



Al Alloys and Casting Processes for Induction Motor Applications in Battery-Powered Electric Vehicles: A Review

Yuxian Li, Anita Hu, Yintian Fu, Sufeng Liu, Wutian Shen, Henry Hu * and Xueyuan Nie

Department of Mechanical, Automotive and Materials Engineering, University of Windsor, Windsor, ON N9B3P4, Canada; li11115x@uwindsor.ca (Y.L.); hu14l@uwindsor.ca (A.H.); fu14@uwindsor.ca (Y.F.); liu1114z@uwindsor.ca (S.L.); shen12a@uwindsor.ca (W.S.); xnie@uwindsor.ca (X.N.) * Correspondence: huh@uwindsor.ca

Abstract: With the rapid expansion of battery-powered electric vehicles (BEVs) in the automotive industry, research interest in lightweight Al alloys as well as their casting processes and applications has increased considerably. The substitution of castable aluminum alloys with superior strengths and electrical conductivity for copper reduces the weight and size of electric induction motors, and improves the energy efficiency and driving range of the BEVs. The present article was intended to give a general introduction into the common cast Al aluminum alloys and their relevant processes, as well as to motivate the development of high strength and conductive Al alloys for the practical realization of Al applications in the motors of the BEVs. A number of cast alloy systems containing Cu, Si, Ni, Mg, Fe, and Ti were evaluated, in comparison to nanostructured wrought Al alloys. The conventional casting processes suitable for Al alloys, high pressure die casting, squeeze casting, and sand casting were described. Strengthening mechanisms including solid solution strengthening, precipitation strengthening, dislocation accumulation strengthening, and grain boundary strengthening were presented. The phenomenon of electrical conduction for Al alloys was outlined. The mechanical properties and electrical properties of the recently developed Al alloys for casting and deformation processes were comprehensively listed and critically reviewed in association with microstructural characteristics.

Keywords: Al alloys; casting processes; electrical conductivity; electric motor; electric vehicle; mechanical properties; strengthening mechanisms

1. Introduction

With the increasing environmental impact from the automotive industry, batterypowered electric vehicles (BEVs) have become increasingly popular. An induction motor is an important system component in integrated BEVs working on different operating conditions [1], since a rotor of the induction motor is configured of an electrical sheet, a rotor bar, and end-ring (Figure 1), which are usually manufactured by high pressure die casting (HPDC) or sand casting. To improve the efficiency of the induction motor, copper with a high electrical conductivity and low resistivity, is often used. Moreover, this is due to the fact that copper has high electrical and thermal conductivity and is the most important conducting material in electrical engineering. In addition, high corrosion resistance, machinability, and a relatively low cost determine the wide use of copper in the industry in a pure state, as well as in alloys [2]. However, as a lightweight metal with a density of 2700 kg/m³ and a melting temperature of 660 $^{\circ}$ C, aluminum is 70% lighter than copper, and its melting point at 423 °C is lower than copper. Compared to copper, it is very easy to manufacture the induction motor with aluminum-based alloys via casting processes [3], since pure aluminum is rarely used for casting due to its poor castability and low strength.



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Figure 1. Components of an electrical sheet, a rotor bar, and an end-ring in an induction motor [1].

Aluminum and its alloys are very popular for many applications due to its appearance, light weight, fluidity, castability, fabricability, weldability, physical and mechanical properties, hot tear resistance, and corrosion resistance [4]. The addition of silicon to aluminum reduces its melting temperature and improves fluidity. Therefore, the aluminum alloys with silicon have good castability, resistance to hot tearing, reasonable mechanical properties, and excellent corrosion resistance.

2. Classification of Aluminum Alloys

Aluminum alloys can be divided into two major groups, which are wrought and casting alloys. The aluminum association (AA) has adopted a nomenclature of wrought and cast aluminum alloys. The wrought alloy is a four-digit system in the aluminum association. The first digit (Xxxx) indicates the principal alloying element. The second single digit (xXxx), if different from 0, indicates a modification of the specific alloy, and the third and fourth digits (xxXX) are arbitrary numbers given to identify a specific alloy in the series. However, regarding cast Al alloy, the AA used a three-digit system (XXX.X). The first digit in the cast aluminum alloy designation system indicates the major alloying element or elements. Table 1 presents the different alloying elements assigned to each digit. The second and third digits indicate the purity of the aluminum [5]. Among the cast Al alloys, 2xx.x and 3xx.x series are often employed for various cast automotive components for high strength and cast abilities, respectively.

