutions from their perspectives, as well as technological evolution (sorting, smelting, casting, metallurgy) and potential new markets.

The report will follow a similar structure as the work. It will first give a broad view on the current value chain (market and end of life) for aluminium casting alloys. First it will show global figures (production and demand) in Europe and describe the main actors and sectors associated to casting alloys, their respective roles and technologies. Then it will provide information on the different types of casting alloys and aluminium scraps. A second part will focus on the evolutions associated to casting alloy market and the technologies and their potential consequences. Finally, it will list and explain the possible adaptation of the actors, whether they who benefit or endure the expected evolutions.

2 Casting alloy market

2.1 Casting market in figures

In Europe, aluminium casting market amounts to around 33% of the overall aluminium market (10,7 Mt in 2017), with casting demand 3,5 Mt in 2017. Of course, the last two years showed a specific evolution as COVID crisis had a significant impact on the demands and productions, resulting in a drop of more than 24% to around 2,8 Mt in 2020 (CAEF 2020).
Casting demands are mainly for secondary castings (70%) and, thus, only 30% for primary (GRIF Fabio Gobbo; 2019). Germany is the main European consumer and producer of castings with more than 30% of the production, followed by Italy and France (see the distribution by country on Figure 2). In terms of external trade, EU casting production matches EU demand as European net imports of castings are estimated around 0,2 Mt (<10% of the production, see Figure 1). Most casting imports in 2017 were wheels with 190 000 t net imports, mostly from Turkey (40%), South Korea (15%) and China (12%). Exported wheels are mainly sent to the United States, Russia and Switzerland.

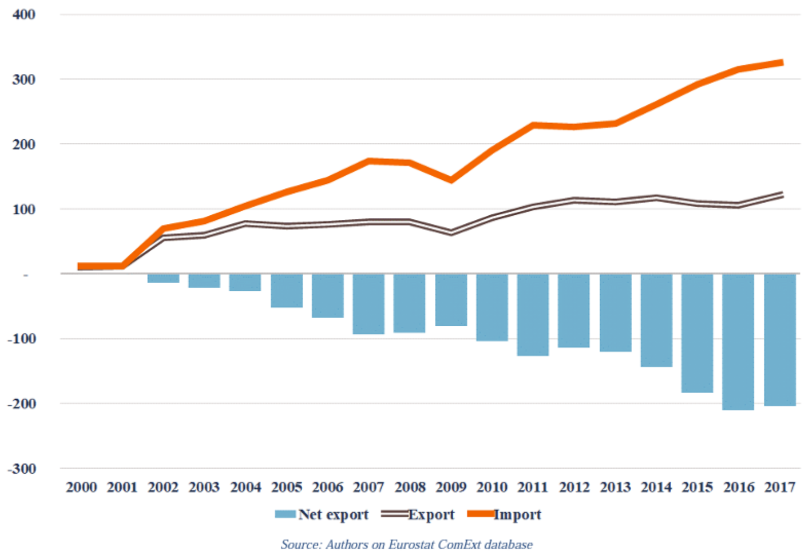


Figure 1: EU net exports of aluminium castings, in thousands of tonnes, 2000-2017 (GRIF Fabio Gobbo; 2019)

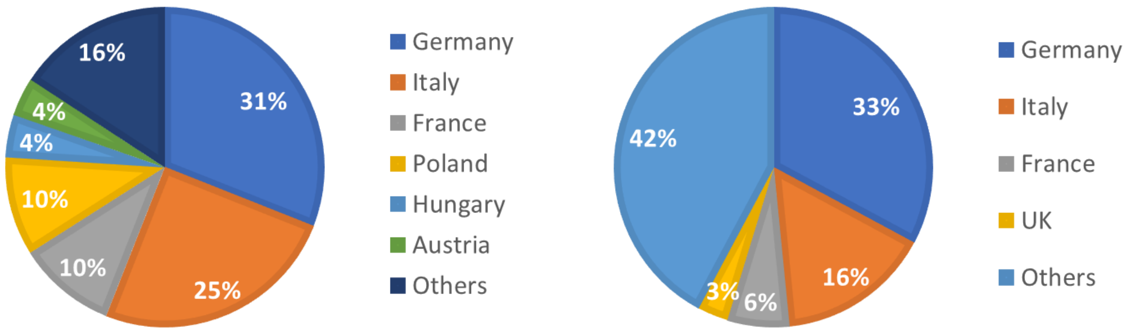


Figure 2: Aluminium production breakdown by country in Europe in 2017. On the left casting alloys alone (3,5 Mt) on the left secondary aluminium (cast & wrought) 3,2 Mt.

Worldwide, before COVID, projections discussed by Lehmhus (2022) suggested a global increase in production of aluminium castings associated to a decline in cast iron almost equal in volumes (Figure 3). Western Europe and NAFTA are supposed to see an increase in aluminium alloys consumption. However, this trend should concern mainly higher value components as the production of lower complexity and thus, lower added value, components would be shifting to lower-wage countries. Lehmhus explains this trend with the fact that “Mexico now has lower manufacturing costs than China […] while costs in Eastern Europe are at parity or above costs in the U.S.”.

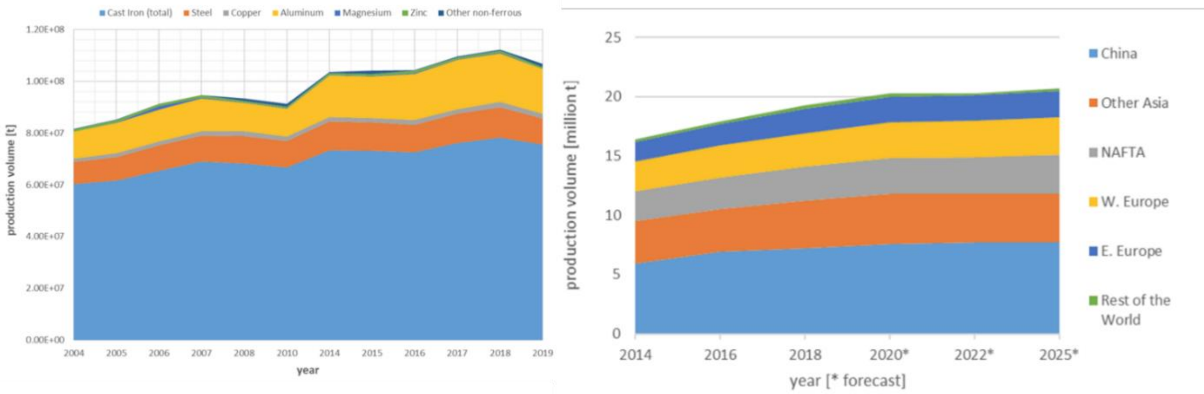


Figure 3: Left: Development of the relative importance of cast materials between 2004 and 2019 based on WFO data. Right: Prognosis regarding future development of the aluminium alloy casting industry until 2025, based on data from Büchner 2020.

2.2 Main applications for casting alloys

Aluminium casting alloys are used in many different applications, from the transportation industry to construction, machinery and household appliances. They have several advantages compared to other materials:

- Lightweight (low density compared to steel),
- Corrosion resistance,
- Ability to be used for the production of complex shapes,
- Possibility to achieve high production volumes with standard processes (e.g., High Pressure Die Casting).

Today, the main driver and consumer of aluminium castings is the automotive and light truck industry with around 2,2 Mt/y: it uses more than 85% of aluminium castings in Germany, around 80% in France and more than 55% in Italy. Castings in the automotive industry are used in a wide variety of components (examples of components are shown on Figure 4):

- Engines: more than 90% of cylinder heads and pistons, close to 70% of engine blocks, 55% of oil pans.
- Transmission and driveline (transmission and clutch cases): most transmission cases, more than 60% of clutch housing,
- Wheels: around 75% of wheels are made from aluminium castings,
- Chassis: about 30% of wheel carriers, subframes (but only around 10% are made from aluminium castings), suspension arms (although most of them are forged), steering knuckles,
- Body structure: structural component in luxury vehicles, such as pillars, shock towers (about 20%),
- Electric motors and batteries: most electric motor housings, some of the battery boxes for hybrid vehicles,
- Brakes: brakes callipers,
- Steering: pump bodies.

Figure 4: Examples of automotive components: structural components on the left and middle (cast knuckle and shock tower) and engine cylinder head (on the right) (European Aluminium 2002)

Although other industrial sectors require significantly less castings alloys than the automotive industry, there are many applications for cast aluminium:

- Construction industry (estimated demand in EU = 0,25 Mt/y[1]): housings for communication boxes, street furniture, door/windows handles,
- Small appliances and consumer goods (estimated demand in EU = 50 kt/y): such as electric and electronic equipment, lawnmowers, hand tools: castings can be used for enclosures/casings,
- Cookware: some pans,
- Mechanical engineering (estimated demand in EU = 50 kt/y): for complex parts such as impellers, blowers, gas cylinder,
- Aeronautics & other transport industry (estimated demand in EU = 1 Mt/y): seat frames & structure, pumps, casings.

[1] Estimations based on a global MFA model

Figure 5: Examples of cast alloy application from small appliances (electric motor casings), construction (door handles) and impeller (mechanical engineering)

3 Value chain description

3.1 Overall value chain

3.1.1 Scrap collectors

First step of the recycling chain is the collection of end-of-life products. The collection is performed by different structures and means depending on the products. There are three main types of organizations:

- Producer responsibility organisations
- Municipal collection services
- Authorized treatment facilities

Producer Responsibility Organisations (PRO) are collective bodies, operating nationally, created and financially funded by manufacturing companies (usually via consumer contributions). Their role is to ensure the meeting of the legislative requirements ("compliance") in terms of design as well as collection and recycling of the products, for example achieving certain recycling targets.
The main types of aluminium containing product dealt by PRO are electric and electronic equipment and packaging (used beverage cans). For Waste from Electric and Electronic Equipment (WEEE), there are more than 35 of such organizations in EU. Their actions can include (Green Best Practice Community 2023):

- Communication to motivate citizens for enhance separation of wastes at source;
- Cooperation (financial, technical and/or logistic) with public authorities at regional/local level;
- Cooperation with social economy actors for the collection and reuse of products;
- Incentivising producers to design more sustainable products (e.g., via "fee modulation");
- benchmarking environmental achievements of different areas covered by the EPR (Extended Producer Responsibility) scheme, e.g., at the level of the territories of public authorities at a regional/local level.

PRO usually don't perform the recycling themselves, they however organize the logistics of collection and processing of the wastes, finding the right actors/facilities to perform collection, reuse/recycling according to current regulations (and at acceptable costs).

Municipal collection services are in charge of organizing waste collection on specific territories, either through curb side collection schemes (door-to-door or collection points) or waste yards. These services are usually funded municipal and specific local taxes. The roles of these services are to collect household wastes and perform first separation processes to obtain different products / materials and ensure their best possible end of life valorisation. The level of separation and actual valorisation process for different waste types depend on the infrastructures and equipment available locally. Typical goods processed by these collection services are for example:

- Packaging items such as beverage cans, aerosol cans and laminated cardboard packaging → they can be separated and bailed for recycling (for example UBC),
- Aluminium foil → can end up in incineration plant and recovered as Incinerated Bottom Ash (IBA),
- Other goods such as bikes, deconstruction wastes (window frames, old radiators, …), cookware can be recovered at waste yard and then send to a shredder for processing…

Automotives/personal vehicles follow a specific collection scheme, separated from other types of products. When reaching their end-of-life, "End-of-Life Vehicles" (ELV) have to first be processed by specific facilities called "Authorized Treatment Facilities" (ATF). This concept was created in EU law by the ELV directive in 2000 (European Commission 2000), although it already existed in some European States before. These facilities are tasked with (Figure 6):

- Collecting ELV: end user should not have to pay for an ATF to take "full vehicle". Thus, ATF collection consists in buying ELV from end user or from insurances companies (damaged vehicles).
- Decontaminating: ELV depollution / decontamination is a mandatory step, where a series of elements (battery, fluids, tires, oils, filters…) have to be removed and processed according to the regulation (ELV directive).
- ELV dismantling: automotive parts and components can be either cleanly dismantled (manually) or with power-destructive tools. The level of dismantling (means, number and types of parts to dismantle) results from an economic balance on the processing costs and benefits from the sales:
    - Dismantling for re-use: engine, drivetrain, cylinder, shock absorber, wings, covers, wheels...

    - Dismantling for recycling: heat shield, cables, structural parts, wheel, hang on parts, engines, frame…
- Selling the ELV carcasses to shredders. Sometimes, dismantled engines can also be sold separated from the carcasses to shredders as well.

At ATF stage, full-aluminium or aluminium containing components can be recovered separated from the rest of the feed (for example wheels, heat shields, transmission parts, doors).

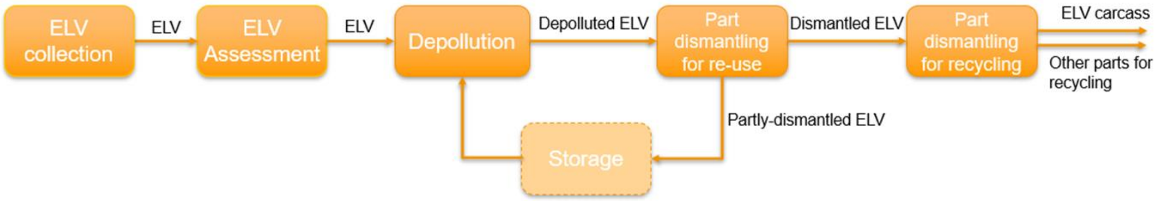


Figure 6: End-of-Life Vehicle recycling scheme at ATF level in Europe

3.1.2 Scrap processors, scrap dealers and traders

There are many different players in the scrap market. They have different roles:
- Scrap processors, also often scrap collectors: they perform collection of EOL products and scraps and process them to separate material and increase their value for recycling. As a side activity, scrap collectors can also only trade specific scraps (no preparation, only storage), that's usually the case for new scrap.
- Scrap dealers: tasked with collecting, storing scrap and organizing trade logistic.
- Scrap traders: only performing trading operations (finding scrap and organizing logistic) between scrap producers and customers.

EOL products and scraps are usually collected locally or national wide, closer than 100 km and up to 200-250 km for EOL products, and usually not more than 500 km for new scrap to reduce logistic costs. However, supply distances depend on the scrap dealer, on volumes of EOL products/scrap available locally, and on its location (labour costs...).

Complex products, such as WEEE and ELV, are collected and depolluted according to regulations (through PRO process and ATF) and then sent to scrap processing plants, most of them with shredding and sorting equipment. There, ELV carcasses and other EoL products (construction wastes, long profiles, common goods from municipal waste yards) follow a process to separate and recover several valuable material fractions, and ensure the achievement of the recycling targets set by the regulations[2].

At scrap processors, most recycling processes for aluminium recovery from wastes are based on the combination of 3 main technologies:
- Comminution to separated attached/joined elements from one another and free aluminium residues from unwanted materials (iron, copper, plastics…),
- Magnetic separation to remove iron containing residues from the feed,
- Eddy current separation to remove plastics and non-metallic residues.

Additional processes are sometimes needed, their utilization depends on:
- Product types,
- Product composition, and thus the nature of the elements which need to be separated from aluminium,
- Expected quality of aluminium residues.

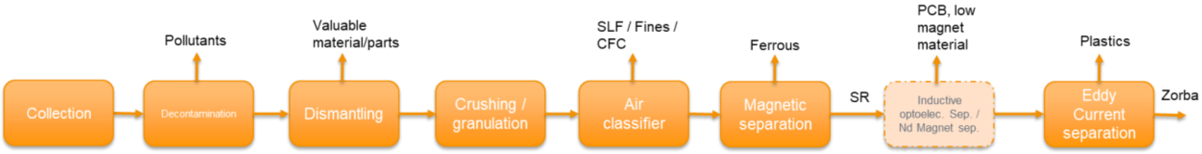
Overall, more than 20 different technologies can be used in the process of aluminium residues preparation. These technologies are usually provided by specific sorting technology manufacturers. Most recycling facilities are designed and engineered by engineering companies which integrate sorting technologies together with other scrap management appliances (storage, conveyor belts, structures/infrastructures, etc.).

The process for ELV is presented on Figure 7, and consists in 6 main steps[3]:

[2] Current ELV directive set the following targets: more than 85% of the mass of the vehicle has to be re-used or recycled and more than 95% re-used, recycled or valorised (energy) → less than 5% can be landfilled.
[3] The order and the technologies used can vary depending on the shredding plant and available equipment.

- Shredding in hammer-mill shredder: usually ELV aren't shredded alone, but mixed with other types of EOL products[4]
- Separation light from heavy residues: this is performed directly in the shredder; a built-in suction system helps recover light residues from the rest of the feed (Heavy Shredder Residues[5] - HSR). The Light Shredder Residues (LSR) mainly contain polymers, foam, and metallic dust.
- Magnetic sorting: This step separate ferro-magnetic residues from the Heavy Shedder Residues, producing ferrous scrap and Non-Ferrous Residues (NFR).
- Screening: before further sorting, the residues are usually separated in different size fractions to optimized the efficiency of the next sorting steps. General ranges are 10-40 mm, 40-120/150 mm, > 120/150 mm.
- Non-Ferrous fraction refining: using eddy-current sorting, separating metallic residues from non-metallic elements. The metal rich fraction obtain here is usually called "Zorba", containing around 50 to 60% of aluminium.
- Heavy media separation: can be performed with different technologies, such as flotation, X-Ray Fluorescence or Transmission (XRF or XRT). This step sorts using material density, to remove lighter and heavier elements (than aluminium). The resulting fraction is called "Twitch", containing generally over 95% of aluminium residues. "Twitch" is a specific type of scrap, which enter to a more global scrap fraction of "shredded aluminium scrap".

WEEE follow similar recycling processes, the equipment used can differ slightly as the material breakdown is not the



same (see Figure 8). Shredded aluminium residues from WEEE processing can take the form of Zorba or Twitch, like scrap from ELV.

