MANUFACTURING with ALUMINUM

HISTORY, FORMING TECHNIQUES AND BEST PRACTICES

EAGLE Aluminum Cast Products

Prepared by

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Table of Contents

1. Introduction

Aluminum is the third most common element on our planet. It's by far the most abundant metal, and it's also one of the most versatile when it comes to manufacturing.

Aluminum is light, strong, flexible and corrosion resistant. It can also be shaped relatively easily, in both a solid and molten state, and can be rolled to widths thinner than the human hair.

You'll find aluminum in everything from buildings to cars, from soda cans to laptops, and from power lines to bullet trains. ***But is aluminum right for your part, product or project?***

In this paper, we explore all aspects of manufacturing with aluminum, including unique properties, common alloys, and the myriad processes that can be use to shape aluminum.

As with anything in the manufacturing world, there's no substitute for expert opinion. *If you think aluminum might be a good choice for you, feel free to contact us any time for an evaluation.*

At Eagle Aluminum Cast Products, Inc., we'd be glad to put our experience to work for you.

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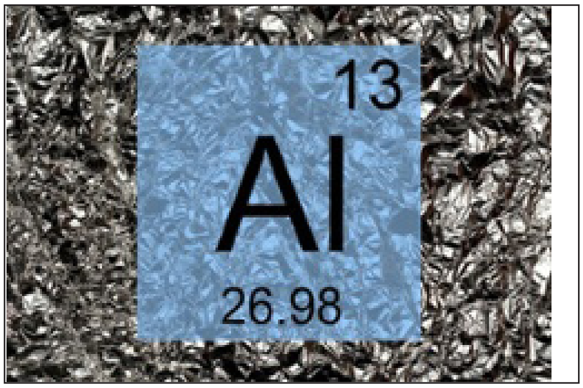
2. Background and History



Aluminum was first discovered in 1824 by Danish physicist **Hans Christian Oersted**. Oersted used the process of electrolysis to separate aluminum from other elements. Over the next 60 years, scientists, industrialists and entrepreneurs developed new processes of obtaining aluminum. Finally, in the late 1880s, three scientists got it right, and opened the door to commercial-level aluminum production.

Named after their inventors, today's main processes of obtaining aluminum from raw ore are the **Hall-Héroult method** and the **Bayer method**[1]**.** The Bayer method produces aluminum oxide from raw ore. The Hall-Héroult method then takes that aluminum oxide and turns it into pure aluminum through **smelting**– that is, by applying heat and inducing reactions on a molecular level.

Where does aluminum come from?

Aluminum is nearly everywhere. It's the third most common element on the planet, making up almost a tenth of the earth's crust. Aluminum is the most common metal by far, but unlike gold, copper and iron, you can't just go out and find a vein or a chunk of aluminum. Aluminum combines with other elements very easily, so you won't find aluminum by itself in nature.

Thanks to the Hall-Héroult method and the Bayer method, we're now able to separate aluminum from the other

Most common elements on earth:

1. Oxygen
2. Silicon
3. **Aluminum**

Kind of ironic that third place gets the bronze medal, isn't it?

non-aluminum substances. Most new Al is extracted from bauxite, a clay-like substance that contains high amounts of aluminum. Bauxite can be found all over the world, in abundant supply.

Today, recycling is also a major source of aluminum. In fact, estimates show that over **75% of aluminum ever produced is still in use today.** Aluminum can be melted, purified and reformed without losing any of its winning chemical properties. Not only that, but the process of recycling aluminum is much less energy intensive than producing new aluminum from bauxite.

All things considered, the Aluminum Association estimates that each recycled can saves enough energy to listen to a full album on an iPod.[2]

3. Properties of Aluminum

Aluminum owes its versatility in manufacturing to a unique set of properties. These include:

- **Low melting temperature**
- **Excellent malleability**
- **Light weight**
- **Corrosion resistance**
- **Electrical conductivity**

Low melting temperature

Stainless steel melts at temperatures above 2,500 degrees F, and steel castings are often poured at temperatures exceeding 3,000 degrees F. Pure aluminum, on the other hand, melts at a chilly 1,221 degrees F.

