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From Bauxite as a Critical Material to the Required Properties of Cast Aluminum Alloys for Use in Electro Automotive Parts

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Abstract: There is a long process to transform bauxite, a critical raw material, into a substance with the required properties of cast aluminum alloys for use in electro automotive parts. Thanks to its unique properties, aluminum has become the material of choice for clean technology manufacturers in applications such as use in the automotive industry, renewable energy, batteries, electrical systems, resource-saving packaging, energy efficient buildings and clean mobility. Restructuring of the economy, the oil crisis, air pollution and global warming are some of the factors that have moved the automotive industry towards electrification since the beginning of the 21st century. This paper aims to highlight the required properties of cast aluminum alloys applied to the production of electro automotive parts, such as their mechanical and thermophysical properties, dimensional stability, corrosion resistance, electromagnetic compatibility and crashworthiness. Furthermore, this paper discusses which of the cast aluminum–silicon alloys, as well as the heat treatments and casting processes, are most suitable.

Keywords: electro mobility parts; casting processes; dimensional stability; corrosion resistance; electromagnetic compatibility; crashworthiness

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1. Introduction

Native elements such as gold and silver, lead, copper, tin and mercury have been known since ancient times, but the first scientific discovery of an element occurred in the 17th century. Although aluminum is a very common metal, comprising about 8% of the composition of the Earth's crust, it was only discovered in the 19th century due to its high affinity for oxygen and, therefore, its inability to be found in nature in its pure form. Pure aluminum was produced for the first time in laboratory conditions by Hans Christian Oerstedt in 1825, using the reduction process. Almost sixty years later, in 1886, two scientists—Hall and Héroult—each patented a process of smelting aluminum, independently of each other. The production of pure aluminum involves the dissolution of aluminum oxide (alumina—Al_2O_3) in molten cryolite and the electrolysis of a molten salt bath [1]. Additionally, Karl Jozef Bayer developed an efficient process for the production of alumina from bauxite in 1982, thereby completing the two-step so-called Bayer–Hall–Héroult process: refining bauxite to obtain alumina and smelting alumina to produce aluminum [2]. Bauxite is a naturally occurring, clay-like sediment that is the principal host for alumina. In general, bauxite is an ore formation consisting of a conglomerate of several minerals containing aluminum, with other valuable impurities. Iron oxides, such as Fe_2O_3 and FeO(OH), as well as clay minerals, kaolinite, rutile, titanium minerals, silica and anatase are among the contaminants. Bauxite is intended for aluminum production due to its high concentration of the aluminum-containing minerals Boehmite—AlO(OH), Gibbsite—$Al(OH)_3$ and Diaspore—AlO(OH).

From an industrial perspective, bauxite is a critical mineral from which alumina is extracted and subsequently used to produce primary aluminum.

Aluminum produced through the Baier–Hall–Heroult process is used to produce various primary casting alloys, which are applied in various industries. According to the available literature [3], the major global use of aluminum in 2021 was for the automotive and transport industry (29%), followed by construction (23%), foils and packaging (16%), electrical engineering and electronics (11%), machinery and equipment (7%), consumer goods (4%) and other applications (10%). The intensity of aluminum's use in the automotive industry and in transportation is increasing because of its unique properties (the combination of light weight and high strength), as well as its recyclability, which contributes to the reduction of greenhouse gas emissions. The global automotive industry has been going through drastic changes in the last several years [4]. One of the fundamental changes is its shift towards electrification. The shift is mainly triggered by new environmental regulations. Nevertheless, the idea to produce electric vehicles is not entirely new—as Figure 1 illustrates, it has existed for more than a century [5]. Several persons in Europe experimented, independently of each other, with electric cars during the second half of the 19th century (e.g., Porsche), while around the same time, in 1897, the Electric Carriage and Wagon Company in the USA introduced the first electric vehicles, which were commercially available [6,7]. However, gasoline-powered vehicles began to dominate the US market after 1920, mainly because of the development of a more comprehensive road infrastructure (including the implementation of petrol stations). Gasoline-powered vehicles could travel faster and further and were seen as superior to electric vehicles, which were slow and had limited driving range. The economic and oil crisis, air pollution and global warming are some of the factors that drastically changed the vehicle production strategy at the beginning of the 21st century, driven by more restricted environmental regulations. In the last few years, we have witnessed that most Original Equipment Manufacturers (OEMs) have introduced Electro Vehicle (EV) models or prototypes within their product portfolio, with increasing expectations for the coming years.