According to some interviewees (players in the recycling chain), overall quality of the scrap fraction "Twitch" has been changing in the past years: it would contain less casting alloys (incidentally more wrought), which would result in a lower silicon content. (No strong proof at the moment, this trend needs to be confirmed in the long run!)
There are although possible explanations for this evolution:

- Evolution of aluminium uses in automotive: there's an increase in aluminium components, especially wrought alloys,
- A reduction of ELV inputs in shredders due to COVID crisis (aluminium in twitch would then mostly come from WEEE and construction wastes, containing more wrought alloys than casts)

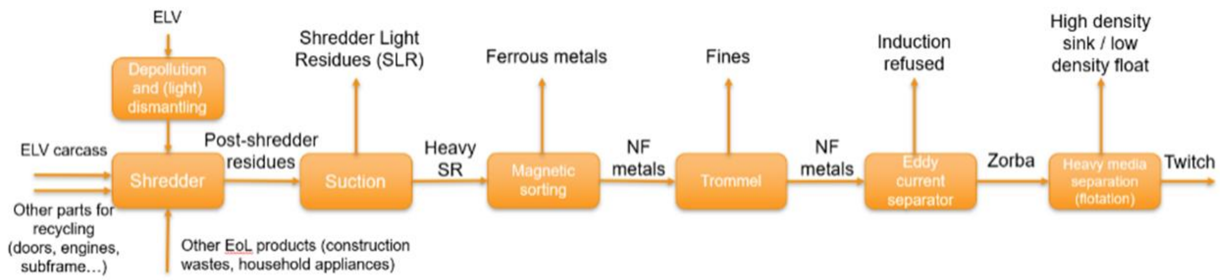


Figure 7: End-of-Life Vehicle recycling scheme and aluminium residues recycling at shredder level in Europe

[4] ELV inputs in shredders vary from site to site and country: In France ~35% of shredder inputs are ELV, Gruppo Fiori (in Italy) ~85%, Stena Recycling in Sweden ~20-25%. These figures were true for 2018-2019, but during the COVID-crisis, the numbers of vehicles reaching EOL decreased and ELV inputs in shredders could decrease to 10 to 20% in France. The amount of shredded ELV is mostly limited by the supply: France, UK and Italy are the main EU producers of ELV, with respectively 1,1, 1,4 and 0,9 million of ELV in 2017.
[5] HSR contain steel, stainless, aluminium, copper, polymers, rubber, glass, wood...

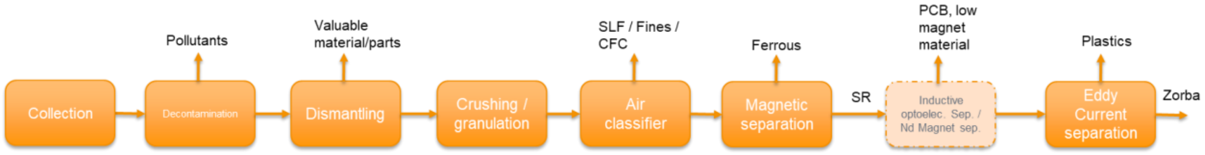


Figure 8: WEEE recycling route, with focus on aluminium

Finally, construction wastes can be processed very differently: long elements with no or low contaminant content can pass through a shear to reduce their dimension and facilitate the logistics (and fusion). Window frames can be processed separately, to remove glass and rubber, before been compacted. Other construction components with mix materials can be shredded with ELV or WEEE and other household appliances.

More information on the different aluminium scraps produced at this step will be given in §3.3.

3.1.3 Refiners and remelters

Refiners and remelters are the main users of aluminium scrap. They can purchase scraps from a wide variety of actors:

- **Scrap dealers** and traders→ EOL and new scrap (both coming from automotive and/or construction industry), EOL products from wastes yard.
- **Shredder plants** → EOL shredded scrap, from ELV, WEEE, construction wastes, household appliances and machinery
- Incineration plants → incinerated bottom ash
- Foundries → production scrap (rejects chips, turnings, runners, sprues and overflows)
- OEMs → new scrap
- Specific customers agreements → new scrap
- Salt slag recyclers

Because of their poor qualities, some scrap fractions purchased by refiners require a preparation step before the melt. This concern mainly refiners, as remelters tend to choose scrap requiring no further processing. This preparation can involve:

- Crushing / shredding of mixed material containing scrap,
- Sieving,
- Sorting (automatic/manual),
- Baling/compacting,
- Drying,
- Partial melt (in rotary furnace for iron removal),
- Delacquering for coated scrap.

Scrap preparation has a significant cost (investment, labour, energy, waste management). Remelters tend to buy clean scraps (preparation performed by scrap processors), whereas refiners prefer buying lower quality/cheap scrap which they will be able to prepare/clean themselves.

For the melting process, several technologies are used by remelters and refiners. The technologies available on a melting plant dictates the types of scrap which can be used:

- (Tilting) rotary furnace can be used for contaminated scraps (organics, other metals...), dross, etc. They are mostly used by refiners.
- (Multi-) Two-chamber furnaces for contaminated scrap (oil, coatings...). They are mostly used by refiners.
- (Gas) Chamber/reverberatory furnace are suited for clean scraps without or with low contamination only, they are thus adapted for the remelters.
- Induction furnace for clean scraps only, for remelters.
- *With or without oxyfuel burner.*
- Holding furnace before casting.

Diverse raw materials are used to achieve the desired metal composition at refiners and remelters. It depends strongly on produced alloy and the alloy range produced by the refiner/remelter. Raw material mix is usually set to meet profitability criteria (type of alloy, scrap availability, quantity vs plant capacity, price of scrap/primary…):

- Producers of single alloy types (e.g., ENAB46000 / A380 / AlSi9Cu3(Fe)) use mostly scrap and a limited number of scrap types:

- Post-shredder residues,
- Shredded and floated casing/engines

- Producers of other alloy types, are usually producing a wide range of alloys. They are more flexible and can produce composition on demand ("hundreds of different compositions"). They require a wider range of raw materials:
  - Mix different types of scrap (post-shredder residues, wheels, new scrap…)
  - Primary aluminium or master alloys,
  - Primary alloying elements (e.g., Silicon)
  - EOL copper scrap,
  - Magnesium new/old scrap…

Producing a wider range of alloys usually result in higher production costs than single alloy elaboration, and lower product capacities. Each melting batch can be different, which is difficult to optimized compared to elaboration of similar batches (the production capacity can thus be reduced by 25%).

Semi-products at this stage are mostly ingots and sometimes liquid metal. As shown on Figure 9, it can take other forms such as slabs, sows, waffles and rods depending on the application (e.g., for master alloys, deoxidation, etc.). The main end market for ingots from refiners, are the foundries for the automotive industry (between 20 and more than 95% depending on the company). Remelters can also produce for other markets (packaging, metallurgy, household goods…).

Figure 9: Source: Brough 2020 (Brough and Jouhara 2020)

Note (information from interviews/discussions, would need to be confirmed by facts/reliable data):
In 2020: production volumes mainly driven by customer demands, today: the main limit is on one hand the scrap availability (and the types of scrap available), but on the other hand, for ENAB46000 producer also the plant capacities.

3.1.4 Foundries

3.1.4.1 Casting activities

Foundries can be divided into main 3 activities:

- OEM owned foundries (OEMs here are often automotive manufacturers),
- Tier1 ("Tier0,5") cast part supplier,
- Tier1 « full component[6] » producers.

There are around 2000 aluminium foundries in Europe, which are mostly SMEs (about 55%) and 44% of large industries. They production capacities range between less than 1000 t/y to more than 15 000 t/y.

[6] "Full component" = assembly of several sub-components, purchased for a global function.

OEM owned and Tier1 foundries perform similar tasks:

- Receiving designs and specifications directly from OEMs: alloy composition, part design, process parameters.
- Performing a technical review, the expected design and casting process to confirm its feasibility. When needed, they can provide suggestions of changes/improvements (in terms of design, alloy and process parameters).
- Melting ingots purchased from refiners/remelters. Ingots composition are ordered according to OEMs specifications.
- Casting using various methods (see next paragraph 3.1.4.2 – casting technologies).
- Machining cast parts when it is possible/needed: cast part suppliers prefer supplying machined parts, which have higher value than simple cast parts.

In terms of raw material, foundries use mainly ingots from refiners. They mostly purchase standardized alloys, but often require customized variations (different ranges of residual content, usually within standardized specification ranges). When custom and specific alloy composition are requested, orders sizes are defined by the logistics and production capacities of the refiners: ingots delivery minimum 15 to 28 t/truck (theoretical smallest order size).

3.1.4.2 Casting technologies

There are 5 main casting technologies[7] for aluminium parts: Gravity Die (or sand) Casting (GDC), Low Pressure Die Casting (LPDC), High Pressure Die Casting (HPDC) and Lost Wax Casting (LWC). In Europe, HPDC is the main technology used in small and big companies, twice as much as gravity and LPDC (Figure 11). Table 1 lists the respective characteristics of each technology. They are used for different applications and alloy types:

- Gravity casting, with sand or die. The process is illustrated on the left side of Figure 10. GDC is also called Permanent Mould Casting. It involves a simple pouring of molten aluminium into a metal die (steel/iron) or sand mould, without any additional force applied.
    - Main applications: for intricated parts or when an empty section is needed at core.
    - Advantage: low costs (compared to other casting technologies), and can be used for small series (a few hundred parts)
    - Alloy types: mostly primary alloys, with low Fe content. For example: AlSi7Mg0.2, AlSi13.

- Low Pressure Die Casting (LPDC), illustrated on the middle of Figure 10. In LPDC, molten metal is injected upward into the bottom of a metallic die (steel) using a relatively low overpressure in the crucible (~0,7 Bar). This specific filling process enable a precise control of the filling, reduces the turbulence and the oxide formation (which prevent porosity creation).
    - Main applications: for high quality parts (usually with safety requirements), such as wheels, suspension and steering parts, also engine components.
    - Alloy types: usually primary alloy with low Fe content to ensure high ductility, for example AlSi7Mg0,3 (>90% of alloy used for wheels). Alloys with high recycled content exist for these applications. For example AlSi7Mg0,3 from Raffmetal's Silval range (Raffmetal 2022), which is produced mostly from EOL wheels, recycled in closed loop.

- High Pressure Die Casting (HPDC), illustrated on the right side of Figure 10. HPDC involves forcing molten aluminium at high speed and high pressure (> 1000 Bar) into a steel die.
    - Main applications:
        - for complex parts & high volumes (>100 000 units/year), usually for engine parts: engine blocks, bed plate, bulk cover, transmission housing, clutch housing, driveline components, valve cover, etc.
        - for complex parts but smaller volumes (e.g., for luxury cars), such as structural or suspension parts (shock towers, A/B pillar)
    - Disadvantages: High investment required.
    - Alloy types:
        - For engine parts, it is mostly secondary alloy: around 85% ENAC46000 (A380 / AlSi9Cu3(Fe)).

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[7] Other processes involve shell mould, centrifugal, investment. Investment casting = lost wax casting. It enables smooth finish reducing the need for machining (aerospace, military, electronics and motorsport industries, or automotive)

- For structural parts, mainly primary alloys, such as AlSi10MnMg, Silafont, Magsimal, Castil 37 → More expensive than ENAC46000 (around 20% more).

- Lost Wax Casting, also called investment casting, is a multi-step process. It involves creating a duplicate of the part with wax, which is then dipped in a ceramic bath to create a shell mould around it. The shell is then put into a kiln to melt and remove the wax. Finally, molten aluminium is poured into the shell to obtain the desired part. It is interesting for complex and thin-wall parts.

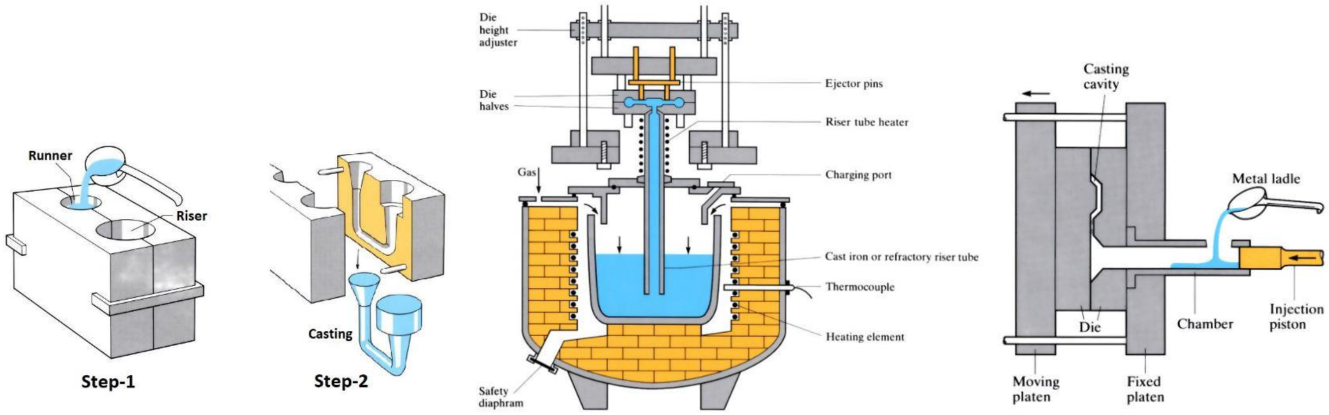

Figure 10: Illustration of the 3 main casting technologies. Gravity Die Casting on the left, Low Pressure Die Casting in the middle and High Pressure Die Casting on the right (Pictures from open.edu)

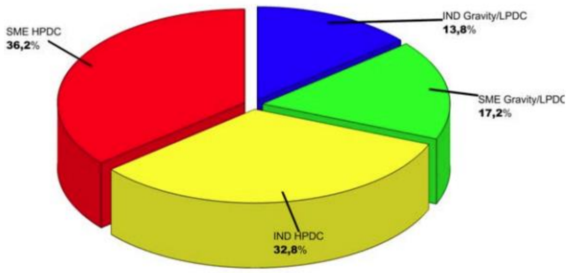

Figure 11: Partition of EU foundries: Gravity and LPDC (Low-Pressure Die-Casting) vs HPDC (High-Pressure Die-Casting), taking into account SMEs and IND (Ferraro 2013)

3.1.4.3 Post-casting technologies:

Machining: after casting, most foundries perform machining on the part to increase the value of the parts.

Heat treatment: heat treatment can help improve the mechanical properties of the cast parts. Several heat treatments exist: T4, T5, T6 and T7 (and variations of each). Operating parameters for heat treatment (temperature range, duration, cooling speed, annealing time & temperature...) depend on the alloy and required properties. Right heat treatment can compensate low/lower quality aluminium, for example high levels of iron and copper.

Waste recycling: All foundry wastes are recycled, either clean scraps, which are recycled directly inhouse (put back into the melt), or small/dirty scrap (turnings, iron containing parts, rejects, etc.) are sold to scrap dealers for recycling. Most foundries optimize their load to purchase as less raw material as possible.

Table 1: Characteristics of the main casting technologies (information from CTIF & IRT M2P)

Characteristics	Sand	Die	Low pressure	High pressure	Lost wax
Production numbers	Low to high	Small to large		Very large	Small to large
Tooling lifespan (number of parts)	-	50 000 à 100 000	50 000 à 100 000	100 0000 à 250 000	10 0000 à 250 000
Dimensions	1 cm to 2-3 m	< 1m	< 700-800 mm	< 700-800 mm, 1 to 2 m with Giga press	1cm to > 1 m
Part weight	1 g to 2 t	< 50 kg	< 35 kg	< 35 kg	1 g to 40 kg
Min thickness	2,3 to 4 mm	2,5 to 3,5 mm	2,5 to 3,5 mm	1 mm	0,8 to 1,25 mm
Max thickness	-	50 mm	50 mm	12 mm	12 mm
Shape complexity (1: low; 5: high)	1	2	2	2 to 5 (?)	1
Production capacity (1: low; 5: high)	2-5	2	2	5	1
Equipment cost (1: low, 5: high)	1	4	4	5	3

3.1.5 OEMs

3.1.5.1 Automotive manufacturers

Automotive manufacturers usually choose cast components when they require complex shapes: casings, wheels and structural parts. Big automotive OEMs, such as Stellantis or Group Renault, produce as much cast aluminium components inhouse as they order from foundries (Tier1 suppliers). According to the OEMs contacted in the frame of the study, most inhouse castings are performed with HPDC (using secondary casting alloys ENAC46000), and external foundries perform other types of parts with primary casting alloys, such as wheel with LPDC for example.
All HPDC components are not produced within OEMs as major foundries, such as Endurance Overseas, produce a large amount of HPDC for OEMs (Figure 11 also shows this trend).

For parts produced outside OEMs, they rely on a global network of suppliers using tender processes to assign the orders. Big OEMs, never work with one single supplier, to avoid supply issues and can rely on several suppliers for the production of one specific part. Most OEMs produce and sell vehicles worldwide, they work with suppliers all over the world (the closer to the plants as possible).

In terms of design and production process, OEMs are the key players, they design cast components and select alloy and casting technology/parameters, for inhouse castings as well as for externally produced parts. The main requirements concern primarily the mechanical and corrosion resistance properties. GHG emissions associated to the component production, begin to be taken into consideration.
Alloy composition, casting technology and casting parameters, as well as potential heat treatment are derived from these technical requirements (and so does the choice of “primary” or “secondary” alloy, or actual recycled content).

The choice of aluminium alloy is thus mainly based on the expected properties of the component:

- “Primary alloys” are usually required for parts with high deformation capacity and corrosion resistance. According to the discussions with OEMs, for “security components” such as wheels, asking for “primary alloy” is simpler as they are well known and “it doesn’t require to specify long list of requirements”.
- “Secondary alloys” are used for standard mass production parts (HPDC), for components which don’t require high deformation capacity or corrosion resistance.

When “full components” are purchased by OEMs, there are generally no alloy specification: OEMs only specify the functions of the component and its “footprint” (size/volume it has to fit in).

3.1.5.2 Non-automotive related OEMs

Beside the automotive industry, aluminium casting parts are used in other industrial sectors, such as household goods or construction. Casting components are indeed used for small appliances (housings, casings for e-motor, evaporator in steam iron, etc.), cookware, etc.