Actual melting and casting temperatures of aluminum depend on other metals mixed into the alloy, but aluminum alloys can generally be cast at less than half the temperature of **ferrous alloys** (alloys containing iron, like steel).

Because of its lower melting temperatures, casting processes for aluminum alloys are less energy intensive than those for ferrous alloys. Setting times


Aluminum ingot

are also reduced, improving factory throughput and further decreasing costs.

Excellent malleability

Malleability is a substance's ability to be deformed without cracking or breaking. Compared to other material groups, metals generally have high levels of malleability, with gold coming in first place. Aluminum is no slouch either, especially considering its other positive attributes.

An excellent example of aluminum's malleability is the ever-present aluminum foil. Aluminum foil is made by squeezing high-purity aluminum through a rolling press. The kind of everyday aluminum foil you probably have in your kitchen can be as thin as .00017 inches–about 400 times thinner than an average human hair.[3]

Aluminum's malleability is also why

lightweight tubing can be made out of aluminum. Tubing is often made through **extrusion**, which removes the center of a piece of aluminum and leaves the sides. A wide variety of industries–from bicycles to lawn furniture–take advantage of aluminum tubing to offer strong, lightweight products.

Light weight

Compared to iron and steel, aluminum is much less dense. That means that a finished aluminum product will be considerably lighter than an iron or steel product of the same shape.

Again, actual measurements differ depending on alloying elements, but a good rule of thumb is that aluminum is around **2.5 - 3 times less dense than steel.**[4] While aluminum is not as strong or hard as steel, its light weight offers design flexibility. For example, a 5-lb aluminum bicycle frame can contain 2.5 times more material by volume than a 5-lb steel bicycle frame.

Inspecting an aluminum helicopter frame (photo courtesy U.S. Navy)

Corrosion resistance

In cases where a product will be exposed to weather and the elements, aluminum comes in ahead of the pack.

Many metals produce an **oxide layer** covering their external surfaces. Oxide layers are formed when compounds react with water, or oxygen in the atmosphere.

Rust and other forms of oxidative corrosion are commonly seen in metals that form less stable oxide layers. These metals react with oxygen in the same way that aluminum does, but rather than maintaining a stable, microscopic thickness, their oxide layers continue to grow until they are visible with the naked eye.

Aluminum, on the other hand, forms a relatively stable oxide layer, preventing it from further reacting with oxygen. If the surface of aluminum is damaged, the oxide layer "heals" itself, re-forming almost immediately. **It's kind of like Wolverine's skin.**[5]

Electrical Conductivity

Take a look at most of your household electrical items, and their cords are made of **copper**. Yes, that's right, Aluminum isn't the most conductive metal out there, but it's definitely high on the list. Added to its high conductivity is aluminum's light weight and relatively low cost, so **for some applications, aluminum is the perfect electrical conductor.**

Next time you're driving down the highway, take a look at those massive high-tension wires connecting suburban and rural areas with power plants miles away. Those wires are usually made of aluminum. For wiring in buildings and household items, weight isn't often a critical factor, so copper can be used. But when it comes to high-volume, infrastructure-grade electrical transfers, Al is the winner.

Aluminum's Weak Points

Depending on the application, some of aluminum's properties can pose challenges. For example, pure aluminum's modulus of elasticity is about one-third that of steel. Essentially, aluminum is not as stiff as steel, and will deform considerably more than steel if acted on by the same force.

Still, aluminum's light weight allows considerable flexibility in design. A product's designer can add design features to impart stiffness, like ribs or corrugations.

If you're thinking of using aluminum for a casting pattern or other part involving high service temperatures, its low melting point can also be a liability. All metals lose strength as they approach their melting point, and aluminum is not recommended for use in temperatures much higher than 300 degrees F.