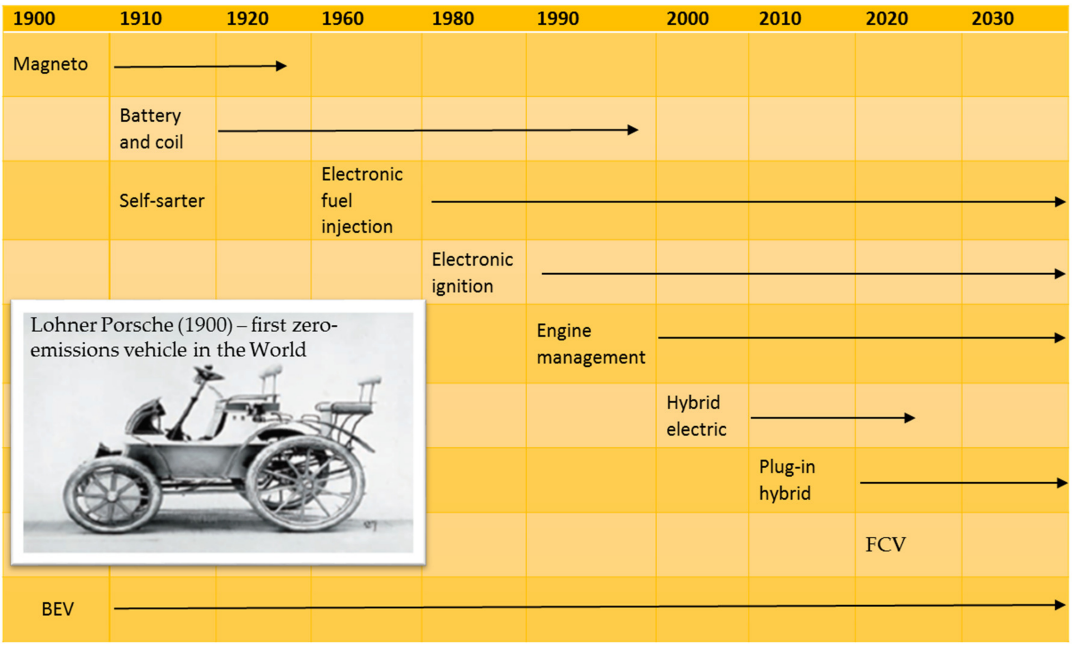


Figure 1. The historical perspective of road vehicle electrification [5].

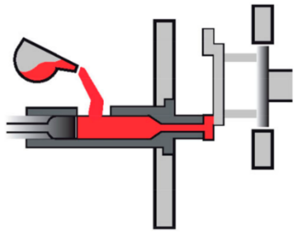
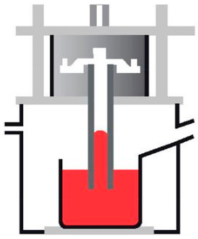
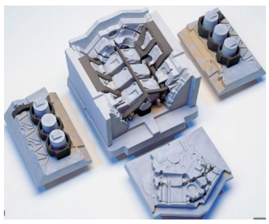
The growing production of electric vehicles has caused the need to consider new properties of aluminum and its alloys in the production of e-mobility parts. Therefore, the goal of this study is to analyze what types of alloys, casting processes and heat treatment can be applied to the production of aluminum in casting plants in order to fulfill the required mechanical and thermophysical properties of electro automotive parts. Moreover, the intention is to highlight their new specific properties, such as dimensional stability, corrosion resistance, electromagnetic compatibility and crashworthiness, all of which are criteria that cast parts need to satisfy in order to be applied in the mobility industry. Electro automotive parts in this text are considered to fall under either e-mobility (e.g., battery, chasses, body, etc.) or e-housing (e.g., engine parts, stator, gearbox, etc.).