Small casings in household goods are often low value sub-components, they are produced by tier 2 suppliers on the basis of general designs from OEMs or footprint (and expected function). Standard secondary alloy together with HPDC can be used.
Cookware, where the casting part is the main element, are produced directly within the OEMs. The aluminium has however strong requirement in terms of composition, to satisfy regulation (food applications): copper and zinc content are limited (Cu≤0,6%; Zn≤0,25%, Sn ≤0,1%, amongst others), which should prevent the use of standard "secondary alloy".

3.1.6 Interactions along the value chain

Over the whole value chain, the players interact with each other on several levels: technical, logistic and economic level.
Refiners and foundries:

- Refiners either produce only one single specific alloy or produce special alloys according to negotiations with customers (spot, monthly and/or yearly).
- Chemical compositions requested are based on alloy standards (EN1706/1676) AND on customer specifications (narrower tolerances).
- Production accepted providing rentability (type of alloy, production capacities, requested volumes, scrap availability…).

Refiners and OEMs:

- Not a lot of direct relations, unless OEMs has inhouse foundries (same relation as for foundries).
- Refiners can use OEM's production wastes (new scrap, but these scraps usually transit through scrap dealers).

Refiners and scrap dealers & scrap processors:

- Refiners specify required old and/or new scrap grades and characteristics (composition, dimensions/shape, max residual content…), when possible, on the basis of existing standards (see §3.3).
- Aluminium scrap prices are linked to primary aluminium market prices but there are also specific prices variations due to scrap availability and demand.
- Refiners depend strongly on scrap dealers/processors/traders which are their direct suppliers. Refiners could have direct contact(s) and contract(s) with new scrap producers, but that endanger their contact with scrap dealers and lead to loss of contracts.

OEMS and foundries:

- OEMs specify design, process, technic and alloy type (composition).
- OEMs develop new products and processes inhouse, it can take time (years) between product development and transfer from inhouse production to external supply.
- OEMs are open to innovations/suggestions from foundries/refiners, but innovation often originate from OEMs themselves (top-down technical innovation rather than bottom-up).

OEMS and scrap dealers:

- OEMs sell new scrap to scrap dealers & scrap processors
- OEMs can work directly with ATF networks to supervise the collection and treatment of ELV
- OEMs can organize recovering schemes to recover specific EOL products and ensure closed-loop recycling

Foundries and Scrap dealers:

- Foundries sell "dirty" production scraps (chips, turnings...) to scrap dealers
- It is theoretically possible for foundries to buy clean scrap to use at melting stage but it is not a common practice. The example of Ronal and Eccomelt is a good example of what is feasible.

Apart from direct interaction along the value chain, there are some levels of cooperation between the different players in the value chain: a few national or European research projects involving scrap processors with aluminium producers and/or sorting machine manufacturer and/or OEMs (e.g., AUSOM, SAMELA, PICK-IT, etc.). The most advance industries are involved in several project and try to have prospective vision at ~10 years. According to the discussions with scrap processors and refiners, most communication on recycling and recycling optimisation is done in the frame of conferences, congresses, salons, mainly through sales persons, not with R&D people. For small companies, such as refiners and foundries, there is little cooperation with other players: R&D projects require fundings and human resources, which are not easily available in SMEs.
Note: most contacted entities understand the need for such cooperations and works, and would welcome any initiatives to help them in that regard.

3.2 Casting alloys

3.2.1 Different casting alloy categories and their applications

Many different casting alloys exist and are used for a wide variety of applications. End applications often dictate the requirements associated with the cast parts (design, mechanical properties, corrosion properties…), which in turns dictates the alloy types and casting technologies. EN 1676:2020 and 1706:2021 standards provide specifications for all major casting alloys (Table 2 and Table 3). The first one for ingots, the second one for cast parts. They specify acceptable compositions (ranges for each element) and expected properties (Table 4).

Several designations exist for aluminium, for example European Standard designation (e.g., *ENAB46000),* AA Designation system (A380), French designation (Al Si9Cu3(Fe), old system AS9U3), etc. Annex 2 explains the principle of European and AA designation systems works.

Figure 12 shows the main casting alloys used by EU foundries. Not surprisingly, it shows that ENAB46000 is widely used in with more than half of the foundries interviewed (ENAB46000 = standard secondary alloy for automotive engines with HPDC). The second most used alloy is ENAB43400, used in brake systems, aeronautics and common goods. Then ENAB42100 and 47100, the first one being widely used with LPDC for wheel production.

*Note: because during the melting at the foundry some metal losses can occur (aluminium oxidation, Mg evaporation, etc.), European standards for casting alloys provide a different specification for ingot and for cast parts. Standard EN 1706:2021 provide composition for cast parts, whereas EN 1676:2020 composition for ingots[8]. For example, for AlSi10Mg (ENA**C**43000 for cast parts, ENA**B**43000 for ingots), maximum iron content is 0,40% for ingots and 0,55% for cast parts.*

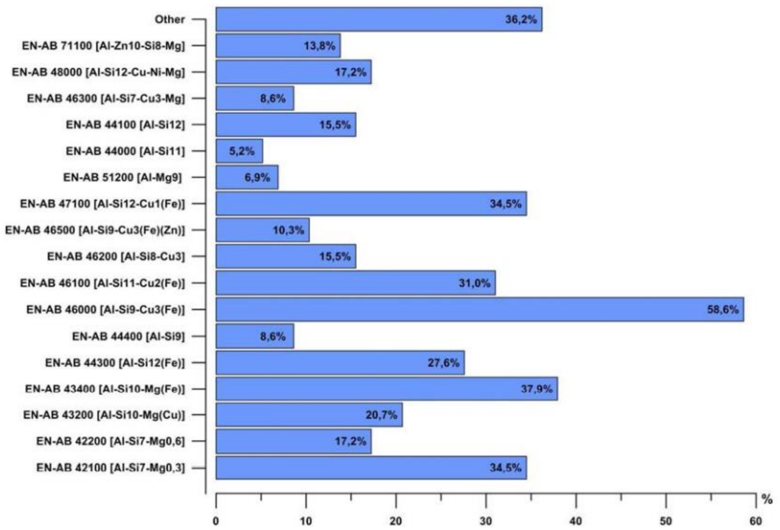

Figure 12: Alloys used by EU foundries (interviewed during Starcast project) – Alloy designation according to EN 1676:2010 (Ferraro 2013)

[8] Compositions for both cast parts and ingots are actually provided in both standards 1706 and 1676.

Table 2: List of standardized casting alloys, with main element composition and casting technology. Table taken from Ferraro 2013, based on EN 1706 standard (Ferraro 2013; Standardization 2021)

AA number	Product(a)	Composition, % Cu	Mg	Mn	Si	Others
201.0	S	4.6	0.35	0.35	...	0.7 Ag, 0.25 Ti
206.0	S or P	4.6	0.25	0.35	0.10(b)	0.22 Ti, 0.15 Fe(b)
A206.0	S or P	4.6	0.25	0.35	0.05(b)	0.22 Ti, 0.10 Fe(b)
208.0	S	4.0	...	...	3.0	...
242.0	S or P	4.0	1.5	...	...	2.0 Ni
295.0	S	4.5	...	...	0.8	...
96.0	P	4.5	...	...	2.5	...
308.0	S or P	4.5	...	...	5.5	...
319.0	S or P	3.5	...	...	6.0	...
336.0	P	1.0	1.0	...	12.0	2.5 Ni
354.0	P	1.8	0.50	...	9.0	...
355.0	S or P	1.2	0.50	0.50(b)	5.0	0.6 Fe(b), 0.35Zn(b)
C355.0	S or P	1.2	0.50	0.10(b)	5.0	0.20 Fe(b), 0.10Zn(b)
356.0	S or P	0.25(b)	0.32	0.35(b)	7.0	0.6 Fe(b), 0.35 Zn(b)
A356.0	S or P	0.20(b)	0.35	0.10(b)	7.0	0.20 Fe(b), 0.10 Zn(b)
357.0	S or P	...	0.50	...	7.0	...
A357.0	S or P	...	0.6	...	7.0	0.15 Ti, 0.005 Be
359.0	S or P	...	0.6	...	9.0	...
360.0	D	...	0.50	...	9.5	2.0 Fe(b)
A360.0	D	...	0.50	...	9.5	1.3 Fe(b)
\380.0	D	3.5	...	...	8.5	2.0 Fe(b)
A380.0	D	3.5	...	...	8.5	1.3 Fe(b)
383.0	D	2.5	...	...	10.5	...
384.0	D	3.8	...	...	11.2	3.0 Zn(b)
A384.0	D	3.8	...	...	11.2	1.0 Zn(b)
390.0	D	4.5	0.6	...	17.0	1.3 Zn(b)
A390.0	S or P	4.5	0.6	...	17.0	0.5 Zn(b)
413.0	D	...	...	...	12.0	2.0 Fe(b)
A413.0	D	...	...	...	12.0	1.3 Fe(b)
4430	S	0.6(b)	...	...	5.2	...
A443.0	S	0.30(b)	...	...	5.2	...
B443.0	S or P	0.15(b)	...	...	5.2	...
C443.0	D	0.6(b)	...	...	5.2	2.0 Fe(b)
514.0	S	...	4.0	...	...	...
518.0	D	...	8.0	...	...	...
520.0	S	...	10.0	...	...	...
535.0	S	...	6.8	0.18	...	0.18 Ti
A535.0	S	...	7.0	0.18	...	...
B535.0	S	...	7.0	...	...	0.18 Ti
712.0	S or P	...	0.6	...	...	5.8 Zn, 0.5 Cr, 0.20 Ti
713.0	S or P	0.7	0.35	...	...	7.5 Zn, 0.7 Cu
771.0	S	...	0.9	...	...	7.0 Zn, 0.13 Cr, 0.15 Ti
850.0	S or P	1.0	...	...	...	6.2 Sn, 1.0 Ni

(a) S, sand casting; P, permanent mold casting; D, die casting. (b) Maximum

Table 3: EN 1706 standard, alloy designation and mechanical properties of alloys commonly used in pressure die-cast (Ferraro 2013)

Alloy group	Alloy designation Numerical	Chemical symbols	Temper designation	Tensile strength [MPa]	Yield strength [MPa]	Elongation [%]	Brinell hardness [HBW]	US AA/ASTM
Al	-	Al 99.6E	F	75	-	10	17	150
	-	Al 99.7E	F	75	-	10	17	
AlSi10Mg	EN AC-43400	EN AC-AlSi10Mg(Fe)	F	240	140	1	70	A360
	EN AC-43500	EN AC-AlSi10MnMg	F	250	120	5	65	365
			T5	270	150	4	80	
			T7	200	120	12	60	
AlSi	EN AC-44300	EN AC-AlSi12(Fe)(a)	F	240	130	1	60	A413
	EN AC-44400	EN AC-AlSi9	F	220	120	2	55	
	EN AC-44500	EN AC-AlSi12(Fe)(b)	F	240	140	1	60	
AlSi9Cu	EN AC-46000	EN AC-AlSi9Cu3(Fe)	F	240	140	<1	80	A380
	EN AC-46100	EN AC-AlSi11Cu2(Fe)	F	240	140	<1	80	384
	EN AC-46200	EN AC-AlSi8Cu3	F	240	140	1	80	380.0
	EN AC-46500	EN AC-AlSi9Cu3(Fe)(Zn)	F	240	140	<1	80	A380
AlSi(Cu)	EN AC-47100	EN AC-AlSi12Cu1(Fe)	F	240	140	1	70	A 413
AlSiCuNiMg	EN AC-48100	EN AC-AlSi17Cu4Mg	F	220	160	<1	90	B390.0
AlMg	EN AC-51200	EN AC-AlMg9	F	200	130	1	70	
	EN AC-51500 [a]	EN AC-AlMg5Si2Mn	F	250	140	5	70	B179-82

[a] *These mechanical properties are typical for wall thickness up to 4 mm.*

NOTE: For F temper (as cast condition), the values specified in this table can be eventually obtained only after holding a few days at room temperature.

Table 4: EN 1706:2010 standard, Chemical composition of alloys commonly used in pressure die-cast (wt%) (Ferraro 2013)

Alloy designation	*Si*	*Fe*	*Cu*	*Mn*	*Mg*	*Cr*	*Ni*	*Zn*	*Pb*	*Sn*	*Ti* [b]	*Others* [a]	
												Each	*Total*
EN AC-43400	9,0 - 11,0	1.0	0.10	0.55	0.20 - 0.50	-	0.15	0.15	0.15	0.05	0.20	0.05	0.15
EN AC-43500	9.0 - 11.5	0.25	0.05	0.4 - 0.8	0.10 - 0.60	-	-	0.07	-	-	0.20	0.05	0.15
EN AC-44300	10.5 - 13.5	1.0	0.10	0.55	-	-	-	0.15	-	-	0.15	0.05	0.25
EN AC-44400	8.0 - 11.0	0.65	0.10	0.50	0.10	-	0.05	0.15	0.05	0.05	0.15	0.05	0.15
EN AC-44500	10.5 - 13.5	1.0	0.20	0.55	0.40	-	-	0.30	-	-	0.15	0.05	0.25
EN AC-46000	8.0 - 11	1.3	2.0 - 4.0	0.55	0.05 - 0.55	0.15	0.55	1.2	0.35	0.15	0.25	0.05	0.25
EN AC-46100	10.0 - 12.0	1.1	1.5 - 2.5	0.55	0.30	0.15	0.45	1.7	0.25	0.15	0.25	0.05	0.25
EN AC-46200	7.5 - 9.5	0.8	2.0 - 3.5	0.15 - 0.65	0.05 - 0.55	-	0.35	1.2	0.25	0.15	0.25	0.05	0.25
EN AC-46500	8.0 - 11.0	1.3	2.0 - 4.0	0.55	0.05 - 0.55	0.15	0.55	3.0	0.35	0.15	0.25	0.05	0.25
EN AC-47100	10.5 - 13.5	1.3	0.7 - 1.2	0.55	0.35	0.10	0.30	0.55	0.20	0.10	0.20	0.05	0.25
EN AC-48100	16.0 - 18.0	1.3	4.0 - 5.0	0.50	0.25 - 0.65	-	0.30	1.5	-	0.15	0.25	0.05	0.25
EN AC-51200 [c]	2.5	1.0	0.10	0.55	8.0 - 10.5	-	0.10	0.25	0.10	0.10	0.20	0.05	0.25
EN AC-51500 [c]	1.8 - 2.6	0.25	0.05	0.4 - 0.8	4.7 - 6.0	-	-	0.07	-	-	0.25	0.05	0.25

[a] *"Others" includes all the elements which are not listed in this Table or without specific values, while it does not include modifying or refining elements such as Na, Sr, Sb and P.*

[b] *Refining agents such as Ti, B or master alloys containing nucleating particles such as TiB_2 shall not be considered as impurities.*

[c] *For alloys with Mg ≥ 3 %, the alloy may contain 0,005 % Be max.*

3.2.1.1 Alloys for automotive industry

As mentioned earlier, the automotive industry is the major consumer of casting alloys, with uses of cast components in several applications detailed in Table 5, from Arowosola (2019): engine (cylinder), rest of engine, transmission, suspension parts, brake systems, wheels.

We can see from Table 5 that more than ten different casting alloys can be used. However, two main alloys cover a significant share of the volumes: 380 and 356, covering about 60 % of aluminium in today's vehicles:

- 380, ENAC46000 according to European designation, is the standard secondary casting alloy. This is the main alloy used for HPDC of engine components (cylinder heads, oil pans...), as well as some transmission elements (gearbox housings). This alloy is used when high strength is required, but not high ductility nor high corrosion resistance.
- 356, ENAC42100 according to European designation, also known as AlSi7Mg0.3, is a standard primary alloy for wheels, produced with LPDC. This alloy is used when high strength, high ductility and corrosion resistance are required.

Other cast components represent lower volumes, but this could change with the use of HPDC and "Giga press" for the production structural components. Indeed, today, most structural components are produced from primary alloys today (e.g., AlSi7Mg), some with LPDC (parts such as rear axles, subframes) and some with regular HPDC (specifically parts in Cadillac, BMW or Audi). Giga cast technology (developed by IDRA, based on HPDC process) could help produce bigger parts, possibly with other types of alloys. At the time, only Tesla uses Giga presses with primary alloys, but other OEMs are starting to invest in the technology (e.g., Volvo).

Table 5: Main aluminium alloys used in the automotive industry from Arowosola (2019)

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, AlZn5Bi4
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

Alloy names given with AA designations. Equivalence with European: 319 = Al-Si5Cu = ENAC 34500; 356 = AlSi7Mg0.3 = ENAC-42100; 359 = AlSi9Mg0.5 = ENAC-43300; 360 = AlSi10Mg = ENAC-43400; 380 = Al-Si8Cu3Fe = ENAC 46500; A380.1 = AlSi9Cu3 = ENAC 46000

3.2.1.2 Construction

Most construction products use wrought or extruded aluminium (gutter, pipes, walling, roofing, panels, windows, shading…). Only a relatively small number of pieces can use cast alloys, and because they usually are low value parts, with low volumes (compared to automotive parts), they are mostly produced outside EU. Table 6 lists casting alloys used in the construction industry and a few examples of products are listed below, and illustrated on Figure 13.

- Gutter fittings, ornaments
- Custom fences
- Handles
- Mounting brackets
- Chimney outlets

Figure 13: Urban panel element AlSi7Mg0.3 (left) - Ornamental use of AlSi10Mg (right) (Pictures from fonderie-aluminium-declercq.fr); drain fittings on the right, from drainagecentral.co.uk

Table 6 : List of casting alloys used in construction industry and main components associated (Davis 2001)

Alloys	**Application**
308	General-purpose permanent mould castings; ornamental grilles and reflectors
356	Bridge railings
413	Architectural, ornamental, street lamp housing
518	Architectural and ornamental castings

3.2.1.3 Other transports - railway

Aluminium for railway applications mainly use wrought alloys for train body (panels) and structure, or forged aluminium for mechanical components such as axle box (7050 – as they are safety parts). There are nonetheless a few applications where casting alloys are used, illustrated on Figure 14:

- Gearbox housing: with AlSi7Mg and AlCu4Ti, from LPDC.
- Seat frames.