In manufacturing, aluminum is rarely pure. Instead, manufacturers form alloys that dramatically increase aluminum's strength and stiffness, while maintaining its other desirable properties.

4. Aluminum Alloys

Professionals and non-professionals alike often make comparisons between aluminum and steel, because the two metals are both used for such a wide variety of products.

But comparing aluminum to steel is a bit like comparing apples to oranges: **steel is already an alloy, while aluminum is an element.** Carbon steel, a basic alloy, is composed of iron (Fe) and carbon (C). Pure aluminum (Al), despite its many winning properties, is too soft and not strong enough for most industrial applications. But aluminum alloys can be thirty times stronger than pure aluminum, and regularly exceed steel in strength-to-weight ratios.

By combining pure aluminum with other elements, manufacturers are able to improve strength while maintaining light weight, conductivity and corrosion resistance.

For manufacturing applications, aluminum alloys can be divided into two categories: wrought alloys and casting alloys.

- **Wrought alloys** are intended for plastic manipulation, and so are designed to be highly ductile and fracture resistant.
- **Casting alloys** are intended for casting, and so must balance low melting points and low coefficients of expansion with attractive characteristics as solids.

The chart on the following page lists several commonly used aluminum alloys, along with their compositions and properties.

Used in electrical transmission lines, **electrical-conductor-grade aluminum (EC Aluminum)** is comprised of a minimum of 99.45% pure aluminum. EC Al wires have 2x the conductivity of copper by weight.

Table 1
Characteristics of wrought and casting aluminum alloys

Alloy	Type	Composition (%)	Characteristics	Common Uses
1350	Wrought	99 Al	Nearly pure Al; excellent conductivity and formability	Electrical wiring
2024-T4	Wrought	4.4 Cu, .6 Mn, 1.5 Mg	Good workability and machinability; good corrosion resistance	Aircraft, automotive parts
6061-T6	Wrought	.28 Cu, .6 Si, 1 Mg, .2 Cr	Strong and corrosion resistant	Architecture, automotive, sports equipment
319	Casting	3.5 Cu, 6 Si, 1 Zn, 1 Fe	Excellent castability and corrosion resistance	Engine parts, gas and oil tanks
A356	Casting	7 Si	Excellent castability, but with increased strength and ductility	High strength structural parts, machine parts, truck chassis
712	Casting	5.8 Zn	High tensile strength; heat treatment not required	Marine castings, machine tool parts

5. Shaping Aluminum

Aluminum can be shaped through a wide variety of processes, including:

Casting

Pouring molten aluminum into a pre-formed mold and allowing it to cool until solidified.

Extrusion

Similar to pushing Play-Doh through a mold, but with metal instead of colorful clay. Used with aluminum to produce bars of varying profiles, and wires of varying diameter.

Forging

Compressing metal through great force to achieve high levels of strength. Used with aluminum to produce the high performance wheels found on racecars and expensive sports cars.

Rolling

Squeezing metal through two parallel rollers to reduce its thickness. Used with aluminum to produce aluminum plate, which can then be machined, or common aluminum foil.

6. Casting Aluminum

When it comes to shaping aluminum, casting is arguably the most versatile of all of the metal working processes, and results in the greatest variety of parts.

The same casting techniques used for other metals can be applied to aluminum, but the most common processes are **permanent mold casting**, **green-sand casting** and **die casting.**

Aluminum casting (courtesy Eagle Aluminum Cast Products, Inc.))

Permanent Mold Casting

Permanent mold casting involves creating a reusable mold from metal with a high melting temperature. If aluminum is being cast, the mold is often made from gray iron or steel. Two halves of the mold are connected and then pre-heated. Molten metal is poured in from a ladle to fill the mold, and is allowed to set until sufficiently solidified to remove the casting. In most cases, the casting is removed to cool as soon as it's solidified; otherwise, the inflexible mold may cause defects to form as the casting cools and contracts. After the casting is removed, the process can be repeated immediately.