2. Aluminum Cast Alloys

Despite the great natural abundant of bauxite, as a primary raw material for aluminum cast alloy production, most of its end users are currently considering the use of secondary (recycled) aluminum for final production, due to very intensive energy consumptions and high CO_2 emission during primary aluminum production. The European Commission (EC) has bauxite listed as one of the critical raw materials (CRM) for 2020, counting on its strategic role in sustainable technologies and sectors from 2030 and 2050. The inclusion of bauxite in the EC's CRM list supports the role of Europe's aluminum industry in its transition to a green metallurgy. Thanks to its unique properties (low density, high thermal conductivity, non-toxicity, excellent corrosion resistance, as well as easy casting, machining and shaping), aluminum is recognized as the choice material for clean technology, especially in uses involving renewable energy, electrical systems, batteries, resource-efficient packaging, even energy-efficient buildings—and of course, aluminum alloys for cast automotive parts. Therefore, the sustainable production of aluminum from bauxite and/or bauxite residues is a very important and critical step for the future. Europe needs to develop a thriving and responsible obtaining strategy for bauxite as a CRM, considering recycling as required step on this road. The supply chain disturbances may be reduced by sustaining an irrepressible and autonomous European aluminum value chain, with the expectation of increased political and social attention. In this case, the aforementioned aluminum value chain can strengthen production capacities, regardless of whether it is primary or secondary aluminum.

The automotive industry has used aluminum–silicon cast alloys for years, primarily due to their outstanding mechanical properties and good casting characteristics in regard to producing body parts, transmission systems and motors. A recent study specially made for European Aluminum, which was conducted by Ducker Carlisle, revealed that the average amount of aluminum has increased by 18% in cars made in Europe, i.e., from 174 kg to 205 kg in the period of 2019–2022 [8,9]. The study predicts that this trend is set to continue, with the average aluminum content projected to increase to up to 256 kg per vehicle by 2030. According to the study, the trend towards light weighting and electrification in the automotive industry is driving a significant increase in aluminum content. This tremendous growth in aluminum usage in Battery Electric Vehicles (BEVs) is mainly attributed to its use in e-drive housing, battery pack housings, ballistic battery protection and cooling plates. Some of the cast aluminum alloys used in the production of Internal Combustion Engines (ICE) such as EN AC—47000 (AlSi12(Cu1)), EN AC—44300 (AlSi12(Fe)), EN AC—43500 (AlSi10MnMg) and EN AC—42100 (AlSi7Mg), will be also used in the production of parts for Battery Electric Vehicles (BEV). According to DIN 1706 [10], these alloys are standard alloys that can be acquired on the market. Definitively, the growth of the BEV market will have positive consequences for aluminum cast producers. Even though BEVs have fewer components and moving parts compared to traditional vehicles with internal combustion, aluminum will be used for some other parts (e.g., e-mobility, e-housings, etc.). Beside good mechanical and thermos-physical properties, these alloys need to satisfy some additional properties such as: dimensional stability, corrosion resistance, electromagnetic compatibility and crashworthiness. Three casting processes, presented in Table 1, have been identified as the most commonly used processes for the production of electro automotive parts: High Pressure Die Casting (HPDC), Low Pressure Die Casting (LPDC) and Core Package System (CPS). Table 1 also briefly summarizes the advantages of all three processes. More details about each casting process can be found in the literature [11,12].

Table 1. Review of some casting processes that can be used for the production of E-parts.

Casting Process		Advantages
High Pressure Die Casting (HPDC)		• High production rates • High level of automatization • Good surface finish • Economic in large quantity • High flexibility in design • Very good dimensional accuracy
Low Pressure Die Casting (LPDC)		• Fair production rate • High quality of cast parts • Moderate tooling cost • High dimensional accuracy • High material utilization—no need for feeders
Core Package System (CPS)		• Tranquil transfer of metal • Minimal content of oxides and non-metallic inclusions • High integrity and dimensional accuracy • Reduced fettling time and no machining required. • High strength and ductility of cast products

3. Mechanical Properties

Electro automotive components are generally relatively uncomplex parts compared to cylinder heads or engine blocks. According to OEM, these alloys need to have a low residual stress level, a high dimensional stability, corrosion resistance, good electromagnetic compatibility and moderate mechanical properties in as-cast condition. These include yield strength (YS) $\geq$ 140 MPa, ultimate tensile strength (UTS) $\geq$ 180 MPa and elongation at fracture (A) between 1 and 2%. Table 2 shows typical mechanical properties of selected alloys taken from DIN 1706 [10] for die pressure casting process. According to Table 2, all selected alloys, even as-cast, achieved the expected mechanical properties (UTS and A).

Table 2. As-cast mechanical properties of die-cast selected alloys.