For these two applications, the demand can be estimated roughly and is quite low (<15 kt/y).

Figure 14: Railway seat frame elements AlSi7Mg0.3 (Pictures from fonderie-aluminium-declercq.fr) ; gearbox housing on the right from Sun (Sun, Han, and Dong 2021)

Table 7 : List of casting alloys used in railway industry and main components associated (Davis 2001)

Alloys	**Application**
295	Railway car seat frames
356	Car seat frames
520	Railway passenger car frames

3.2.1.4 Other transports – Aeronautic and aerospace industry

The share of aluminium used in major aircraft has been decreasing significantly in the past years, due to the high penetration rate of composites materials. Indeed, composites which represented around 20% of the mass of Airbus/Boeing planes 15 years ago, are now reaching 50% (see Figure 15 and Table 9). This trend has been reducing the share of aluminium to around 20% in the latest aircraft designs[9]. Current demand worldwide of aluminium for aeronautic is estimated around 300 to 350 kt/y (Djukanovic 2016).

Most aluminium used in the aeronautic is high grade wrought aluminium for body, panels and structure. According to Bhat (2018), aluminium castings have only been used in non-structural parts in aircrafts. They are used in pulley brackets, quadrants, doublers, clips, ducts, valve bodies of hydraulic control systems. The philosophy is to use casting alloys in the structures where failure cannot cause loss of the aircraft. Table 8 lists the main casting alloys used in aeronautic and aerospace, as well as associated components.

Table 8 : List of casting alloys used in aeronautic and aerospace industry and main components associated (Davis 2001)

Alloys	Application
201	Aerospace housings
242	Heavy-duty pistons; aircraft generator housings
295	Gear housings; aircraft fittings; compressor connecting rods
354	Premium-strength castings for the aerospace industry
356	Aircraft wheels; airframe castings; railings
357	Corrosion-resistant and pressure-tight applications
359	High strength castings
360	Instrument cases; cover plates
520	Aircraft fittings

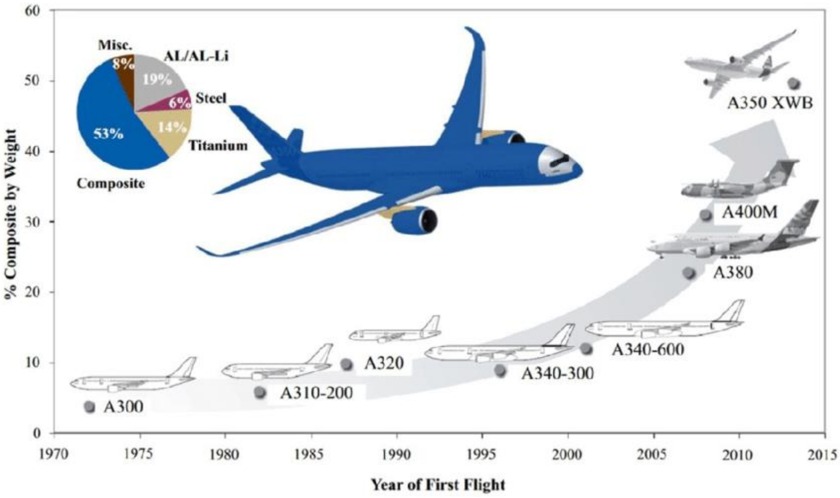

Figure 15: Trends in the use of composite materials in Airbus aircraft (Trzepieciński et al. 2021)

Table 9 : Materials used in Boeing aircrafts (weight%) (Gloria et al. 2019)

Boeing Series	Al Alloys	Ti Alloys	Steels	Composites	Others
747	81	4	13	1	1
757	78	6	12	3	1
767	80	2	14	3	1
777	70	7	11	11	1
787	20	15	10	50	5

[9] This trend could change in the next 5 to 10 years (and go back to past practices) as aircraft manufacturers are confronted to difficult management of the end-of-life of their products, with as of today, no efficient recycling process for composite materials.

3.2.1.5 Home appliances

Aluminium castings are used in many appliances and consumer durables, in motor housing in lawn mowers, casings, cookware, etc. Aluminium is also used in many small electric and electronic appliances, such as smartphones and laptops. However, these applications use wrought aluminium (6013, 6061, 6063, 7005, 7075). Moreover, most of these appliances aren't produced in Europe. Table 10 lists some of the casting alloys used for common goods and home appliances.

Table 10 : List of casting alloys used in home appliances and main components associated (Davis 2001)

Alloys	Application
360	Cover plates
380	Housings for lawn mowers and radio transmitters; air brake castings
443	Cookware, pipe fittings

3.2.1.6 Naval industry

Like other transport industries, naval industry uses aluminium. It can be used for casings/housings and motor parts, or like for the construction for fittings. The volumes are however quite low compared to the automotive industry. Table 11 lists some of the casting alloys used in this industry.

Table 11 : List of casting alloys used in naval industry and main components associated (Davis 2001)

Alloys	Application
360	Marine castings, outboard motor parts
413	Marine equipment, outboard motor pistons
443	Pipe/marine fittings

3.2.2 Contaminants

Casting alloys are subject to contamination with different elements, which can be called trace or tramp elements. Each element can have a different influence on the alloy, sometimes beneficial, sometime detrimental. Table 12 lists the main effects of the major trace elements: lower corrosion resistance or weldability, reduction of ductility… Table 13 explains the mechanisms and consequences associated to the presence of these elements the microstructure of aluminium alloys: influence on phase, grains, grain boundaries, growth, etc.

During the melting stage, aluminium has a tendency to keep most of the elements in the metal phase, alloying elements as well as undesirables. This can be seen on Figure 16, a radar diagram showing the phases where elements can be extracted (or not) during the melting of different metals (from thermodynamic equilibrium). It can be seen that only Ca, Mg and Be could be recovered in the slag phase, and Hg, Cd and Zn in the gas phase. All other elements tend to remain in the metal phase (i.e., with aluminium). Moreover, some elements are actually desired alloying elements for some specific alloys, but can be contaminants for others alloys. For example, high Si (silicon) content is bad for 2xx-series alloys (Si <0,1%); high Cu for 4xx and 5xx series, etc. That's the main reason why recycling mixed scrap is a challenge.

Standard secondary alloys (319 and 380) have great impurity tolerance (in Fe, Cu, Zn), but they show great variations in strength and elongation values as well as a significant susceptibility to corrosion due to these elements. That makes these alloys usually unsuitable for applications in safety–critical components.

Table 12: Effects of different contaminants on cast alloys (Raabe et al. 2022)

Impurity element	Undesired influence on alloy and processing
Cu	Lowers corrosion resistance, Lowers weldability
Fe	Forms coarse intermetallic phases, Embrittling effect
Zn	Embrittling effect Promotes oxidation of the liquid
Mg, Ca, Na	Promote oxidation of the liquid, Lead to mold sticking

Table 13: Overview of the possible impact of scrap elements on processing and properties (Raabe et al. 2022)

	Mechanism	Consequence	Effect on
Trace elements (impurities)	Segregation to grain boundaries	Modify grain boundary energy	Grain growth
		Modify heterogeneous nucleation energy	Precipitate nucleation
		Modify grain boundary mobility (solute drag)	Grain growth Recrystallization
	Segregation to dislocations	Dislocation pinning / cross-core diffusion effect	Plastic response / Portevin-Le Chatelier effect
	Trapping of vacancies	Reduce/increase effective diffusion coefficient	Precipitation / clustering kinetics
		Change lattice concentration of vacancies	Extension of precipitation free zones
	Heterogeneous nucleation	Increased nucleation rates	Precipitate/dispersoid density
Precipitate-forming elements	Precipitate/dispersoid formation	Capture other alloying elements	Precipitate formation / change of precipitation sequence
	Enter into precipitates	Change its crystal structure	Change thermodynamic stability

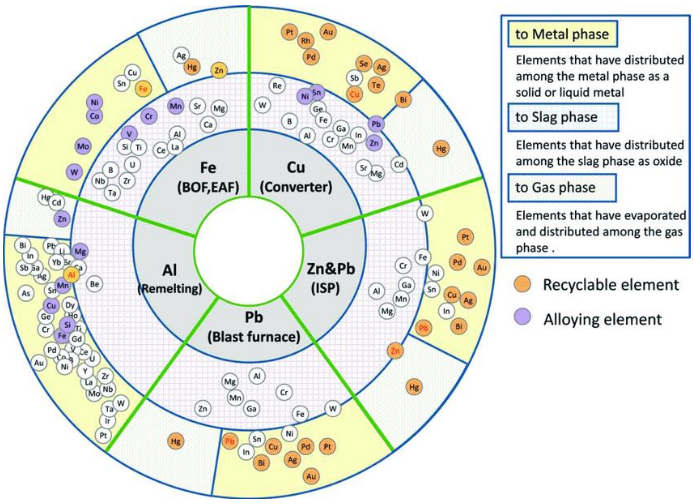

Figure 16: Element radar chart for the metallurgical process of base metals (Nakajima et al. 2010)

3.3 Scrap types and composition

3.3.1 Scrap volumes estimations

Material Flow models can help estimate current and future theoretical[10] scrap volumes. Knowing how much semi-products were put on the market in the past 50 to 70 years and the average lifespan of each type of products, it is possible to evaluate how much aluminium should reach end of life today and in the next 10 years. For 2020, these volumes were estimated here (data from IRT M2P):

- Automotive industry: around 1,8 Mt of aluminium from ELV should be available in 2020, figure which should reach up to 2,9 Mt in 2040. Due to the specific end of life treatment process, aluminium can be recovered in different fractions of scrap:
    - Scrap as shredded residues in “Twitch” quality ~ 500 to 1500 kt/y from ELV + mixed with other EOL products (construction, MSW)
    - Full or shredded separated engine parts ~ 200 to 500 kt/y (cylinder heads, transmissions, etc.)
    - Wheels ~ 90 à 300 kt/y
- Waste from electric & electronic equipment > 500 kt/y
- UBC ~ 300 to 500 kt/y. UBC are partially recycled in closed loop, but part of them can be shredded with other products or end up in incinerated bottom ash. Another part is collected and bailed for use at refiners.

[10] Theoretical = if all EOL products were actually collected and processed in EU. For example, current ELV estimated collection rates in Europe are estimated between 50 and 75%, depending on the segment and country. What is not included in the collection rate is the share of ELV which are either exported outside Europe (for re-use/dismantling/recycling), collected at illegal facilities (not authorised), or doesn’t reach EOL yet. Part of the ELV not collected through official and authorised process can thus be recycled in Europe, but it is difficult to estimate how much.

- Construction wastes ~ 500 to 900 kt/y. This category contains many different products, some of it is recovered in « Twitch » fraction from the shredder, window frames can be recovered and treated separately, cables can be collected and processed separately to produce clean high-quality aluminium granulates.
- Other products (packaging, other transports, industry...) >1000 kt/y
- New scrap (all types) is estimated to amount to more than 1000 kt/y

It is also important to take into account the impacts of trade, and look at the export of scraps. According to Gobbo (GRIF Fabio Gobbo; 2019), Figure 17, the net aluminium scrap export from EU amounted to around 450 kt in 2017: more than 900 kt were exported, but more than 400 kt were also imported. If the global trend from the past 15 years is confirmed, export of scrap should continue to decrease and could be compensate by the imports.

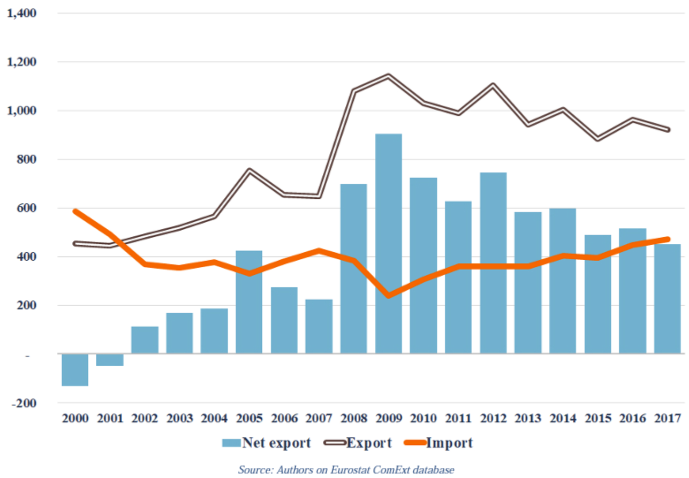

Figure 17: EU net exports of aluminium waste and scrap, in thousands of tonnes. Figure from (GRIF Fabio Gobbo; 2019)

3.3.2 Aluminium scrap in standards and classifications

As shown in the previous paragraphs, aluminium scraps stem from a wide variety of products and alloys, cast and wrought. They can thus take many shapes and have very diverse composition and qualities. To help standardize the recycling process, there are standards and official scrap classifications, which list scrap categories and their acceptable compositions. In Europe, standard EN 13920:2003, lists 15 categories of aluminium scrap. This standard specifies the acceptable composition as well as information on physical properties (thickness, dimensions, etc.). Table 14 gives information on the composition from this standard (the last column gives example of associated product – not from the standard).

Table 14 – List of aluminium scrap categories from Standard BS EN 13920:2003 and their main characteristics (2) – Chemical composition given in %. (European Committee for Standardization 2003)

	Si	Fe	Cu	Mn	Mg	Ni	Zn	Ti	Pb	Sn	Others	Associated products
2 - Unalloyed aluminium	0,25	0,4	0,05	0,05	0,05	-	0,07	0,05	-	-	0,05	Lithographic sheets
3 - Wire and cable	0,25-0,6	0,4-0,3	0,05	0,05-0,6	0,05	-	0,07	0,05-0,1	-	-	0,03-0,05	Wires and cables
4 - Single wrought alloy												Lithographic sheets?
5 - Two or more wrought alloys-same family	0,7	0,7	0,4	0,5	0,6	-	0,4	-	0,1	0,1	0,1	ELV, construction, transport, engineering
6 - Two or more wrought alloys	1-1,5	0,8-1,2	0,8-1	0,5	1	-	0,6-2	0,2	-	-	0,1-0,15	ELV, construction, transport, engineering
7 - Casting	13,5	1,1	3,5	0,5	0,3	-	1,2	0,15	0,2	0,1	0,15	ELV, construction, transport, engineering
8 - Shredded (not separated)	9	1,1	3,5	0,5	0,5	0,3	1,2	0,15	0,2	0,1	0,15	ELV, construction, transport, engineering, EEE, kitchenware
9 - Shredded (separated)	9	1,1	3,5	0,5	0,5	0,3	1,2	0,15	0,2	0,1	0,15	ELV, construction, transport, engineering, EEE, kitchenware
10 - UBC	0,3	0,5	0,2	1,1	1,3	0,01	0,05	0,05	0,01	0,05	0,05	BC from selective collection
11 - Al-Cu radiators		0,7	40								0,2	AC units, ELV
14 - Coated packaging	1	1	2,5	0,4	0,2	0,8	0,2	-	0,2		0,1	Packaging
15 - De-coated packaging	1	1	2,5	0,4	0,2	0,8	0,2	-	0,2		0,1	Packaging
16 - Dross												Smelting process wastes

Apart from the European Standard, there are other types of classifications available:

- The Institute of Scrap Recycling Industries (IRSI), a US based trade association on scrap, created a thorough scrap specifications guide (ISRI 2020), which provides specifications for all types of scraps (ferrous, non-ferrous, glass, plastics…). Concerning aluminium, 48 scrap categories are defined, including 15 new scrap/turning/boring categories. For each category, a code-name is given (for aluminium scrap it usually starts with the letter "T", except for “Zorba”[11]), a title and a definition, providing information on the form of the scrap, sometimes listing unwanted elements (free metallic elements, coatings, etc…), and maximum content of such elements. This classification is mostly used by the recycling industry (shredder, scrap dealers).

- Russia also has classification of non-ferrous scrap (GOST R 54564-2011), which contains 38 categories of aluminium scrap: from A1 to A38. For each category, several requirements are listed, such as metal yield, contaminant content, minimum width, etc.. (АГЕНТСТВО and ПО ТЕХНИЧЕСКОМУ РЕГУЛИРОВАНИЮ И МЕТРОЛОГИИ ; 2013)
- The European Waste Catalogue (EWC) also lists different waste categories, it deals with waste in general, and not actually “scrap”. In the EWC, wastes are classified by types into categories, two levels of sub-categories, using a code with 2, 4 or 6 digits[12].

All these scrap classifications and categories are however not always used by the aluminium industry (aluminium producers, refiners and remelters), they each use generic names or codes, but there are a few exceptions:

- From the ISRI classification, three codes are often used in the aluminium industry: Zorba, Twitch and Taint tabor.
- From the standard classification, some are often used such as UBC, casting, shredded, wires, dross.

When EN 13920 or ISRI codes are used, they are usually provided with additional specifications from the buyers, which can differ from the official guidelines. These can be more or less restrictive and can concern both the physical and chemical properties of the scrap. For example, the maximum admissible content of tramp elements can be lower than defined in standard specification for some refiners, or the maximum admissible length for extrusion scrap can be greater for remelters which have equipment such as shears.

Although the codes/names of the categories used by the aluminium industry can differ from EN 1390 or ISRI categories, they usually cover similar or specific sub-categories, for example “Lithographic sheets” (“Tablet” in ISRI) or “Automobile castings” (“Trump” in ISRI).

Figure 18: Example of aluminium scraps on a refiner scrap yard. Source: IRT M2P (pictures from a French refiner scrap yard) (left: shredded residues, middle: compressed used beverage and aerosol cans; right: mixed scrap from construction)

3.3.3 Scrap composition

The forementioned standards and classifications are useful for scrap dealers and users to based their trades on common and clearly defined scrap categories. It is however important to confront to the expected compositions to real EOL scraps based on their analysis. Refiners who are used to dealing with many different scrap types and several scrap suppliers usually have extended databases based on historical scrap compositions. As this is part of their know-how and expertise, it is difficult to access such databases. However, some information is available online and in the scientific literature, it is presented in the following table (Table 15). It gives the content for major elements and when available the scrap group or product associated, as well as the time period. The 11 last lines correspond to information from a presentation at European Aluminium Workshop[13]. These lines are interesting as they show the expected composition from scraps before and after automated sorting technologies (XRT and LIBS).