2.1. Al-Cu Alloys

In the designation system of the cast aluminum alloy, the aluminum with copper as the major alloying element is in 2xx.x series. The aluminum-copper alloys typically contain between 2 to 10% copper, with smaller additions of other elements. Copper (Cu) has the single greatest impact of all the alloying elements regarding the strength and hardness of aluminum cast alloys, in both cast and heat-treated conditions [6]. The investigation of the properties after copper was added into the aluminum alloy is crucial for many industrial applications. The phase diagram of Al-Cu system has been evaluated [7], as shown in Figure 2.

Alloy Series	Principal Alloying Element
1xx.x	Pure Aluminum (≥99%)
2xx.x	Copper
3xx.x	Silicon and/or Copper and/or Magnesium
4xx.x	Silicon
5xx.x	Magnesium
6xx.x	Not used
7xx.x	Zinc
8xx.x	Tin
9xx.x	Other

Table 1. Cast aluminum alloy designation system [5].



Figure 2. Phase diagram of Al-Cu system [7].

Figure 3 reveals the variation in properties of Al-Cu alloys as a function of their Cu content. The value of hardness increases with increases of the Cu content. However, strength and ductility depend on whether the Al₂Cu phase is present in a solid solution as evenly distributed spheroidized particles or as a continuous network at the grain boundaries. Alloys with fine Al₂Cu (T6) particles have the largest increase in strength, and retain substantial ductility. Conversely, alloys where Al₂Cu is present as a continuous network at grain boundaries do not show an appreciable increase in strength, but rather a loss of ductility [8].

2.2. Al-Cu-Si Alloys

In the designation system of the cast aluminum alloys, the series of 3xx.x always contains copper and silicon. The most popular HPDC alloy due to excellent castability and low cost is the A380 alloy. Silicon, as one of the most common elements, is used in these alloys. The benefits of alloying silicon are the improvement of castability and strength, and resistance to abrasive wear. Silicon in combination with magnesium allows the strengthening of the alloys by precipitation hardening. As seen in Figure 4, depending on the Si concentration in weight percentage, the Al-Si alloy systems are divided into three major categories: Hypoeutectic (<12 wt% Si), Eutectic (12 wt% Si), Hypereutectic

(>12 wt% Si) [9]. It can be easily revealed that the fluidity of the alloy increases with the increasing content of Si in aluminum. Fluidity is one of the most important properties for casting alloys. Generally, the smaller the solidification temperature range, the lower the viscosity, the lower the surface tension of the melt. In addition, the fewer the amount of inclusion present, the better the fluidity of an alloy [6].



Figure 3. Mechanical properties of Al-Cu alloys as a function of Cu content [8].



Figure 4. Al-Si binary eutectic phase diagram with composition ranges of various alloy types [9].

2.3. Mechanical Properties of Al-Si Alloys

Abdel-Jaber et al. [10,11] found that the increasing Si content from 3% to 8% slightly increased the ultimate tensile strength (UTS). A linear increase in UTS was revealed with the increase in silicon content from 8% to 15%. The study by Elzanaty [12] showed that the yield strength (YS) and the ultimate tensile strength hardness of Al-Si alloys increased with the increase in silicon content, while the total elongation decreased with the increase in silicon content, while the total elongation decreased with the increase in silicon content, as shown in Figure 5. The mechanical properties (ductility and toughness) of Al-Si alloys depended more on the distribution and the shape of the silicon particles than on the silicon content. Alloys, in which the silicon particles (eutectic or primary) were small, round, and evenly distributed, were usually highly ductile. On the other hand, alloys, in which the silicon particles are faceted and acicular, were usually considerably less ductile, but exhibited a slightly higher strength [13].