Alloy	As-Cast Mechanical Properties		
	UTS, MPa	YS, MPa	A, %
AlSi9Cu3(Fe)	240	140	<1
AlSi10Mg	240	140	1
AlSi10MgMn	250	120	5
AlSi12(Fe)	240	130	1
AlSi12Cu1(Fe)	240	140	1

Recently, some OEMs have begun to ask for solutions of BEV engines with very high torque (>1000 Nm). To reach this, e-housing and mobility parts need to provide significantly higher strength: YS > 240 MP and elongation: A = 2–3%. It means that the mechanical properties of future e-vehicle parts need to be improved through increasing strength and elongation at the same time. The dilemma of how to improve the strength of presently used alloys without sacrificing elongation is well known from the literature [13]. Figure 2 illustrates this well-known dilemma. As Figure 2 shows [13], applying various strengthening strategies such as: foreign particle reinforcement (blue closed squares), grain refinement (black closed circles), alloying (open squares) and optimized casting (green closed triangles), the strength of A356 alloy can be improved with minimum impact on elongation. From the literature and from foundry experience, it is known that the strength of HPDC aluminum–silicon cast alloys applied to the production of electro automotive parts can be improved by proper selection of casting processes (different cooling rates), applying heat treatment processes (solid solution strengthening mechanisms) and the selection of appropriate alloying elements (second phase strengthening and/or grain refinement).

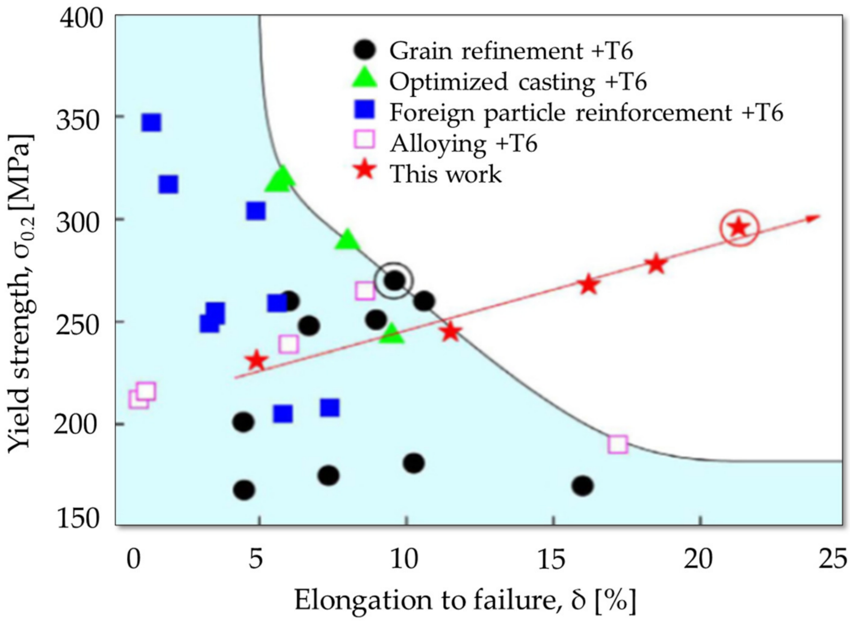


Figure 2. Strength–ductility trade off dilemma [13].

4. Improvement of Strength through Selection of Appropriate Heat Treatment Process

Cast aluminum alloys are lightweight structural materials that can be strengthened by further alloying. Additionally, some of the aluminum alloys which contain Cu, Mg and Zn can be further strengthened by heat treatment. The heat treatment of aluminum castings is carried out to change the properties of the as-cast alloys by subjecting each casting to a thermal cycle, or a series of thermal cycles. The conditions of thermal treatments of castings, as defined by EN 1706 [10], are as follows: F—as cast; T1—controlled cooling from casting and naturally aged; T4—solution heat treated and naturally aged; T5—controlled cooling from casting and artificially aged or over-aged; T6—solution heat treated, quenched (with water or air) and artificially aged; and T7—solution heat treated, quenched (with water or air) and over-aged (stabilized). The microstructure of materials is changed during the heat treatment process. Mechanical properties including strength, toughness, hardness, ductility and wear resistance are affected by the ensuing phase transformation [14]. As Figure 3 illustrates [15], by selecting the proper heat treatment process, strength or elongation can be significantly increased. By selecting T6 and T5 heat treatment states, the strength of the material can be increased, while by applying T7 and/or T4 its elongation can be improved. According to Figure 3, it should be considered that requested mechanical properties can be fine-tuned by selecting the optimal content of alloying elements, in this case magnesium. Besides improving mechanical properties, heat treatment also stabilizes the microstructure of cast parts and improves their thermal conductivity.