[11] Zorba is actually a mix of aluminium with other valuable material such as copper, stainless, magnesium. Although it contains mainly aluminium (>50%), it is not really a “aluminium scrap type” per se.

[12] The first two digits of the EWC code define the main category, the following two the subcategory, and the last two the sub-subcategory. For example, a ECW code starting with “15”, correspond to the category “WASTE PACKAGING; ABSORBENTS, WIPING CLOTHS, FILTER MATERIALS AND PROTECTIVE CLOTHING NOT OTHERWISE SPECIFIED” ; “15 01” code is for “packaging (including separately collected municipal packaging waste)” and in this sub-category exists the sub-sub-category “metallic packaging” (EWC code “15 01 04”) (SEPA 2015).

[13] European Aluminium Workshop = Driving sustainable aluminium: recycling and critical raw materials for aluminium alloys in e-mobility, November 2022. Reference: (Scamans 2022)

Table 15: Scrap compositions from different scientific studies

Products	Scrap group	Si	Fe	Cu	Mn	Mg	Zn	Ni	Cr	Pb	Sn	Ti	Reference	Year
ELV	Bumpers	0,39	0,38	0,32	0,09	0,78	0,75							1994
ELV	Body sheet	0,47	0,21	0,57	0,19	1,34	0,07						1	1994
ELV	Wheels	6,28	0,11	0,01	0,07	0,61	0,01						1	1994
ELV	Brakes	1,54	0,4	0,62	0,14	1,23	0,12						1	1994
ELV	Heat exchangers	2,88	0,44	0,68	0,59	0,21	0,2						1	1994
ELV	All-aluminium engine and transmission	8,61	0,68	2,69	0,27	0,3	1,26						1	1994
ELV	Separated transmissions	10,3	0,9	3,79	0,28	0,21	2,17						1	1994
ELV	Additional engine	7,96	0,57	2,06	0,25	0,36	0,77						1	1994
ELV	Misc. (including shredded ELV hulk)	4,88	0,53	1	0,11	0,64	1						1	1994
ELV	Cylinder heads	5,82	0,38	1,74	0,22	0,06	0,17	0,06	0,01	0,1	0,08	0,02	2	2009?
ELV	Cylinder heads	5,86	0,51	2,93	0,25	0,06	0,18	0,04	0,01	0,06	0,06	0,06	2	2009?
ELV	Cylinder heads	5,46	0,71	3,09	0,29	0,04	0,27	0,04	0,01	0,12	0,08	0,06	2	2009?
ELV	Cylinder heads	6,06	0,43	1,22	0,28	0,08	0,16	0,02	0,01	0,07	0,05	0,05	2	2009?
ELV	Pistons	7,88	0,9	1,61	0,08	0,47	0,11	1,83	0,02	0,06	0,1	0,1	2	2009?
ELV	Pistons	8,56	0,61	2,05	0,07	0,7	0,08	1,73	0,02	0,04	0,06	0,06	2	2009?
ELV	Pistons	8,02	0,84	2,31	0,26	0,84	0,1	1,73	0,02	0,05	0,07	0,05	2	2009?
ELV	Gearbox and rear axle	7,14	0,82	3,3	0,14	0,08	1,14	0,14	0,03	0,13	0,16	0,05	2	2009?
ELV	Gearbox and rear axle	7,09	0,85	3,02	0,19	0,06	0,66	0,1	0,03	0,09	0,08	0,04	2	2009?
ELV	Gearbox and rear axle	7,28	0,86	3,21	0,21	0,06	0,86	0,12	0,03	0,12	0,09	0,06	2	2009?
ELV	Gearbox and rear axle	8,13	0,9	3,49	0,26	0,07	0,75	0,15	0,05	0,13	0,18	0,04	2	2009?
ELV	Gearbox and rear axle	8,45	0,9	3,07	0,23	0,06	0,68	0,11	0,03	0,13	0,18	0,04	2	2009?
ELV	Miscellaneous (mixed parts)	6,75	0,71	3,54	0,2	0,13	1,32	0,23	0,02	0,15	0,18	0,04	2	2009?
ELV	Miscellaneous (mixed parts)	7,14	0,72	2,04	0,22	0,15	0,62	0,29	0,02	0,12	0,12	0,05	2	2009?
ELV	Miscellaneous (mixed parts)	5,62	0,67	1,9	0,24	0,13	1,2	0,13	0,03	0,1	0,18	0,06	2	2009?
ELV	Miscellaneous (mixed parts)	7,34	0,9	2,35	0,19	0,18	0,48	0,59	0,02	0,09	0,09	0,05	2	2009?
ELV?	Radiator scrap	1	0,6	0,2	1		0,8						3	1998
ELV	Car scrap	7,8	0,9	3,1	0,4	0,4	0,6						3	1998
Unknown	Dirty sash scrap	0,7	0,8	0,4		0,2	0,8						3	1998
Unknown	Fragmentiser aluminium scrap (from ISRI?)	7+/- 1	1,1+/- 0,2	2,7+/- 0,9	0,3	0,3+/- 0,15	1,5+/- 0,2	0,1	0,1			0,04	4	Unknown
ELV/Construction/MSW	Twitch Galloo (measured 2021)	5,5	0,53	0,85	0,21	0,51	0,4	0,083	0,036	0,04	0,03	0,017	5	ELV/Construction/MSW
ELV/Construction/MSW	Big Twitch Galloo (estimation)	7,5	0,6	1,7	0,22	0,25	1						6	ELV/Construction/MSW
ELV/Construction/MSW	Small Twitch Galloo (estimation)	8	0,6	2	0,22	0,16	0,8						6	ELV/Construction/MSW
ELV/Construction/MSW	Wrought Galloo (estimation)	2	0,5	2	1	1	1						6	ELV/Construction/MSW
Unknown	Twitch from XRT (Pellenc equip.) wrought fraction	1,38	0,37	0,2	0,23	1,19	0,13	0,017	0,03	0,017		0,024	7	Unknown
Unknown	Twitch from XRT (Pellenc equip.) cast fraction	6,53	0,55	1,93	0,24	0,09	0,99	0,064	0,02	0,065		0,057	7	Unknown
Unknown	Twitch from XRT (Steinert equip.) wrought fraction	1,66	0,29	0,27	0,24	0,81	0,17	0,01	0,02	0,02		0,03	7	Unknown
Unknown	Twitch from XRT (Steinert equip.) big cast fraction	6,53	0,5	2,33	0,2	0,31	1,24	0,07	0,02	0,07		0,05	7	Unknown
Unknown	Twitch from XRT (Steinert equip.) small cast fraction	6	0,52	2,34	0,24	0,16	1,15	0,01	0,03	0,06		0,05	7	Unknown
Unknown	Twitch from XRT (RedWave equip.) wrought fraction (~60% feed)	2,18	0,28	0,25	0,19	0,87	0,17	0,01	0,02	0,02		0,04	7	Unknown
Unknown	Twitch from XRT (RedWave equip.) cast fraction (~40% feed)	8,57	0,69	2,68	0,21	0,48	1,15	0,1	0,03	0,09		0,06	7	Unknown
Unknown	Twitch from XRT RedWave (average)	4,67	0,45	1,1	0,22	0,52	0,41	0,04	0,02	0,03		0,04	7	Unknown
Unknown	Twitch	3,78	0,38	0,74	0,21	0,42	0,3						7	Unknown
Unknown	Twitch sorted by LIBS fraction A (~60% ?)	0,59	0,31	0,1	0,18	0,5	0,06						7	Unknown
Unknown	Twitch sorted by LIBS fraction B (~40% ?)	6,1	0,53	1,28	0,22	0,07	0,46						7	Unknown

References: 1: Gorban 1994 (in Kircain 2007); 2: Mbuya 2010; 3: Sotome 1999; 4: Hoyle 1995; 5: IRT M2P; 6: Galloo 2020; 7: Scamans 2022

From these scrap compositions, we can notice that there's not one typical « EOL scrap », but many qualities, with varying residuals/alloying elements content. For cast scrap, silicon levels can vary between 5% and 10%, iron levels between 0,38% and 1,1%, copper between 0,62% and 3,8% and zinc between 0,08% and 2,17%.
Furthermore, scrap quality and residual content from one shredding plant can vary over time: depending on the actual shredded products, amount of ELV available during the period, types of construction wastes, WEEE and also with the evolution of the design and materials of the products.
Another interesting information from Scamans' data (2022): innovative automated sorting equipment (XRT and LIBS) can help separate cast from wrought or produce low/high Si/Fe/Cu content scrap. More information on that will be given in paragraph 4.4.5.1.

Scientific studies based on MFA also estimated the future flows (volumes) of aluminium scrap and their theoretical compositions. For example, Hatayama (2012), calculated the future volumes of aluminium scrap in Europe in 2030, for each type of products, and their composition (Table 16). Details for each type of aluminium alloys are presented in the table for the automotive scrap. Although the study has over 10 years, the estimated volumes are close and consistent with the figures calculated by IRT M2P for 2020 (§3.3.1).

Table 16: Expected aluminium scrap composition in 2030 according to Hatayama (Hatayama et al. 2012)

	Scrap type	Amount of Discard [kt]	Si	Fe	Cu	Mn
Building		1,014	1.78	0.48	0.47	0.21
Vehicles	1000 series	327	0.33	0.38	0.09	0.05
	2000 series	0	0.78	0.73	4.94	0.81
	3003	43	0.60	0.70	0.20	1.50
	3004	0	0.30	0.70	0.25	1.50
	Other 3000 series	0	0.60	0.75	0.28	1.11
	4000 series	81	13.50	1.00	1.30	0.00
	5052	45	0.25	0.40	0.10	0.10
	5182	5	0.20	0.35	0.15	0.50
	Other 5000 series	29	0.29	0.31	0.13	0.56
	6061	0	0.80	0.70	0.40	0.15
	6063	250	0.60	0.35	0.10	0.10
	Other 6000 series	1	0.96	0.50	0.23	0.63
	7000 series	11	0.18	0.22	2.08	0.16
	8000 series	0	0.23	1.25	0.05	0.00
	ADC12	1,194	12.00	1.30	3.50	0.50
Vehicles	*average*	*1986*	*7,92*	*0,96*	*2,21*	*0,37*
Transportation		651	9.41	1.08	2.68	0.42
Container and packaging		1,765	0.29	0.59	0.22	1.14
Electrical equipment		571	2.91	0.59	0.84	0.21
Machinery		517	2.76	0.30	0.80	0.12
Consumer durables		371	3.40	0.62	1.04	0.19
Other		518	2.69	0.88	1.08	0.55

3.3.4 Contaminants in aluminium scrap

As explained in §3.2.2, there are many contaminants for cast aluminium alloys. Mixing different types of products, and thus different alloys, can reduce significantly the range of alloys which can be produced from that mix. Figure 19 shows an illustration on a specific case study, showing the amount of scrap (for 8 scrap types – on the left) which can be used in the production of 4 aluminium alloys (2 wrought and 2 cast). Casting alloy 380 on the right is the standard secondary alloy, it can be produced from different scrap mixes (with 45 to 95% of scrap utilisation rate), but will still require some addition to achieve the right composition. For the second casting alloy (355) and the wrought alloys, the scrap utilisation rate is much lower (0 to 40% for 6xxx series). A quick comparison has been made in Annex 3 between 5 different scrap composition from Table 15 and 6 different cast alloy composition from standard specifications. The last table of the annex lists the elements whose content are too high in the scraps for the production of each alloy.

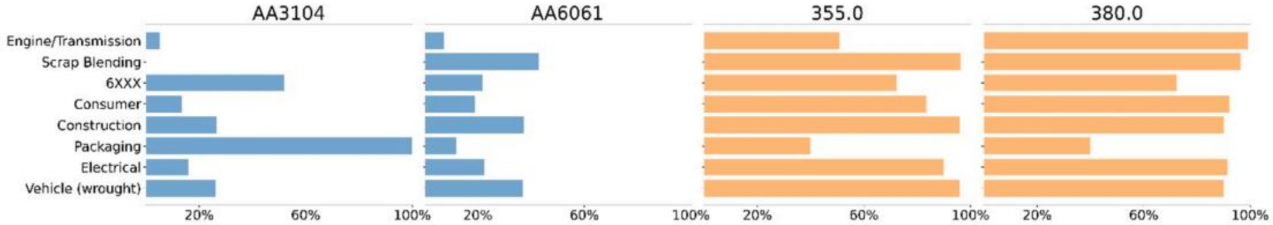

Figure 19: Case study illustrating an idealized view of maximum scrap utilization (%) for wrought and cast aluminium alloys, starting with a typical scrap mixes (Paraskevas et al. 2015)

Also, because EOL scrap is produced from EOL products, most scrap inherit pollution from these products. Due to the increasing complexity of products, there's also an increase in joining points between aluminium parts and other materials. Current recycling processes at EOL can't efficiently separate and remove all the impurities originating from

these assembly points. EOL wheels can be polluted by balancing weights. They weight up to 60 grams. They used to be made out of lead (banned in EU since 2005, but old vehicles could still contain some). Today balancing weights are mostly in Zinc (and in a lesser extend steel + Zn coating). Wheels can also contain valves/screws (iron).
For housings, for example for batteries, they can require joining elements (glue, steel inserts or screws), which are hard to remove with current processes (examples on Figure 20).
In some cases, refiners purchase scrap directly from scrap yards or automotive ATF, which are not processed in a shredder (and automated sorting process). These scraps can contain foreign elements such as steel, copper or zamak parts. These foreign elements can end up in the melt if the scrap is not prepared.

Figure 20: Example of scrap pollution in eV battery casing (steel screws) (pictures from M2P at a French refiner scrap yard)

Finally, contaminants can also stem from bulk parts or components alloy composition. For example, casting alloys for wheels in EU and North America are quite standard today. Around 90% of new wheels are made from heat treated A356 (AlSi7Mg0,3 / EN AC 42100, with addition of strontium) but EOL wheels in Europe are still a mix of different alloys: some contain Sb (especially old French wheels, for which such alloys were used until ~2005), older wheels for other countries were also produced with other casting alloys such as AlSi11Mg.

4 Expected evolutions and trends

4.1 Expected evolutions

4.1.1 Geopolitical and economical constraints

Over the past three years, the combination of crisis has had serious consequences on global economy, which have been impacting most industrial sectors. COVID-19 pandemic led to a sharp slowdown at the beginning of 2020, and then supply issues, reducing the overall consumption and production of goods. This had and has been having an effect on the production of new vehicles (-30% between 2019 and 2022) and thus on the availability of “good quality” scrap for refiners/remelters/aluminium producers (reduction of new and old scraps). Since, the war in Ukraine added an energy crisis, increasing the costs for most aluminium operations, and more particularly refining and casting operations. This reduces the possible margin for these activities, which jeopardize their economic model.
Apart from these specific and contextual crises, “the third wave of globalization[14]” has also been impacting casting alloy market. As mentioned by Lehmus (2022), the costs of casting in Eastern Europe are at parity or above costs in the U.S.. As a consequence, the production of lower complexity and lower added value components is being shifted to lower-wage countries. This globalization impacts the whole supply chain, putting margin pressure on the OEMs, and their suppliers (foundries, refiners, scrap dealers). Also, the economic growth of manufacturers (and foundries...) outside Europe could result in an increasing scrap demand outside EU, leading to potential increase in scrap exports if no policy is put into place to prevent.

4.1.2 EU regulations and policies for the automotive industry

Automotive industry is one of the most regulated sectors in Europe with over 125 regulations, concerning mostly safety aspects, technical requirements and environment. As automotive is the main consumer of casting alloys, current and future regulations in Europe (European Commission 2021, 2022) can have a strong influence on the future consumption of casting alloys, in terms of volumes and alloy types. Three main trends can be pointed out:

- Reduction of CO_2 emissions of the automotive industry, at short term. It should have two main effects:

[14] There is said to be 3 waves or eras of globalization, the first one between 1860 and 1914 with the political leadership of Great Britain and colonialism, the second one between 1944 and 1971 with the leadership of USA and with the cold war and the third “multi-polar” globalization which started in 1989 and is still ongoing, with the adoption of free trade worldwide.

- Reduce emissions in the use phase, encourage light-weighting, including an increase use of aluminium (wrought, extrusion and casts), which mean probably an increased diversity of alloys, and also increased number of multi-materials joining points.
- Reduce emissions in the production phase, automotive manufacturers should favour the use of high recycled content material, which should increase the need for secondary aluminium.

- Reduction of CO_2 emissions of the automotive industry, at longer term, with a shift towards 100% electric vehicles by 2035. This trend is already noticeable today (Figure 21). This could have several effects:
  - Replacement of ICE by electric motors will lead to a reduced demand for standard secondary cast aluminium (ENAC46000).
  - Cars could get bigger to integrated bigger batteries, which would lead to higher material demand.
  - Demand might increase for other cast alloys (high Si alloys, e.g. AlSi10Mg).

- Evolution of the European ELV directive: according to Arowosola (2019), setting high recycling rate targets for full ELV can have a detrimental effect and drive recycling actors to prioritize the achievement of the targets and put recycled content in the easiest sink possible.