Advantages of permanent mold casting:

- Since the mold is reusable, initial tooling costs can easily be recouped with high-volume runs
- High dimensional accuracy can be achieved
- Repeatability is high, and little preparation needs to be made between castings.

Disadvantages of permanent mold casting:

- "Permanent" molds don't last forever, and may need to be replaced

midway through a large run
- Inflexible molds can lead to defects if castings are not removed promptly
- Tooling costs are relatively high compared to greensand casting

Greensand Casting

Greensand casting is a common form of sand casting that uses "green," or moist, sand to form a mold. First, sand is packed around a metal pattern to form a mold cavity. Then, the mold cavity is placed in a brace and paired with its other half, similar to permanent mold casting. The pattern is removed, and molten metal is poured into the cavity. After the casting has solidified, the mold is broken and the casting is removed and finished. Many facilities are able to reclaim a high percentage of the sand used in greensand casting.

Advantages of greensand casting:

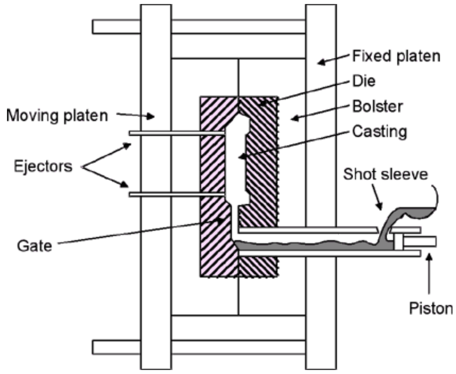
- Nearly any part can be cast using this method, with virtually no size or weight limitations
- Tooling and materials costs are very low

Disadvantages of greensand casting:

- Surface finish is not as smooth as other casting methods
- Dimensional accuracy is also lower than other casting methods

Die Casting

Die casting is similar to permanent mold casting in that it makes use of a reusable metal mold, rather than disposable sand-based molds. In die casting, however, molten metal is often injected into the mold at high pressure. The high pressure results in greater detail and finer surface finish compared to other casting methods, but durability of die castings can be compromised by trapped pockets of air. While die casting is preferred for high-volume runs of smaller parts, the complexity of die castings is limited. The configuration of the die casting apparatus limits the variety of cores that can be inserted.



Die casting diagram

Advantages of die casting:

- Parts can be cast with greater detail and superior surface finish
- Dies, often machined from high-grade tool steel, last longer than other molds

Disadvantages of die casting:

- Initial tooling costs are very high
- Complexity is limited, especially for products with hollow sections
- Overall strength can be compromised by porosity and other defects

A variety of cast aluminum products, created using greensand and permanent molding (Eagle Aluminum Cast Products, Inc.)