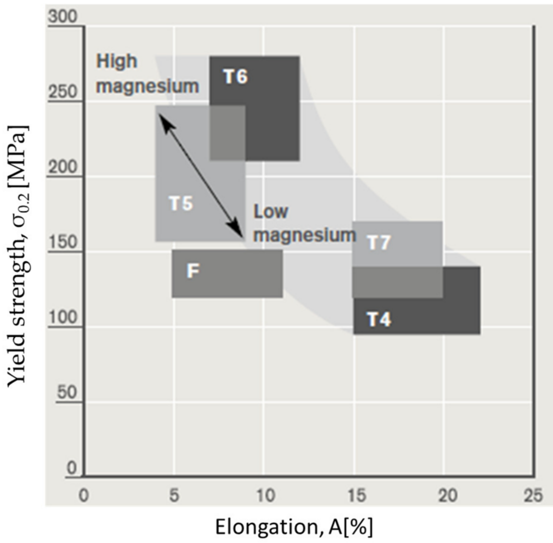


Figure 3. Impact of heat treatment processes on the elongation and strength of HPDC alloys [15].

It is well known from the literature that a combination of natural and artificial aging, as Figure 4 illustrates [16], can significantly improve strength at the expense of elongation. It appears that during natural ageing, small, coherent, finely distributed precipitates are formed, and during artificial ageing at higher temperatures, rather few, but coarse, incoherent particles precipitate. In addition, a combination of the two precipitation variants leads to the highest strengths in the casting parts [17].

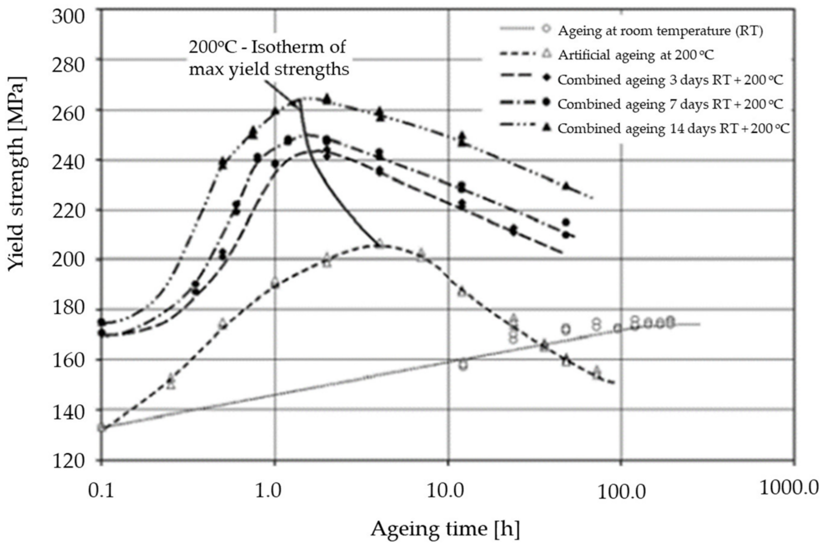


Figure 4. Increases in the yield strength through a combination of natural and artificial ageing at 200 °C; the isotherm shows the influence of natural ageing time on the maximum strength [16].

5. Improvement of Strength through Selection of Appropriate Alloying Elements

The effects of alloying elements on aluminum alloys include precipitation hardening (age hardening); dispersion strengthening; solid solution hardening; grain refinement; alteration of metallic and intermetallic phases; grain growth suppression at high temperatures; and so on. The mechanical properties of cast aluminum alloy components are determined largely by the shape, size and distribution of precipitated particles in the aluminum matrix. The impact of major and minor alloying elements on the mechanical properties (UTS, YS and A) of cast aluminum parts have been summarized in Table 3. More information regarding the impact of each alloying element on the mechanical properties of cast aluminum alloys can be found in the corresponding references listed in Table 3.

Table 3. A summary of the effects of some alloying elements on the mechanical properties of cast aluminum alloys.