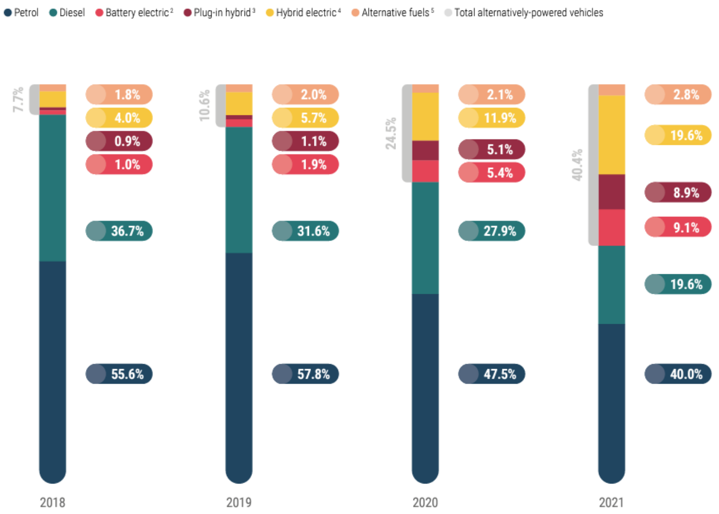

Figure 21: New car market share in the EU by fuel type – Market share 2018/2021 (ACEA 2023)

4.1.3 Strategies and new technologies at company level

With growing concern towards climate change, combined with potential regulation evolutions, major companies have been starting to set medium to long term environmental strategies. These strategies usually set targets in terms of CO_2 emissions[15], recycled content, or re-manufacturing schemes to prolong the life of the products.
As a consequence, most product manufacturers and metal producers look for ways to reduce their carbon footprints (Modern Casting 2021). It involves an increased integration of recycled (EOL) aluminium into wrought and cast aluminium production.
The automotive industry is forced to start shifting toward electric vehicle, requiring new technologies and expertise which are today centralized at OEMs. Currently, the knowledge and knowhow for electrification (i.e., the production of electric motor, battery housing, etc.) is maintained mostly within OEMs. Most external suppliers, such as foundries, can't really take part directly in the "electrification process" yet. This means that electrification process currently results in a net drop in volumes for these foundries.

Finally, new technologies could be used to replace casting components: additive manufacturing, although still fairly uncommon, could become a competing technology to casting. The emergence of this technology could reduce the need for foundries, but not for refiners. Indeed, regular casting alloys can be used in additive manufacturing, such as AlSi7Mg0,6 and AlSi10Mg. These however, are primary alloys, it would be interesting to know whether secondary alloys could be easily used in such applications.

[15] Examples of targets: Stellantis: industry-leading carbon net zero emissions by 2038; Renault Group: carbon neutrality in Europe by 2040 and worldwide by 2050; Audi Group: all production sites carbon-neutral by 2025…

4.1.4 Customers behaviours

Automotive customer behaviours can also have influences on the casting market, but with potential opposite effects:

- In the past ten years, there's a clear trend showing a growing demand for large vehicles (SUV), from about 15% in 2010 to more than 45% in 2021 (Figure 22). This means a higher material intensity, and then again, a growing need for aluminium. It should although be noted that EU regulation could prevent some of this effect with regulation on vehicle weights.
- The lifespan of the products, again more particularly cars, could increase, resulting in a reduction of the demand for car (and thus materials). Nowadays, average scrapping age of ELV tend to increase in Europe. For examples, ELV scrapping age gained 4 years between 2000 and 2020 in Finland (Autoalan Tiedotuskeskus 2022), see Figure 23, and more than 2 years between 2013 and 2021 in France. Furthermore, automotive manufacturers could help prolong the lifespan with more virtuous practices. For example, new production schemes such as Renault's Re-Factory scheme, with "retrofitting" to switch ICE vehicles into BEV.
- The model of car ownership will probably change. In Europe, the old model of buying a car will evolve as more and more people living in cities will use short term subscription to EV when they need it. It is not clear yet which effects it will actually have, as the number of personal cars should be reduced, but the number of cars for rent will strongly increase. On the other side, outside Europe, growing population and car ownership will probably increase, which could lead to growing need for material in the rest of the world.

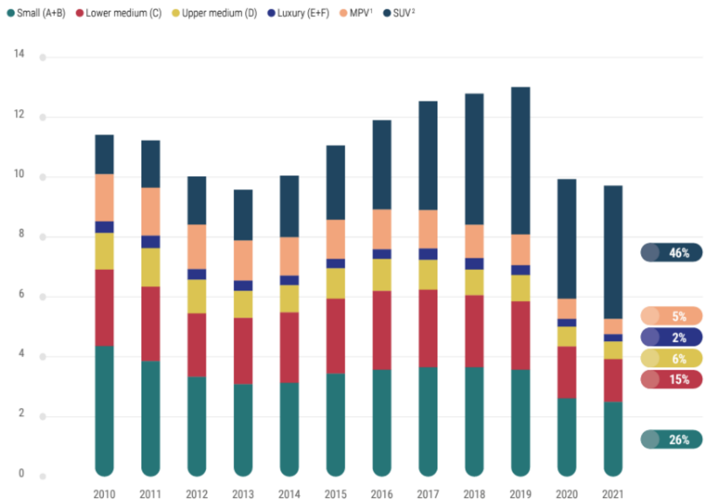

Figure 22: New car market share in the EU by segment – In million units, % share / 2010-2021 (ACEA 2023)

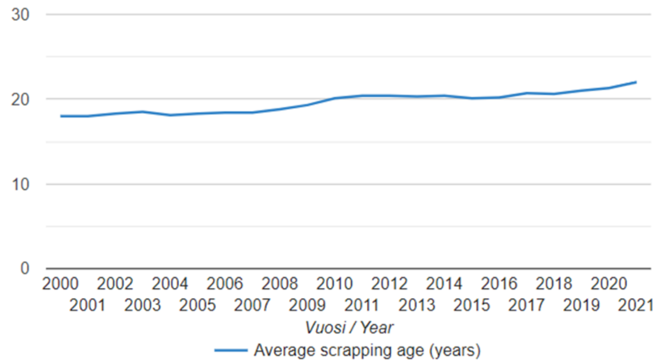

Figure 23: Average ELV scrapping age in Finland (Autoalan Tiedotuskeskus 2022)

4.2 Issues and consequences

All of the previously described evolutions will have consequences, either on the volumes of aluminium, on the types of casting alloys, or the actors of the value chain themselves.

4.2.1 Geopolitical constraints lead to margin pressure on the whole value chain

First of all, the recent geopolitical changes due to past crisis and globalization are putting pressure on the whole value chain. They will probably continue to do so in the near future:

- Because of increasing production costs (energy, supply, labour), European refiners and remelters have to limit their scrap purchase prices to remain profitable compared to foreign suppliers.
- On the other side, scrap dealers and traders could look for exporting more EOL products and scrap metal (outside Europe), leading to:
  - A potential reduction of scrap metal available for new products,
  - Losing alloying elements: scrap aluminium contain alloying element, sometimes critical material (between 0,7 and 3,6 kg of critical material in aluminium per vehicle (Arowosola and Gaustad 2019; Tan et al. 2021)),
  - Exporting scrap is virtually also a loss of energy as scrap can be considered as an “energetic bank” (energy from primary elaboration).

Note: scrap dealers and scrap processors currently export part of their aluminium scraps production, because they consider that the demand is low and also to sell to the highest bidder. Should the local demand & purchase prices increase, they would be able to sell more within EU.

4.2.2 Global (world) automotive aluminium demand is expected to boom by 2050

A second important consequence is a significant growth in aluminium demand by 2050, in particular in the automotive industry. According to Billy (2023), “Aluminium use in passenger cars is likely to quadruple towards 2050” worldwide. This concerns all aluminium products, castings as well as wrought and extruded aluminium parts. Moreover, the growing demand will be coupled with an increasing need for high recycled content aluminium, which will “equal or overtake demand for primary aluminium” according to Hydro (Hydro 2022). European Aluminium expects European aluminium demand to reach 18 Mt in 2050, with 9 Mt produced from scrap.

According to several academic studies (Van den Eynde, Bracquené, et al. 2022; Billy and Müller 2023) (and previous works from NTNUs team), this increasing aluminium demand could be accompanied by a potential global aluminium “scrap surplus”, if no change is made in recycling and sorting practices. The “scrap surplus” is defined as the amount of low-quality scrap (mix scrap from ELV and other products shredding), whose composition wouldn’t allow for remelting and production of new products. It would be essentially caused by the shift toward electric vehicles, whose production couldn’t use standard secondary cast aluminium (ENAC46000).
According to existing studies, worldwide scrap surplus could amount to up to 5.4 Mt in 2030 and 8,7 Mt in 2040 (Van den Eynde, Diaz-Romero, et al. 2022) and more than 10 Mt/y in 2050 (Billy and Müller 2023). Figure 24 from Van den Eynde (2022) shows potential evolutions of the scrap surplus, with different scenarios, showing a variation of scrap surplus between 5 and more than 13 Mt in 2030.

Note: results from these academic studies must be mitigated. They consider that all scraps are collected and recovered as mixed residues "twitch-like scrap", excepted UBC which are considered recovered separately. Nowadays in Europe, a significant part of aluminium scrap is already recovered separately (engine blocks, wheels, window frames, cables...) and can be recycled in “closer loop”.

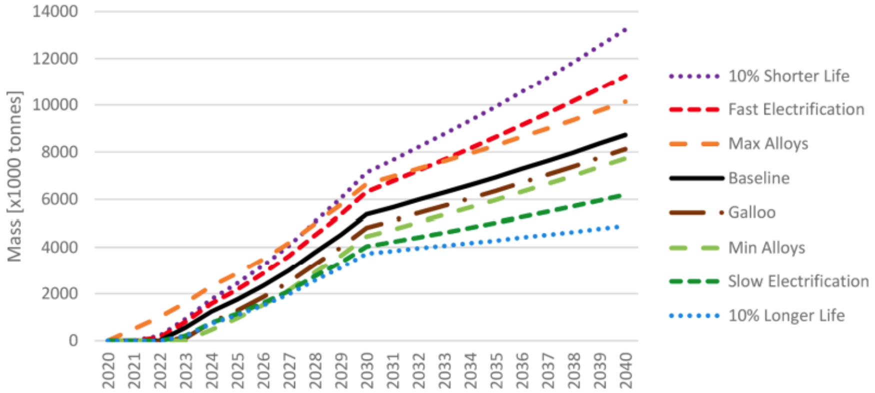

Figure 24: Sensitivity analysis for the evolution of the annual global aluminium scrap surplus (Van den Eynde, Diaz-Romero, et al. 2022)

4.2.3 Evolution of aluminium alloy types in the automotive industry

While global aluminium demand for automotive applications will increase, so will the number of aluminium components, and changes in the alloy types:

- The need for light-weighting, for bigger cars, heavy car for battery integration will require the need for more wrought aluminium, possibly more alloy types (if nothing is done to “regulate”).
- As already mentioned, a reduction of the need for standard secondary cast aluminium (ENAC46000) is expected due to the disappearance of ICE. On one hand, because switching from ICE to full BEV should lead to a reduction of aluminium use in powertrain applications (> 30% of reduction, according to Lehmhus on Figure 25). On the other hand, because currently, standard secondary alloy is not easily applicable for the production of electric motor or battery housings, as there are technical issues (discussed in §4.4.3).
- As explained earlier, to meet future CO_2 emission targets (EURO 7?), automotive manufacturers will require the use of high recycled content aluminium (wrought and cast).

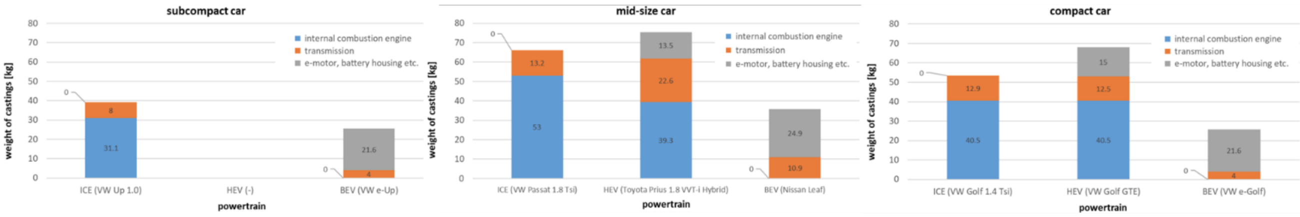

Figure 25: Aluminium weights in powertrain for ICE, PHEV and BEV for 3 segment market (Markets and Lehmhus 2022)

Note: most scrap processors as well as ENAB46000 producers are expecting a demand reduction for this alloy. However, they are looking for clear signs of this trend. Most of them don’t have any issue yet, and they would want proof confirming this trend.

4.2.4 Evolution of the practices at scrap processors and primary aluminium producers

Scrap processors are aware of the expected evolutions cited previously and they understand that there are opportunities there. Recycling processes can evolve, with the use of automated sorting technologies to improve the separation of post-shredder aluminium residues. Such improvements could help channelling “high purity” scrap (wrought, or low alloying element content) toward wrought producers, for close to closed loop recycling. This could lead to a potential reduction of “good quality” scrap availability for refiners (reduction in terms of volumes, and an increase in alloying or residual content).

4.3 New markets for secondary cast alloys

The main application for aluminium casting alloys, today and for the next 10 to 15 years, is automotive (as can be shown in Cullen and Allwood’s diagram on Figure 26). Although the production of ICE vehicles will decrease sharply until 2035 in EU, they are still produced today and this type of secondary casting alloys should continue to be used in ICE and transmission parts[16] until then. Evolutions of the practices and the technologies have potential to help optimized the use of EOL castings:

- Wheel to wheel (closed-loop) recycling: this strategy is already technically feasible, performed at some extent and could be applied European wide (for example at Refinal in France or Raffmetal in Italy). Today, Ronal, a wheel producer, is starting to work with Eccomelt, but in that case the wheels come from Canada.
- Using standard secondary casting alloy (with current HPDC) for the production of eV components.
  - However, there are currently technical issues because of the requirements for such components (in particular regarding heat dissipation).
  - R&D together with component design evolutions could help find a solution.

- The development of new casting practices and technologies (including Giga press) should help developing the production of big structural parts.
  - Today the use of secondary casting alloys in these applications are limited because these big structural parts have to meet high ductility requirements → low iron, copper and zinc content are required (Fe<0,15%).
  - However, R&D on alloy development could help channel secondary cast toward this application. Current works involve, for example, AlSi10Mg0.4 with 0,55%Fe or Al-Mg-Zn-(Cu), uni-alloy[17] (Raabe et al. 2022)

- According to Che (2019), there could be potential in applications related to sensors: new automotive require more and more sensors, some of them requiring housings with corrosion resistance and dimensional stability.

[16] As shown on Figure 25, transmissions parts as still necessary for BEV, but in lower amount than for ICE.
[17] Uni-alloy = universal alloys, which can be used for numerous applications, for example by applying specific heat treatment depending on the application.

Although the volumes wouldn't compensate the shift from ICE to BEV motors, HPDC produced housings for such sensors could be an end market.

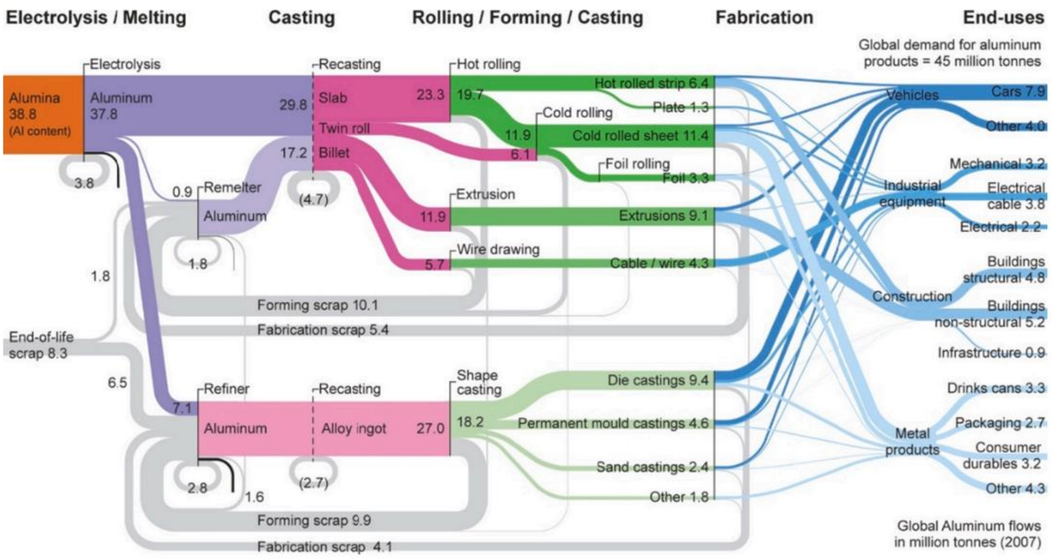

Figure 26: Sankey diagram showing the flow of aluminium from liquid metal into products. Figure from Cullen 2013, quoted by (Raabe et al. 2022)

Today, no other applications could absorb the same amount of casting volumes as automotive industry does:

→ The aerospace, aeronautic and railway industries consume low volumes of casings today (<0,1 Mt), most applications requiring high performance material which limits strongly the use of secondary cast. Moreover, in these sectors there's a competition between aluminium and composite materials, parts historically made from casting alloys are now produced or will be produce with carbon fibre composite (R&D) for weight reduction purposes.

→ For electric, electronic and other home appliances: these are mostly low added value components and a significant share is produced outside Europe. High value products, such as smartphones and laptops, there are also mostly produced outside EU, and mostly with wrought alloys (for mechanical, corrosion and aesthetics properties). Possible solution would involve relocating lower added value industries inside EU.

→ Today, the construction sector uses low volumes of casting alloys (most aluminium construction products are wrought/extruded). Castings are mostly for fittings and customized parts, with high resistance to corrosion. These don't represent high volumes (which is not adapted to HPDC), and the expected properties don't match those of standard secondary castings.

4.4 Possible adaptations and opportunities

4.4.1 Adaptations at scrap dealer or scrap processor level

According to scrap dealers and scrap processors interviewed in the study, if local (EU) demand for conventional scrap (Twitch quality or shredded cast) decreases in the next few years, two main adaptations would be possible:

- Develop export of scrap: part of aluminium scrap produced in Europe is already exported outside Europe. With growing car ownership outside Europe[18] and because the shift toward electric vehicles concerns mainly Europe for the moment, it is expected that changes will occur later in other parts of the world. This could mean a constant or growing demand worldwide, allowing export (this trend have to be confirmed).
- Scrap processors can adapt using new or innovative sorting technologies: to prevent the production of "not recyclable scrap", scrap processors are performing R&D and/or investing in innovative sorting equipment to improve the quality of scrap. They aim at addressing the market of wrought aluminium producers, which are currently trying to integrate EOL recycled content in their products. New sorting technologies should help scrap processors:
    - Sort wrought from cast components/residues,
    - Produce several new qualities, part of them dedicated to primary/wrought aluminium producers.