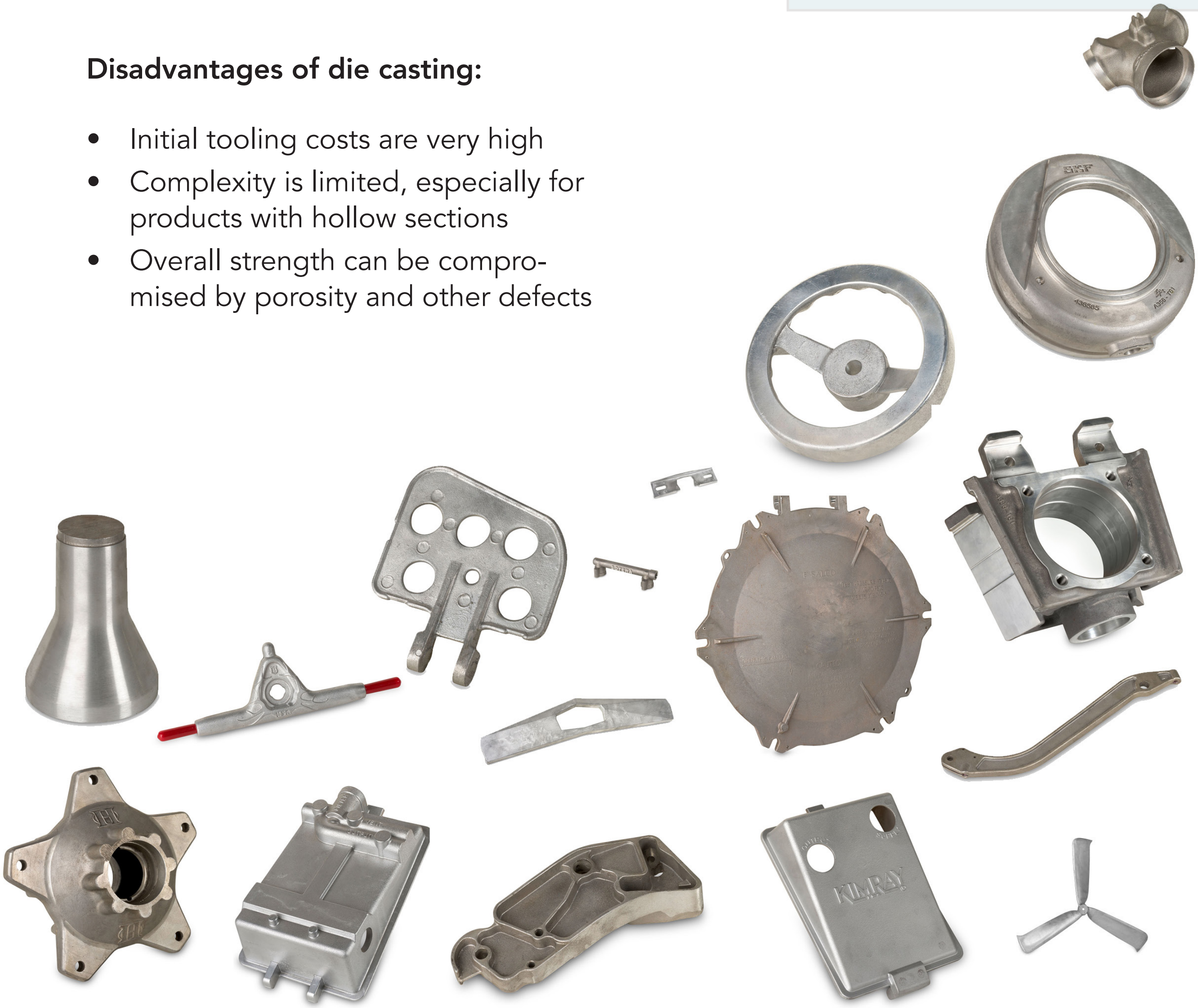


Table 2: Comparison of aluminum casting methods

	Tooling Costs	Labor Costs	Typical Tolerances	Surface Finish	Typical Volume
Permanent Mold	High	Low	+/- .01 -.03 in.	Good	Medium-High
Greensand	Low	Low	+/1 .03-.06 in.	Average	Low-High
Die	Very High	Low	+/- .01-.015 in.	Very good	Very High

Pouring molten aluminum into a greensand mold (Eagle Aluminum Cast Products, Inc.)

7. Case Study: Permanent Mold Casting with Aluminum

The purpose of this case study is to illustrate a typical process of working with an aluminum casting foundry to produce a medium-high volume run of bespoke products.

Initial contact

A major manufacturer of ventilation systems contacted Eagle Aluminum Cast Products, Inc. when demand was growing and they were ready to make a change.

The customer had already been producing 48″ fan blades for agricultural use through greensand casting, but they'd outgrown that method. Demand projections suggested that **permanent mold casting** would yield lower per-part costs, with the added benefit of greater consistency.