Alloying Element		UTS	YS	A	References
Major	Si	↗	↗	↘	[18]
	Cu	↗	↗	↘	[19]
	Mg	↗	↗	↘	[20]
	Mn	Insignificant	Insignificant	↗	[21]
	Zn	↗	↗	↘	[22]
Minor	Fe	↘	↘	↘	[23]
	Pb	Insignificant	Insignificant	Insignificant	[24]
	Sn	↘	↘	↗	[25]
	In	↗	↗	↗	[26]
	Be	↗	↗	↗	[27]
	Cr	↗	↗	↘	[28]
	Ni	↗	↗	↘	[29]
	Zr	↗	↗	↘	[30]
	Mo	↗	↗	↘	[31]
	Sc	↗	↗	↘	[32]
	La	↗	↗	↘	[33]

A literature review has shown that there are commercial HPDC alloys (e.g., AlSi7Mg, AlSi10MgMn) available on the market which can be utilized to create electro automotive parts with those essential characteristics. The mechanical properties of these alloys can be further improved by selecting a proper heat treatment process (T5, T6 and/or T7), which can adjust the strength and elongation of electro automotive parts produced using selected HPDC alloys. Selected HPDC alloys can further improve their strength characteristics by alloying with some major (Mg, Mn, Zn and Cu) and minor (Zr, Mo, Sc, La, etc.) alloying elements. The content of added elements needs to be optimized for each product to reach required mechanical, thermophysical, corrosion and other needed properties [34,35]. Additional consideration needs to be taken when using minor alloying elements. Their prices are significantly high and they are, therefore, sometimes not suitable for commercial application.

6. Dimensional Stability

In aluminum cast parts, the dimensional stability (irreversible casting growth) plays a significant role. In general, any precipitation of aluminum alloys during ageing is accomplished by the sample volume's growth, whereas dissolution during solid solution is followed by its size decreasing. This volume variation is caused by the precipitation of different phases (e.g., Mg_2Si, Al_2Cu, $Al_5Cu_2Mg_8Si$, and so on) during natural or artificial aging. Alloys with higher copper and magnesium contents are more prone to irreversible growth. This is mainly due to the Θ, Θ′ and Θ″ metastable copper-rich phases (the pre-stage of the Al_2Cu stable intermetallic phase), which precipitate during ageing. Applying T5, T6 or T7 temper conditions causes those metastable phases to become more stable, and no significant further irreversible growth is expected during service thereafter.

Figure 5 shows that temperature and time strongly affect the dimensional stability of the proposed alloys. Lower test temperatures (lower working temperature conditions) for tested alloys Nr. 1 and Nr. 3 (Nr. 1—base alloy with higher content of copper and magnesium, and Nr. 3—alloy with lower content of copper and magnesium) resulted in lower irreversible casting growth rates. Measurements run at 100 °C for up to 400 h did not show any significant difference in the irreversible change of length for the two investigated alloys. As can be observed in Figure 5, irreversible growth increases with increasing ageing temperature (operating temperature). Beside temperature and time parameters, the amounts of precipitated phases play a significant role on the irreversible growth. It is obvious from Figure 5 that alloy Nr. 3, with a lower content of copper and magnesium, has a considerably smaller irreversible change of length compared to alloy Nr. 1 independently of the test temperatures (125 and 150 °C). Therefore, irreversible growth could be a significant issue only at localized positions of electro automotive parts that are exposed to temperatures higher than 120 °C.

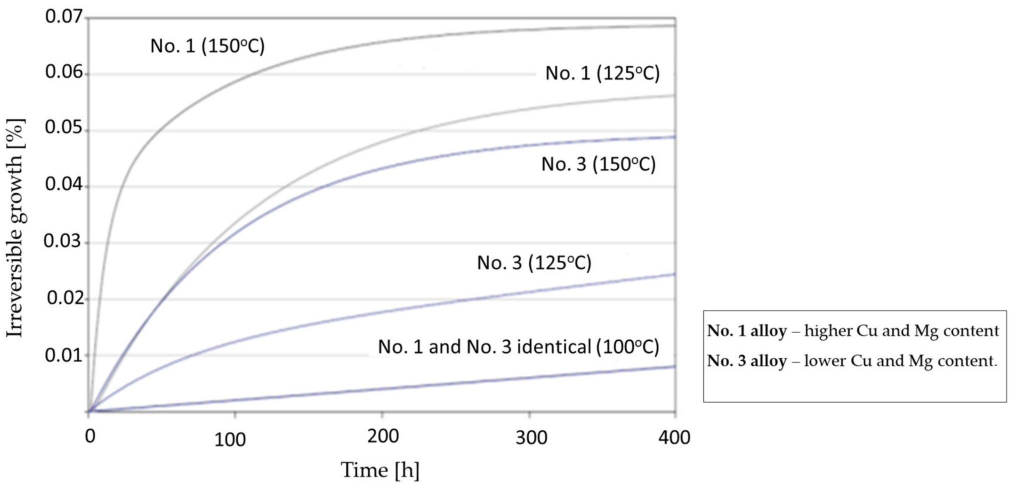


Figure 5. The impacts of temperature and time on irreversible growth during engine working conditions for an engine block [36].