[18] Projections from the European Environment Agency in 2010 expected car ownership increase by 60% in India and China and between 2020 and 2030. Car ownership in Eastern Europe was also supposed to increase by 10% over this period.

4.4.2 Adaptations at refiner and remelter level

Today, producers of ENAB46000 don't have any issue and if the demand was to decrease, producers will probably develop their activities to export towards Asia and the US. For refiners who produce other types of casting alloys, they are already having a major issue: reduced availability of "good quality scrap" at acceptable price. To compensate, they are adapting their processes to use lower quality scrap (low-yield, high impurity). However, this type of adaptation has a cost: increasing the use of primary to dilute or using new sorting technologies.

Notes:

- *ENAB46000 producers contacted in the frame of the study currently work at full capacity. From their point of view, current market set by scrap availability, not by foundry demand. They consider that future secondary alloys types and volumes will evolve with the average composition & volumes of scraps.*
- *Refiners, and more generally all aluminium producers are willing to adapt their practices and processes. But to do so, they need reliable information, figures on future volumes of scrap and their expected composition, information on new technologies available, etc.*

4.4.3 Adaptations at foundry level

As mentioned in § 4.3, there are two main technical opportunities for foundries to adapt to the probable evolution of casting components and alloys:

- Producing casting components for e-mobility: motor or battery pack housings. This is however complicated from a technical point of view: high conductivity and cooling channels/water jackets are required in these types of components. Standard secondary alloy doesn't meet the conductivity criteria, and HPDC process is not adapted to the production of parts with cooling channels.

- Moving towards structural castings (for automotive industry):
    - Casting structural components such as shock towers and longitudinal beams: they used to be dedicated to luxury vehicles, but it is starting be used for more mid-range segment cars.
    - Using giga cast/giga press technology: HPDC of large structural parts is already used by Tesla and other OEMs start investing or considering using the technology.
    - It is however important to note that currently, standard secondary alloy not used for these applications. Only primary alloys are used (AA386/EN with low iron content is used at Tesla). R&D must be performed to break this technological lock. Moreover, only OEMs are currently investing in the technology

- Use of giga press for other sectors: this technology can be used for specific applications. There's one example of a giga press (Impress-Plus DCC 6000 machine) delivered to Glovitech in Vietnam for the production of large Faraday cages for 5G mobile base stations (add ref).

To address the issue of CO_2 emissions and reduce the carbon footprint of cast components, one technical solution for the foundries is to follow the approach of Ronal and Eccomelt (illustration on Figure 27). It involves purchasing EOL scrap with the exact same composition (as the alloy to be produced). This will help reducing the need for energy consumption for melting at the refiner. This requires an adaptation of the whole value chain: at EOL product collection and then processing to avoid contamination (wheel separation by alloy, removing of coating and other pollutants). Foundries would also need to have tower melting furnaces to be able to use such raw materials.

Figure 27: On the left, sample of EOL wheel scrap, produced by Eccomelt, which ca be melted directly by the wheel producer. On the right, picture of a giga press (add ref)

4.4.4 Adaptations at OEM level

Most adaptations at OEM level (automotive industry) are related to the evolutions of EU regulations and customer behaviour, to reduce CO2 emissions during the use phase (electric vehicles and light-weighting) and the production phase (increased use of recycled material). As explained earlier, this will lead to:

- Increased used of wrought aluminium and potential increased of mix material parts (joining)
- Reduced need for standard secondary casting alloys (used in ICE)
- Need for low carbon materials (electrification will exacerbate environmental impact of production stages)
    - Need for increased recycled content (wrought and cast aluminium)
    - Need for GHG reduction in the production processes (electric furnaces?)

In terms of technology, we are already seeing an evolution of the size of casting press (e.g., Giga press of Tesla and Volvo for body structure parts), there should be more and more castings for structural parts, with bigger size.

From the point of view of the rest of the value chain, more particularly the foundries and refiners, there is a request for OEM to focus on properties, not on alloy composition when designing new components. New component should be the result of a compromise between design, expected properties, production process and aluminium alloy.

4.4.5 Technical opportunities

4.4.5.1 Improving scrap qualities (at scrap processor/refiner):

The first technical opportunity is the improvement of the scrap qualities either at scrap processing sites, or at refiners. Recent or innovative technologies can help refine shredded scrap or separate residues with different composition. The main technologies are:

- XRT (X-Ray Transmission) based sorting, combined with ejection technologies: enable the separation of cast from wrought aluminium (from Twitch fraction, for example) (see result in Table 15)
- LIBS (Laser Induced Breakdown Spectroscopy), combined with ejection technologies (Figure 28): can be used for several applications:
    - Improved sorting of Twitch to obtain separated cast / wrought fractions
    - Improved sorting of Twitch to separate low/high Si, Cu, Zn content
    - Separate wheels by alloy type

  The main downside is that LIBS sorting equipment are quite costly and have low productivity (<6 t/h)
- Multipick system (developed by Comet Treatment & ULg & CITIUS Engineering). This is a hybrid technology, using robot arms, a set of cameras and XRT sensor, with potentially LIBS in future versions. This technology is designed to be used on Zorba fraction (non-ferrous fraction from shredding units of ELV, construction wastes, WEEE), to produce separated fractions of cast/wrought aluminium[19] (Engelen et al. 2022). With the use of LIBS, it could be possible to refine the sorting level. One plant is supposed to be online in 2023 in Belgium (capacity 20 kt Zorba/y).
- Enhanced dismantling of aluminium components before shredder (*see previous study for European Aluminium – contact Benedetta Nucci). Enhanced dismantling could be helpful for:*
    - Single component recovery using manual or mechanical dismantling, and thus clean separation between alloys. This is however economically complicated for most components at the time due to low amount in current vehicles. It could get economically feasible in the near future, with the penetration of aluminium in the automotive industry.

[19] Zorba fraction = non-ferrous fraction from EOL product shredding

- ATF practices are evolving: door or hood dismantling for separated shredded is possible. Again, economic feasibility must first be checked, as it need large enough volumes for such schemes to work.

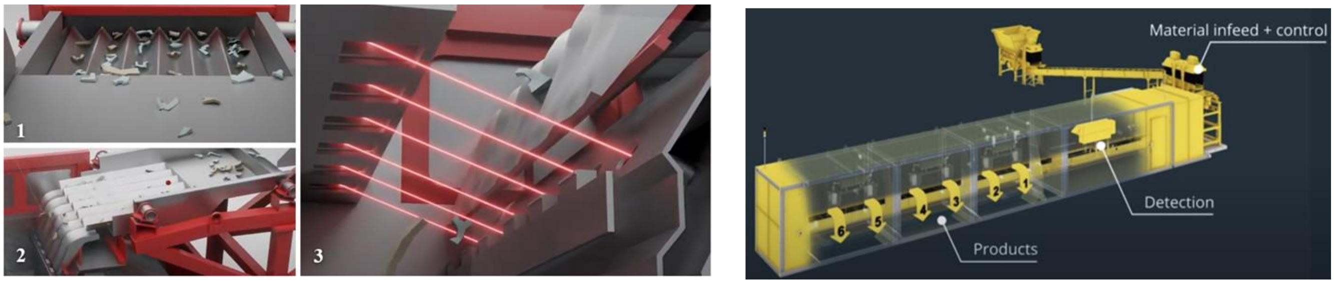

Figure 28: Two LIBS sorting equipment: Austin AI technology on the left, Steinert on the right (austinai.com / Steinertglobal.com)

4.4.5.2 Tramp element reduction during melting:

The first technic to reduce the residual content in a melt is a simple dilution, using primary aluminium, alloying elements and/or law-alloyed and clean scrap. This solution is already often used and has disadvantages (primary production is impactful, and requires extraction). Nonetheless, it can make sense as the aluminium demand is still growing and is expected to remain larger than the amount of aluminium scrap available for recycling in Europe. Indeed, today, aluminium demand in Europe amounts to ~14 Mt/y, whereas the estimated volume of scrap lies around 6 Mt/y[20] (figures for 2050 are, respectively, 18 and 9 Mt/y, according to European Aluminium 2050 vision).

There are three traditional methods for melt refining (fluxing, floatation and filtration), and three more recent (sedimentation, distillation and liquation). Each of these technics has pros and cons, which are briefly summarized in Table 17 (taken from (Wu et al. 2022)).

Of all of these solutions, the injection of chlorine gas or the use of chlorides in molten aluminium, can help remove phosphorus and/or antimony contained in the melt. According to Hiraki (2014), it can also help removing Ca, Ce, Dy, Dg, Ho, La, Li, Mg and Sr, potentially Be. The use of such gas is however restricted as it causes environmental issues (requires specific treatment for the fumes).

[20] According to European Aluminium Circular Action plan (European Aluminium 2020), post-consumer scrap "will increase from 3.6 million tonnes per year in 2019 to 6.6 million tonnes in 2030, reaching 8.6 million tonnes by 2050." ; according to IRT M2P calculations, including new scrap, the amount of scrap theoretically available should lie around 6 Mt in 2020 ; Results from Hatayama (2012) indicate figures around 7,5 Mt of post-consumer scrap in 2030.

Table 17: Main traditional Al melt purification methods with their pros, cons and specific applications.

Process	Pros	Cons	Main application
Fluxing	Removing oxide inclusions, reducing the penetration of hydrogen, absorbing non-metallic inclusions, assisting grain refinement, melt modification, having a lot of kinds for various applications.	Need solid additions, low contact with molten Al leading to low purification performance, needs to the high amount of fluxing materials, toxicity, utilization of toxic substances, it is not able to produce high purity levels of Al melts.	Removal of non-metallic inclusions.
Floatation	Easy transformation of hydrogen gas to melt surface, providing high surface area-to-volume ratio, eliminating the use of harmful chlorine and fluorine-containing salts, it can remove non-metallic solid particles.	Usually needs rotary systems, need to fast prevention of off-gas, it is a step-wise process, can remove non-metallic solid particles, it is not able to produce high purity levels of Al melts.	Reduction of hydrogen and inclusions content.
Filtration	It can remove any contaminants, non-metallic inclusions, trapped oxides, extraneous particles, etc, it has numerous kinds with specific applications.	The type of used filter has an influential effect, it is not effective for finer inclusions, it is not able to produce high purity levels of Al melts.	Removal of relatively large inclusions.
Sedimentation	Able to remove elements with a tendency toward oxidation, can separate both oxide films and primary intermetallic compounds.	Smaller inclusions are settled much slower than the large ones to the bottom of the furnace.	Removal of intermetallic phases.
Distillation	Efficient and effective removal of impurities such as Sb, Bi, Al, Au, Ag, Cu from melts.	Need to reach the boiling point of elements, need precise temperature control, needs vapor collection and condensation, the complexity of design and optimization, expensive method.	Removal of specific elements from Al melt.
Liquation	Efficient and effective removal of impurities with low melting points.	The necessity of having divergence in the melting point, needs high temperatures and expensive.	For the refinement of metals with a low melting point that has impurities with high melting points or vice versa.

However, the major pollutants in scrap, Cu and Fe, (also Si and Mn), are difficult to remove from the metal phase using traditional technics. Technologies based on aforementioned methods or using similar principle have been or are currently being developed. For example:

- Fractional crystallisation: a method of cooling at partially solidified metal. During fractional crystallization, metal crystals formed have a purer composition than that of the molten metal. The technic can be used to reach highly refined Al (> 99,97% according to Wu (2022)). Academic research was performed in the 1990s and 2000s, and has been patented (Patent US7537639) (Sillekens, Verdoes, and Boender 2002). Table 18 shows several examples of refining processes based on fractional crystallisation, applied to different types of scrap, from quite clean scrap (< 0,3% impurities) to automotive cast scrap (>7% Si, 0,9% Fe, etc.).

- High Shear Melt Conditioning technology (HSMC) (Lazaro-nebreda et al. 2017; Lazaro-Nebreda et al. 2022), whose principle is described on Figure 29: a high shear device is used to speed up the production of iron containing particles, helping separating them from the aluminium in a second chamber (sedimentation chamber). This technic could help increase iron tolerance in raw material feed and cast alloy, as it would remove part of the iron and the remaining iron particles tend to be smaller and better dispersed, improving the mechanical properties of castings. This technology is currently in development to improve process efficiency.

Table 18: Refining of aluminium scrap by means of fractional crystallisation: experimental data from literature (Sillekens, Verdoes, and Boender 2002)

SOURCE	PROCESS	ALLOYING CONTENTS [wt %]*	OBTAINED PURITY [wt %]	PURIFICATION EFFICIENCY η [%]	YIELD P [%]
Layer-based methods					
Alcan International Limited [5]	Cool crucible wall (batch-wise)	99.7 Al; Fe; Si; Ti; V	99.92 Al	73 (overall)	n.a.
Aluminium Pechiney [6]	Horizontal, revolving cylinder (continuous)	Al; 0.2 Fe	0.05 Fe	75	n.a.
Suspension-based methods					
MEL (AIST–MITI) [7]	Pressure filtering – rheo-refining (batch-wise)	Al; 0.2 Ni (1 stage) Al; 50 Sn (2 stages)	99.91 Al 98.4 Al	55 96.8	37.8 66.7
University Toronto [8]	Pressure filtering (batch-wise)	Al; 4.7 Si	0.9 Si	80	n.a.
NEDO–JRCM [9–10]	Pressure filtering (batch-wise)	Al; 3.0 Si	1.1 Si	62	n.a.
		Al; 1.0 Si; 1.0 Mn; 0.6 Fe; 0.2 Cu; 0.8 Zn (radiator scrap)	0.6 Si; 0.94 Mn; 0.4 Fe; 0.1 Cu; 0.6 Zn	40 (Si); 6 (Mn); 33 (Fe); 50 (Cu); 25 (Zn)	47.9
		Al; 7.8 Si; 0.4 Mn; 0.9 Fe; 3.1 Cu; 0.6 Zn; 0.4 Mg (car scrap)	2.8 Si; 1.0 Cu; 0.38 Zn; 0.12 Mg	64 (Si); 68 (Cu); 37 (Zn); 70 (Mg)	40.6
		Al; 0.66 Si; 0.76 Fe; 0.36 Cu; 0.78 Zn; 0.24 Mg (dirty sash scrap)	0.32 Si; 0.28 Fe; 0.18 Cu; 0.64 Zn; 0.11 Mg	52 (Si); 63 (Fe); 50 (Cu); 18 (Zn); 54 (Mg)	n.a.
Alcoa [11]	Three-phase sedimentation (batch-wise)	Al; 290 ppm Si; 610 ppm Fe; 4.8 Mg; 0.13 Cu; 90 ppm Mn; 0.37 Zn		max: 93 (Si); 80 (Fe); 55 (Mg); 75 (Cu); 0 Mn; 60 (Zn)	variable
Commonwealth Research Organisation [12]	Gravitational reflux column (continuous)	Al; 0.2 Fe+Si	0.001 Fe+Si	99.5 (overall)	n.a.

* If not otherwise stated

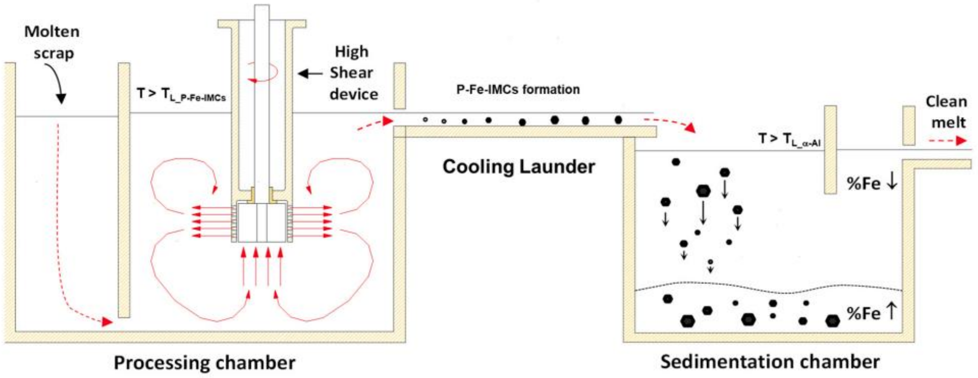

Figure 29: Schematic of the HSMC technology for batch and continuous processing of aluminium alloy scrap, for the removal of iron from the melts (Lazaro-Nebreda et al. 2022)

4.4.5.3 Reducing the residual content via electrolysis:

The residual content of aluminium alloys can also be reduced by the means of electrolysis processes. Two main technologies are mentioned in the literature: Solid State Electrolysis (SSE) process (Lu et al. 2022) and electrolytic purification (Scamans 2022).

- Solid State Electrolysis process: aluminium is dissolved from scrap and deposited on the cathode. Alloying elements (Si, CU, etc.) fall down the electrolysis tank and are removed as anode slime. A schematic of the process is shown on Figure 30. The results from Lu's study (2022), show that 95.6% of the aluminium could recovered by electrolysis, with a purity in the cathode deposit of 99.9%. A major issue with the SSE process is its energy consumption, but it is estimated to be less than half that of the primary aluminium production process.

- Electrolytic purification of aluminium scrap, described in Scamans presentation (2022), is a process based on Hoopes Cell. A schematic of the process is shown on Figure 31. The process can help refining post-consumer aluminium scrap and recover alloying additions like Mg and Si. According to the presentation, high purity could be achieved (0,01%Si and 0,01%Fe) from any post-consumer scrap.