Design and production

EACP received a CAD file from the customer with part designs, and their engineers went to work to decide how to produce the part through permanent molding. EACP found optimal placements for feeding and gating. Because of the shape of the fan blade, they placed the gating near the hub–the thickest area–so that the metal could easily travel to the thinner blade edges.

Since permanent molding was the process being used, engineers also had to account for ejector pins and ejector tabs. Greensand casting doesn't require these additions, because the casting is released by simply breaking the mold. In permanent mold casting, the mold is reused again and again, and the casting must be removed each time by pushing on ejector pins and/or tabs. In order to ensure even weight distribution across all blades, EACP decided to place ejector pins inside the hub, and tabs at the end of each blade.

EACP makes use of advanced **lean manufacturing** to produce these parts. In fact, an entire fan blade can be produced by one operator, from molten aluminum to final delivery. Not only does EACP's use of lean manufacturing result in better quality and efficiency, it also leads to lower inventory costs and, ultimately, lower per-part costs for the customer.

Improving the production process

Initial production runs were successful, but **over time the operators and managers at EACP noticed trends that could lead to improvement.** Today, the streamlined manufacturing process results in a very low number of factory returns.

Maintaining Consistent Mold temperature: Some of the castings were forming defects called heat cracks, caused by excessive heat from the mold itself. The solution was to install a cooling system near the hub of the mold. Engineers at Eagle Aluminum also modified the design to allow a more direct connection between the hub and the fan blades, improving metal flow. These adjustments have removed all instances of heat cracking.

At the other end of the spectrum, EACP noticed that the blade areas of the mold, particularly farther out from the hub, were cooling too much between runs, resulting in sub-optimal metal flow to the blade tips. To solve the problem, they added external burners to keep the blades heated.

Cooling Brace to Aid Solidification: EACP noticed that a number of parts were bending slightly as they cooled outside the mold, and they designed an innovative solution: a cooling brace. Engineers replicated the shape of the mold, and installed cooling elements to surround it. Now, each part is moved from the mold directly into the cooling fixture, which holds the part's shape while it cools and solidifies. Instances of bending were reduced to zero. EACP has since applied this process to several other parts, with excellent results.

Finishing and Delivery

EACP is equipped to handle basic finishing for their castings. They saw off gatings and grind down runners, ejector pins and tabs. Then, they do a pre-balance check and conduct a visual inspection. After each part passes, it's delivered to a local balancing company.

The balancing company is a specialized machine shop. In the casting, EACP has included tabs at the end of each fan blade. The balancing company grinds down the tabs with a high degree of accuracy to ensure a perfect operating balance.

After balancing, the fan blades are sent to the customer for final assembly. This particular customer handles the rest of the process in-house. They assemble the fan blade, the drive, the housing and any other auxiliary parts to produce an agricultural fan ready for installation.

Why Aluminum Is Perfect for This Part

Aluminum is the perfect material for this product for a number of reasons:

- **Weight:** aluminum's low density leads to lighter parts. Lighter fan blades lead to more efficient ventilation systems. They also allow greater freedom in installing the ventilation systems, which are often placed on posts or non-load-bearing structural elements.
- **Process:** Permanent mold casting just doesn't work with heavier, higher melting point alloys, like stainless or carbon steel. Even if the product would function with the added weight, the process would have to change. The customer initially made the switch from greensand, which could have accommodated different alloys. Stamping is another possibility. Permanent molds are generally made from steel or iron, and so casting with ferrous metals is often not an option.
- **Corrosion resistance:** These fan blades are often installed in agricultural environments, where they pump fresh air into enclosed spaces. As such, they are placed at the barrier between inside and outside, and are constantly subjected to the elements. Ferrous alloys, which are known for rusting, would not be ideal for these environments.
- **Cost:** EACP uses alloy 319 F for these castings. The cost of this alloy is very low compared to other alloys. Since EACP negotiates a fair market price for aluminum ingot, they can pass their savvy onto their customers in the form of savings.