7. Corrosion Resistance

Aluminum is a very active metal—it reacts immediately with oxygen if exposed to air, which naturally creates a passive adherent oxide layer on the surface, and its corrosion resistance is influenced by the passivity that this protective oxide layer creates [37]. In most environments, this thin layer instantly reforms after being damaged and keeps shielding the aluminum from corrosion. Corrosion happens when the film is taken off or damaged in a way that prevents self-repair. Aluminum is corrosion resistant in neutral solutions, but is highly susceptible to both basic and acidic solutions. In the pH range between 4 and 9, the amorphous protective oxide layer, with a thickness of 2 to 4 nanometers, is formed in water or air [38–40]. One of the fastest metals to oxidize is aluminum due to its extremely electronegative potential. The naturally passive layer, however, makes aluminum behave as a very stable metal, especially in oxidizing media like air and water. An aluminum alloy's ability to resist corrosion depends on both metallurgical and environmental factors [41–43]. Corrosion is influenced by metallurgical factors such as composition (see Figure 6), heat treatment (proper temper selection), mechanical working and the presence of impurities [39]. These influence the microstructure, which determines the type of attack and whether localized corrosion takes place.

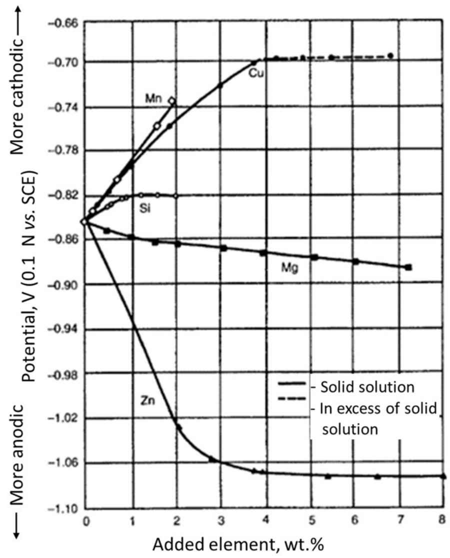


Figure 6. The effects of aluminum's major alloying elements on the electrolytic solution's potential [39].

Localized corrosion in aluminum alloys used in commercial engineering is typically brought on by microscopic flaws, like non-metallic inclusions or insoluble intermetallic particles with a size range of between several microns and a nanometer [40,44]. In addition, aluminum alloying elements also have some impacts on the corrosion. Elements such as silicon, manganese and copper can be precipitated in the form of intermetallic, in which form they are more cathodic (does not corrode, but stimulates corrosion in the adjacent matrix zone), while zinc and magnesium in intermetallic form are more anodic (stimulating corrosion). Therefore, aluminum alloys suitable for the production of electro automotive parts should have a lower copper content [40]. In the Al-Si-Cu alloys, precipitation of Al_2Cu at the grain boundaries (Al_2Cu is electrochemically nobler than the Al-matrix) can deplete the copper in the areas close to the boundaries, turning them anodic in comparison to the centers of the grains and causing intergranular corrosion to happen quickly. Therefore, when using cast alloys containing copper, some OEM producers of electro automotive parts expect a corrosive attack, especially on sealing surfaces and subsequently on the electrical connections [43]. In operation, electro automotive parts reach lower temperatures compared to combustion engines, which significantly aggravates a corrosive attack. Also, the use of stronger encapsulation can cause condensation phenomena, which likewise strengthens a corrosive attack. Therefore, the use of alloys with lower copper content is required [36,37].

Since there are numerous factors that affect corrosion, aluminum's suitability cannot be determined solely by a particular product or environment. It is crucial to have in-depth knowledge of impurities, operating circumstances, operating part design, as well as alloy microstructure. The most valuable experience comes from past service applications that were successful. However, improvements in fabrication (alloy selection, melt cleanliness), heat treatments and the development of suitable methods of protection may result in the successful application of Al-Si alloys with different copper contents in many corrosive environments [36–44].