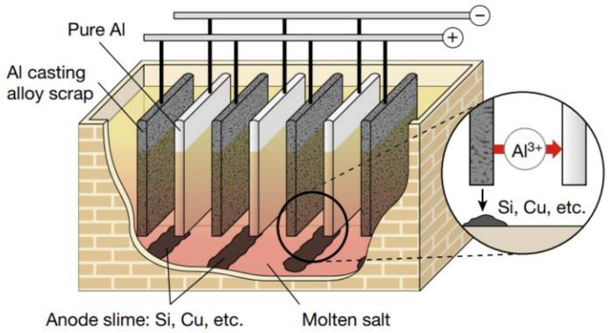

Figure 30: Schematic and electrochemical principle of the SSE process (Lu et al. 2022)

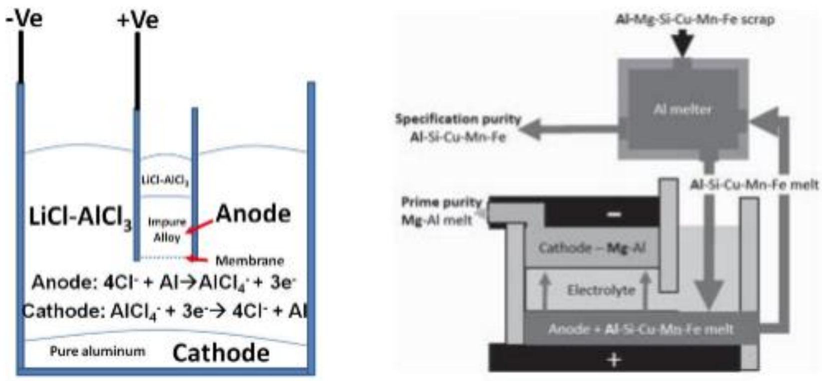

Figure 31: Schematic of the electrolytic purification process for aluminium scrap (Scamans 2022)

4.4.5.4 Improving the cast part properties:

One last opportunity for improving the use of end-of-life casting alloy scrap, is to have a broader approach when design new cast components: cast part properties are dictated by alloy composition but also casting process/conditions, which depends on part designs:

- Of course, the composition is important as alloying elements can have an influence. For example, Mn, Mo, amongst others, can help compensate harmful elements (Fe, Cu) (Shaha et al. 2016)
- Controlling the cooling rate of cast part (depends on wall thickness and casting process) enables to control the SDAS (secondary Dendrite Arm Spacing), which can dictate the mechanical properties of a cast part (Gan et al. 2015; Camicia and Timelli 2016)
- Heat treatment can help refine grain structure and intermetallic phases, which also influence the mechanical properties

According to Raabe (2022), "*Microstructure tuning should generally be preferred over composition tuning when adjusting and developing materials for new products*". This is an opportunity for OEMs and foundries to optimize the use of EOL castings alloys:

- Designing components together with the casting and heat treatment process (cooling speed, etc.), can help use "lesser quality alloys".
- It could also reduce the number of alloys use in standard products.
- Could help develop new alloys, for example "Uni-alloy" or "crossover alloy".

This approach, based on R&D, can help redesigning heat treatment, quenching and ageing processes to increase the tolerance in tramp elements and expand the property range of regular alloys, or new "recycling friendly" alloys.

5 Synthesis

The market for aluminium casting alloys in Europe is demand driven market, mostly by the automotive industry. The main casting alloy and process used are ENAC46000 (standard secondary) and High Pressure Die Casting (HPDC) process. Currently there is an important demand for this alloy and scrap is available to produce this quality. As this quality of scrap mainly comes from ELV (shredded ICE and transmission parts), there should be constant volumes of such scrap for at least the next 10 to 15 years (ELV age is approximately 15 to 20 years in Europe).

Other casting alloys are consumed by the automotive industry (and other sectors), together with HPDC process or other castings processes. (Lists here main alloys which can be recycled or not). For the elaboration of other "secondary" alloys, European refiners can have issues obtaining scrap at acceptable price and quality, some of them feel the need to adapt, which can involve producing new alloys and/or increase the use of primary aluminium to meet customer requirements.

The most influential players along the value chain are the OEMs (automotive companies) as influence the volumes, types of alloys and associated casting processes. They have a technical influence as they can have own production facilities (casting plants), they usually design the components and select the alloys and the casting processes. They influence the demand volumes and also drive the prices because they rely on many suppliers.
Scrap processors and scrap dealers also have a significant influence on the market, as they control and influence the volumes of raw materials sold to EU refiners, as well as the scrap qualities. Indeed, they perform the collection of new and EOL scraps and process them to obtain "sufficient" quality (for them to be able to sell). They sell to the highest bidder, in and outside EU.
Over the whole value chain, foundries and refiners have the less comfortable position. They strongly depend on OEMs and sometimes OEMs suppliers. Most of them rely on high investments, which require large production volumes to compensate. Material prince fluctuation as well as the energy crisis have significant impact on their operating margins. As many of them are small companies, participating in the development of new technology or new alloy can be challenging. Some refiners currently have issues and expect future issues with scrap availability, more particularly, they expect a future competition with wrought alloy producers to access good quality scrap. Other refiners, ENAB46000 producers, don't have these issues: scrap is available and demand is sufficient to max out their production capacities. For these refiners, should the demand decrease in EU, they could adapt by exporting their production.

6 Perspectives

Apart from the automotive industry, there is currently no "big market" identified in Europe for future use of current secondary alloys. Automotive industry is and should remain the main consumer of cast aluminium alloys. Indeed, aluminium demand in Europe is expected to increase up to 18 Mt per year by 2050, including around 8 Mt in the transport sector. Half of this demand should be met with recycled aluminium. Because of current automotive technologies (ICE), we expect around 0,5 Mt of secondary EN46000 quality to reach end-of-life in 2040.

Many technical opportunities exist and are listed in this study (§ 4.4), with potential to help reach these target[21]:

- Technologies for purifying or reducing tramp elements would probably be costly options but they have the potential to turn "low quality" scrap (mixed cast and wrought) into "clean aluminium". If all Twitch or twitch-like qualities passed through such processes, up to 2,5 Mt of clean aluminium could be produced each year from end-of-life sources.
- Improvement in casting technologies to include a significant share of "lower quality" aluminium into the production of structural components and/or electric vehicles specific components, could lead to an increased consumption of up to 0,8 to 1 Mt of EN46000 type aluminium.
- Dilution of "scrap surplus" is a also solution, which can already be used today and would require primary aluminium but could lead to the production of 0,5 to 3 Mt of "usable" quality aluminium, depending on the dilution ratio.
- Enhanced sorting or dismantling of EOL products could lead to 0,5 Mt available for closed loop recycling (wheels) and up to 0,6 Mt of wrought qualities.

Part of the solution is in the "sustainable aluminium alloy" concept, described by Raabe (2022). It requires improving several axes:

- There should be an increased collaboration over the whole value chain, and with policy makers to:
    - Develop closed-loop business models with customers, and define new standards & practices.

[21] The figures listed below are based on estimations whose assumptions are described in appendix 4.

    - Prevent material degradation at EOL through better product and recycling design, rather than optimizing recycling systems in isolation.
- Working on the improvement of scrap management:
    - Alloy-specific scrap collection (new and old scrap), e.g., via enhanced dismantling of EOL products.
    - Advanced scrap sorting to favour “closed-loop” recycling.
    - Avoid scrap production during manufacturing: requires to work on production process and component design.
- Work on alloy design:
    - Minimal use of processing steps and ingredients; achieve properties by microstructure and not by composition adjustment
    - Fewer alloys: design of universal/crossover alloys, scrap tolerant alloys
- Product design, production and use:
    - Design part for higher composition tolerance and easier recycling.
    - Longevity means slower replacement cycles and reduce material use.

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List of acronyms

ATF	Authorized Treatment Facility
BEV	Battery Electric Vehicle
CAEF	European Foundry Association (previously "Committee of Associations of European Foundries")
ELV	End-of-Life Vehicle
EOL	End-Of-Life
EPR	Extended Producer Responsibility
EU	European Union
EV	Electric Vehicle
GDC	Gravity Die (or sand) Casting
HPDC	High Pressure Die Casting
HSMC	High Shear Melt Conditioning
HSR	Heavy Shredder Residues
IBA	Incinerated Bottom Ash
ICE	Internal Combustion Engine
IRSI	Institute of Scrap Recycling Industries
LIBS	Laser Induced Breakdown Spectroscopy
LPDC	Low Pressure Die Casting
LSR	Light Shredder Residues
LWC	Lost Wax Casting
MFA	Material Flow Analysis
MSW	Municipal solid waste
NAFTA	North American Free Trade Agreement
NFR	Non-Ferrous Residues
OEM	Original Equipment Manufacturer (mostly automotive manufacturer)
PHEV	Plug-in Hybrid Electric Vehicle
PRO	Producer responsibility organisations
SDAS	Secondary Dendrite Arm Spacing
SME	Small and Medium-size Enterprises
SSE	Solid State Electrolysis
UBC	Used Beverage Cans
US	United States of America
XRF	X-Ray Fluorescence
XRT	X-Ray Transmission
WEEE	Waste from Electric and Electronic Equipment

APPENDIXES

Annex 1 - Future scrap availability / alloy demand in automotive industry (estimations based on MFA models)

Volumes in 2035	Scrap [kt]	Demand [kt]	Alloys used today	Alloys in 2035	2035 hypothetic
Engine blocs	581	0	ENAC46000	-	-
Transmission	159	128	ENAC46000	ENAC46000?	ENAC46000
EV motor housing, battery pack	102,5	287	Wrought, AlSI10Mg	AlSI10Mg?	Refined EN46000?
Wheels	500	560	AlSi7Mg0,3	AlSi7Mg0,3	Recycled AlSi7Mg0,3
Body structure (body, crash management...)	190	380	Wrought	AlSi10MnMg	Uni/crossover alloys?

Annex 2 – Aluminium alloy designation systems

European designation (Jacob 2001):

- EN for all standardize alloys (European Norms)
- Letter A for « Aluminium »
- A second letter designing the type of product (B: ingots; C: cast parts; M: mother alloys)
- Numerical designation with 5 figures for alloy composition
  - First figure = main alloying element
    - Copper: 2XXXX
    - Silicon: 4XXXX
    - Magnesium: 5XXXX
    - Zinc: 7XXXX
  - Second figure = alloy group
  - 3rd figure = arbitrary
  - 4th figure= usually 0
  - 5th figure = 0, except for aerospace applications
- Casting process: S = sand casting, K = Die casting, D = pressure, L = lost wax
- Heat treatment: F=brut; O=tempered; T1 to T7

AA Cast Aluminium Alloy Designation System (ESAB 2023) (direct extract from the website)
The cast alloy designation system is based on a 3 digit-plus decimal designation xxx.x (i.e., 356.0). The first digit (Xxx.x) indicates the principal alloying element, which has been added to the aluminium alloy (see table 2). The second and third digits (xXX.x) are arbitrary numbers given to identify a specific alloy in the series. The number following the decimal point indicates whether the alloy is a casting (.0) or an ingot (.1 or .2). A capital letter prefix indicates a modification to a specific alloy.

For example, Alloy - A356.0 the capital A (Axxx.x) indicates a modification of alloy 356.0. The number 3 (A3xx.x) indicates that it is of the silicon plus copper and/or magnesium series. The 56 (Ax56.0) identifies the alloy within the 3xx.x series, and the .0 (Axxx.0) indicates that it is a final shape casting and not an ingot.

Table 19: Meaning of the different digits

Alloy Series	Principal Alloying Element
1xx.x	99.000% minimum Aluminium
2xx.x	Copper
3xx.x	Silicon Plus Copper and/or Magnesium
4xx.x	Silicon
5xx.x	Magnesium
6xx.x	Unused Series
7xx.x	Zinc
8xx.x	Tin
9xx.x	Other Elements

Temper Designation System
Subdivisions of H Temper – Strain Hardened

The heat-treatable alloys acquire their optimum mechanical properties through a process of thermal treatment, the most common being solution heat treatment, and artificial aging. Solution heat treatment is the process of heating the alloy to an elevated temperature (around 990 Deg. F) to put the alloying elements or compounds into solution. This is followed by quenching, usually in water, to produce a supersaturated solution at room temperature. Solution heat treatment is usually followed by aging. Aging is the precipitation of a portion of the elements or compounds from a supersaturated solution in order to yield desirable properties.

The first digit after the H indicates a basic operation:
H1 – Strain Hardened Only.
H2 – Strain Hardened and Partially Annealed.
H3 – Strain Hardened and Stabilized.
H4 – Strain Hardened and Lacquered or Painted.
The second digit after the H indicates the degree of strain hardening:
HX2 – Quarter Hard
HX4 – Half Hard
HX6 – Three-Quarters Hard
HX8 – Full Hard
HX9 – Extra Hard
Table 5. Subdivisions of T Temper – Thermally Treated
T1 – Naturally aged after cooling from an elevated temperature shaping process, such as extruding.
T2 – Cold worked after cooling from an elevated temperature shaping process and then naturally aged.
T3 – Solution heat treated, cold worked, and naturally aged.
T4 – Solution heat-treated and naturally aged.
T5 – Artificially aged after cooling from an elevated temperature shaping process.
T6 – Solution heat-treated and artificially aged.
T7 – Solution heat treated and stabilized (overaged).
T8 – Solution heat treated, cold worked, and artificially aged.
T9 – Solution heat treated, artificially aged, and cold worked.
T10 – Cold worked after cooling from an elevated temperature shaping process and then artificially aged.
Additional digits indicate stress relief.
Examples:
TX51 or TXX51 – Stress relieved by stretching.
TX52 or TXX52 – Stress relieved by compressing.

Annex 3 - Maximum scrap utilization for wrought and cast production

Scrap group	**Si**	**Fe**	**Cu**	**Mn**	**Mg**	**Zn**	**Ni**	**Cr**	**Pb**	**Sn**	**Ti**
1 - Mixed all scrap	7,0375	0,731875	2,554375	0,208125	0,198125	0,54875	0,456875	0,0225	0,0975	0,11	0,051875
2 - Twitch Galloo (measured 2021)	5,497	0,531	0,852	0,208	0,507	0,399	0,083	0,036	0,04	0,03	0,017
3 - Big Twitch Galloo (estimation)	7,5	0,6	1,7	0,22	0,25	1					
4 - Small Twitch Galloo (estimation)	8	0,6	2	0,22	0,16	0,8					
5 - Twitch ?	3,78	0,38	0,74	0,21	0,42	0,3					

Alloy (chemical des.)	**Si**	**Fe**	**Cu**	**Mn**	**Mg**	**Zn**	**Ni**	**Cr**	**Pb**	**Sn**	**Ti**
AlSi7Mg	6,5-7,5	0,55	0,2	0,35	0,2-0,65	0,15	0,15		0,15	0,05	0,25
AlSi7Mg0,3	6,5-7,5	0,19	0,05	0,1	0,2-0,45	0,07					0,25
AlSi10Mg	9-11	0,55	0,05	0,45	0,2-0,45	0,1	0,05		0,05	0,05	0,15
AlSi10Mg(Fe)	9-11	1	0,1	0,55	0,2-0,5	0,15	0,15		0,05	0,05	0,15
AlSi9	8-11	0,65	0,1	0,5	0,1	0,15	0,05		0,05	0,05	0,2
AlSi9Cu3(Fe)	8-11	1,3	2-4	0,55	0,55	1,2	0,55	0,15	0,29	0,15	0,25

List of elements whose content are too high in scrap (#1 through 5), for the production of 6 different cast alloys (according to standard specifications).

	AlSi7Mg	AlSi7Mg0,3	AlSi10Mg	AlSi10Mg(Fe)	AlSi9	AlSi9Cu3(Fe)
1	Fe, Cu, Zn, Ni, Sn, Ti	Fe, Cu, Zn, Ni, Ti	Fe, Cu, Zn, Ni, Pb, Sn, Ti	Cu, Zn, Ni, Pb, Sn, Ti	Fe, Cu, Mg, Zn, Ni, Pb, Sn, Ti	OK
2	Cu, Zn	Fe, Cu, Mn, Mg, Zn, Ni	Cu, Mg, Zn, Ni	Cu, Zn	Cu, Mg, Zn,	OK
3	Fe, Cu, Zn	Cu, Zn	Fe, Cu, Zn	Cu, Zn	Cu, Zn	OK
4	Si, Fe, Cu	Si, Fe, Cu, Mn, Zn	Fe, Cu, Zn	Cu, Zn	Cu, Zn	OK
5	Cu	Fe, Cu, Mn, Zn	Cu, Zn	Cu, Zn	Cu, Mg, Zn	OK

Annex 4 – Assumptions used to assess the potentials of new practices and technologies

		Scrap or product concerned by the evolution		Aluminium quality produced/consumed		
Technical evolution		Scrap/product type	Expected volumes [Mt/y]	Aluminium type	Expected volumes [Mt/y]	# assumption
Purification / tramp element reduction	Electrolysis to purify	Twitch	2,5	"Clean Al"	2 to 2,5	1
	Tramp element reduction during melting	Twitch	2,5	"Clean Al"	2 to 2,5	1
Casting technologies improvement	Giga cast	Structural components (new premium cars)	0,3 to 0,4	EN46000 quality consumed	0,08 to 0,2	2
	Component for e-mobility	E-motor components	0,35	EN46000 quality consumed	0,17 to 0,35	3
	Structural castings	Structural component (new premium cars)	0,8 to 1,4	EN46000 quality consumed	0,08 to 0,35	4
Dilution	Dilution	Various scrap	> 2,5	"Clean Al"	-0,16 to - 2,25	5
				Diluted cast alloys	0,7 to 3	5
Enhanced sorting or dismantling	Enhanced sorting	Twitch	2,5	EN46000 quality	1,7 to 1,9	6
				Wrought alloys	0,6	6
	Enhanced dismantling	Twitch	2,5	EN46000 quality	1,9 to 2,3	7
				Secondary wheel quality	up to 0,5	7
				Wrought alloys	0,15 to 0,5	7

#	Assumptions
1	All of Twitch from ELV, WEEE and a part from construction processed by purification process to obtain almost pure Aluminium
2	25 to 50% of body in white from "premium segment car" would be produced with giga casting technologies (1,5 to 2 M of premium, vehicles, 200 kg of structural components per vehicle in 2030)
3	50 to 100% of e-motor produced from conventional EN46000
4	10 to 25% of structural and suspension part from "premium and medium segment vehicle", produced from castings (8 to 9,5 M vehicles, 100 to 150 kg structural/suspension parts per vehicle in 2030)
5	25 to 75% dilution of all cast containing scrap
6	All Twitch fractions separated into cast/wrought fraction and/or with high Cu/Fe / low Cu/Fe separation. Assumption that Twitch contains 75% cast, 25% wrought
7	25 to 75% of components dismantled and sorted by alloy type (cast / wrought)

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