Additional variations of the original fan blade produced by Eagle Aluminum Cast Products, Inc.

8. When Aluminum Is the Right Material

Aluminum foil. Image courtesy of Jurii Benutzer

When choosing the right material for a new cast product, you'll need to consider a broad range of factors. Every material has its own set of benefits and drawbacks. Even in the world of metal manufacturing, a product cast in aluminum will differ greatly from a product with the exact same shape and dimensions cast in stainless steel.

Strength to weight ratio

The most important factor, when considering aluminum as a material, is the strength to weight ratio. This ratio is where aluminum really shines (so to speak). In simple strength, steel can still beat aluminum, but when you need considerable strength along with light weight, aluminum could be the most reasonable choice. However, when weight is not a consideration–as in stationary equipment–other materials may be able to offer the same or greater strength at a lower cost.

Corrosion resistance

Many ferrous alloys, like carbon steel, are much more susceptible to corrosion than aluminum and its alloys. If your product will spend a lot of time outside in the elements, underwater or even exposed indoors, aluminum will improve the product's longevity.

However, aluminum is not 100% corrosion-proof. In normal environments, aluminum products may corrode slightly. They won't show the same red-orange rust that you'll see on ferrous alloys, but aluminum surfaces will turn whitish and develop pits. In extremely acidic or basic environments, aluminum can actually corrode faster than other materials.

Machinability

Casting is rarely the end of the line for metal products. Many also undergo machining processes to bore threads, stamp holes and impart greater accuracy to critical areas.

Compared to nickel-based alloys and stainless steel, aluminum is highly machinable. That means lower costs, shorter lead times and more flexibility in the machining stage. In addition to cutting, stamping and other material-removal processes, aluminum can also be shaped through bending and extrusion more easily than other materials.

Cost

Aluminum's default competitor, stainless steel, is often more expensive to purchase and process. Nickel and copper-based alloys are much more expensive. Due to its wide availability and easy recyclability, aluminum is a relatively low-cost option. Even in cases where aluminum is not the ideal material–as in electrical wiring–its low cost makes it the best option.

There are certainly less expensive options than aluminum, like ductile iron or carbon steel, but these materials won't offer anywhere near the same strength-to-weight ratios or corrosion resistance.

The Jaguar XE sports sedan, built with an "advanced aluminum" frame. Image courtesy Jaguar MENA