8. Electromagnetic Compatibility

The ability of a unit of equipment or a system to operate effectively in its electromagnetic surroundings, without bringing intolerable electromagnetic disturbance into that environment, is known as electromagnetic compatibility. In other words, electromagnetic compatibility is the ability to tolerate a specific degree of interference. Due to the increasing use of electronic devices (automotive applications, personal computers, communication tools, and so on), electromagnetic compatibility is becoming more important in the automotive industry. In cases where selected alloys applied during the production of electro automotive parts are not in compliance with electromagnetic compatibility, the practical impacts can be recognized in both the minor (e.g., cell phone interference) and major consequences (e.g., improper deployment of airbags). Therefore, it is important to recognize the potential hazards of applying various aluminum alloys for use in electro automotive parts (e.g., battery housing), as their emitted magnetic fields can compromise the function and control of vehicles. Generally, aluminum and its alloys are well-protected against electromagnetic fields. Aluminum has very low magnetic permeability ($\mu R = 1.0002$), classifying it as part of the group of materials with paramagnetic behavior. A material's magnetic permeability—the level of magnetization it develops in response to an applied magnetic field—is a measure of its capacity to support the generation of a magnetic field within itself. Contrary to aluminum, iron has very high magnetic permeability (μR = 300 to 10,000), indicating ferromagnetic behavior in this metal. Copper in aluminum alloys precipitates in the form of copper-rich Al_2Cu phase, which reduces electromagnetic fields by absorbing electromagnetic waves. The low electromagnetic permeability of aluminum alloys does not result from the fact that copper is a diamagnetic element (diamagnetic element means that this type of element is not attracted by magnets), but from the fact that an eddy current is induced at the surface, which protects against the electromagnetic fields. In addition, the presence of copper increases the eddy current, protecting against even stronger electromagnetic fields. Therefore, regarding electromagnetic compatibility, aluminum alloys with copper are suitable for application in the production of electro automotive parts.

9. Crashworthiness

The capacity of a structure to safeguard its users during impact is known as crashworthiness. This is frequently tested when examining the safety of vehicles and aircrafts. When a vehicle is said to be crashworthy, it means that its structural integrity can withstand reasonable deceleration loads and still maintain enough survival space for its users. In the case of a collision, all produced electro automotive castings which are part of the body structure, such as battery housings, must deform plastically in a short period of time (milliseconds) to absorb the crash energy in a controllable manner without cracking. At the same time, aluminum alloys used for electro automotive parts should be light weight, having sufficient flexibility and torsion stiffness for proper application and handling. All previously mentioned alloys (EN AC—47000 (AlSi12(Cu1)), EN AC—44300 (AlSi12(Fe)), EN AC—43500 (AlSi10MnMg), EN AC—42100 (AlSi7Mg)) have satisfactory ductility, which can be, when needed, further improved through alloying (e.g., modification by adding magnesium or strontium) and/or appropriate heat treatment processes. The solid solution treatment is mostly responsible for crashworthiness, as it involves modifying and separating silicon particles, minimizing crack initiation. The addition of strontium into aluminum alloys modifies large, plate-like silicon particles with sharp edges into small ones with rounded shapes, thereby improving the crashworthiness of the alloys.

10. Conclusions

Cast aluminum alloys are extremely attractive prospects for the production of electro automotive parts due to their respectable properties, such as: good mechanical and thermophysical properties, great dimensional stability, acceptable corrosion resistance, known electromagnetic compatibility and predictable crashworthiness. It means that this market will need more aluminum in the future. There are several cast aluminum alloys

(EN AC—47000 (AlSi12(Cu1)), EN AC—44300 (AlSi12(Fe)), EN AC—43500 (AlSi10MnMg), EN AC—42100 (AlSi7Mg)) available in the world market that can be used for the mass production of electro automotive parts by applying the following casting processes: HPDC, LPDC and CPS. The mechanical properties of these alloys can be further improved through suitable heat treatment processes (T5, T6 and T7) and additional alloying with major and minor alloying elements. The main concerns in regard to the addition of alloying elements to existing aluminum alloys are related to their limited content and their effect on the corrosion of the cast parts. Moreover, the cost of some alloying elements may potentially be the limiting factor for their use in the production of electro automotive parts.

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