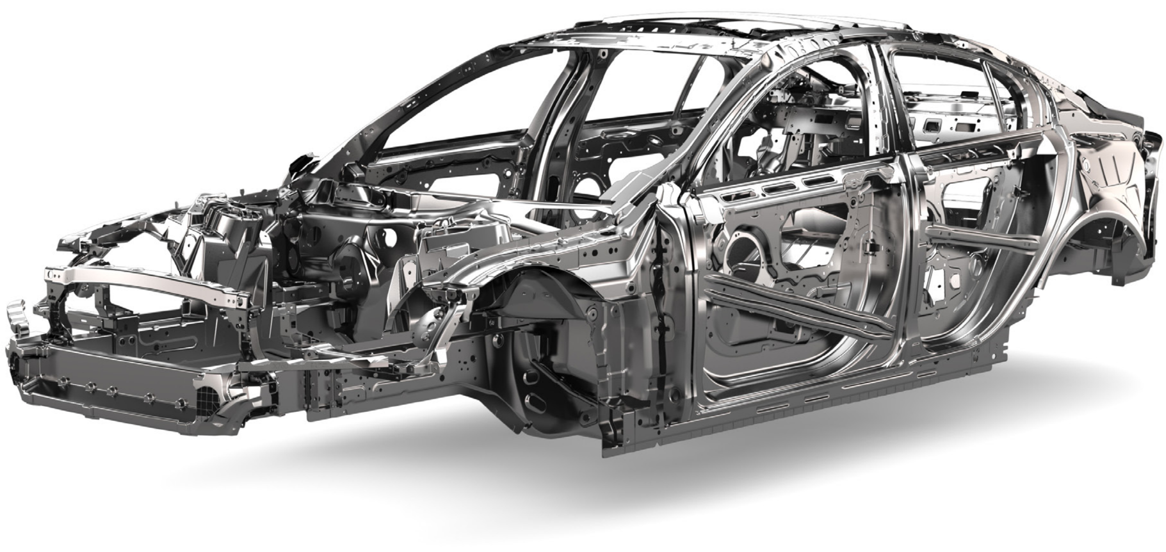


Table 3:

Comparison of commonly casted metals

	Ductile Iron	Stainless Steel	Carbon Steel	Copper Alloy	Nickel Alloy	Aluminum
Corrosion Resistance	Very Low	High	Low	High	Very High	Medium
Machinability	High	Low	Medium	High	Low	High
Price	Very Low	High	Low	Very High	Very High	Medium
Tensile Strength	Medium	Very Low	Medium	Low	Medium	Low
Hardness	High	Low	Medium	Low	Medium	Very Low
Weldability	Very Low	Medium	Very High	Very High	Low	Medium
Wear Resistance	Medium	Very Low	Medium	Low	Low	Low
Toughness	Very Low	Very High	High	Medium	High	Medium

9. Glossary of Terms

Alloy - A metal created by combining two or more elemental metals

Bauxite - A clay-like mineral compound containing high amounts of aluminum

Bayer method - The process of refining bauxite into aluminum oxide

Carbon Steel - A ferrous alloy made of iron and carbon

Casting - The process of pouring a molten substance into a pre-formed mold and allowing the substance to solidify

Casting Alloy - An alloy intended for casting

Die Casting - A type of casting involving a reusable mold and pressurized insertion of a molten substance

EC Aluminum - Electrical Conductor aluminum, a high-purity (99%) aluminum alloy used in electrical wiring

Electrolysis - The process of passing an electrical current through a substance in order to break it down into simpler substances

Extrusion - A forming process in which a workpiece is forced through a smaller hole with a particular cross

Ferrous Alloy - Any alloy containing iron, like cast iron, carbon steel or stainless steel

Forging - Compressing a metal part through great force to maximize strength

Greensand Casting - A type of casting involving disposable molds made of and an emulsion

Hall-Héroult method - Also known as smelting, the process of obtaining pure aluminum from aluminum oxide

Malleability - The ability of an object to be manipulated without breaking

Modulus of Elasticity - The tendency of an object to deform, or bend, when acted on by forces perpendicular to a given axis

Non-Ferrous Alloy - Any alloy not containing iron, like bronze, brass and aluminum alloys

Oxide Layer - The molecular layer that forms when the surface of a substance reacts with oxygen in water or air

Permanent Mold Casting - A type of casting involving a reusable mold

Rolling - The process of passing metal through a pair of rollers to reduce its thickness

Smelting - See Hall-Héroult method

Stainless Steel - A ferrous alloy made of iron, carbon and other alloying elements like chromium, nickel and molybdenum

Wrought Alloy - An alloy intended for plastic manipulation, like forging, extrusion or rolling

For a more comprehensive glossary, take a look at the Eagle Group's ***Metal Casting and CNC Machining Glossary***, available here:

https://www.eaglegroupmanufacturers.com/glossary/

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About Eagle Aluminum Cast Products, Inc.

Based in Muskegon, Michigan, Eagle Aluminum Cast Products, Inc. is a versatile aluminum foundry and pattern shop that specializes in permanent mold and greensand casting.

Eagle Aluminum is part of the Eagle Group, which is made up of three foundries and a CNC machining house. Together, the Eagle Group provides outstanding customer service and quality machined castings using several different processes and a wide range of alloys.

To learn more, visit us on the web at

www.eaglealuminumcastproducts.com

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