Figure 5. Effect of different Si contents on the mechanical properties. (**a**) Ultimate strength, (**b**) yield strength, (**c**) elongation, and (**d**) hardness in Al-Si alloys [12].

3. Casting Processes

3.1. High Pressure Die Casting (HPDC)

Die casting is a versatile process for producing engineered metal parts, where the molten metal is forced under high pressure into reusable steel molds. These molds can be designed to produce intricate shapes with a high degree of accuracy and repeatability. Casting parts, using high pressure, can be sharply defined with smooth or textured surfaces and are suitable for a wide variety of attractive and serviceable finishes. HPDC is popular among the highest volume, mass-produced items manufactured by the metal-working industry. HPDC components can be found in thousands of consumers, commercial, and industrial products. To date, they are widely and successfully used from automobiles to

toys. The HPDC process is generally divided into two groups, which are the conventional die casting process and high integrity die casting process [14]. The conventional HPDC has two different types of processes, which are hot chamber and cold chamber. In the field of the high integrity die casting process, squeezed casting is one of the important processes.

Conventional die casting (CDC) is a net-shape manufacturing process, where a permanent metal die is employed to produce components ranging in weight from a few grams to over 30 kg quickly and economically [15]. Although the hot-chamber HPDC is not often used to produce large components, very large products, such as car door panels, engine blocks, and transmission housings, can be produced using advanced cold-chamber HPDC technologies. A wide range of alloy systems, including aluminum, zinc, magnesium, lead, and brass can be employed by the HPDC processes.

3.1.1. Hot-Chamber Die Casting Process

A schematic of a hot-chamber die casting machine is shown in Figure 6. A significant portion of the metal injection system is immersed in the molten metal at all times. This helps keep the cycle times to a minimum, as molten metal needs to travel only a very short distance for each cycle. Hot-chamber HPDC processes are rapid in operation with cycle times varying from less than 1 s for small components weighing less than a few grams to 30 s for castings of several kilograms. Dies are normally filled between 5 and 40 ms. The hot-chamber HPDC is traditionally used for low melting point metals, such as lead or zinc alloys, as well as magnesium alloys. Higher melting point metals, including aluminum alloys, cause the rapid degradation of the metal injection system [14].



Figure 6. Graphical illustration of hot-chamber die casting process [14].

3.1.2. Cold-Chamber Die Casting Process

Cold-chamber die casting machines are typically used for relatively high melting point alloys, such as magnesium, aluminum or brass. An illustration of a cold-chamber die casting machine is presented in Figure 7a. Unlike the hot-chamber machine, the metal injection system is only in contact with the molten metal for a short period of time. This process starts with ladling the liquid metal into the shot sleeve for each cycle. The die cavity and plunger tip are normally sprayed with an oil or lubricant to provide further protection from severe degradation. This increases the die materials life and reduces the adhesion of the solidified component. Figure 7b is an illustration of the cycle using the cold-chamber die casting process as a model. In a cycle, liquid metal is ladled into an injection system (i),

which is then immediately pushed (ii) through a runner system (iii) into a die cavity at a very high speed (iv), and a high pressure applied for intensification. High pressures are maintained on the alloy during solidification. After complete solidification, the die opens (v) and finally the component is ejected (vi) [14].



Figure 7. (a) Graphical illustration of a cold-chamber die casting machine. (b) Casting cycle for cold-chamber die casting [14].

3.2. Squeeze Casting Process

The concept of squeeze casting was originally introduced in 1819 via a British Patent [16] and further envisioned by Chernov [17]. With about a two-century development, squeeze casting has been successfully applied to the manufacture of aluminum automotive components. Squeeze casting (SC) is a generic term to specify a fabrication technique where the slow cavity filling is applied, and solidification is promoted under high pressure within a re-usable die. It is a metal-forming process, in which the solidification of molten metal in a closed die is under an imposed high pressure. It combines permanent mold casting with die forging into a single operation, where molten metal is solidified under applied hydrostatic pressures. Other terms used to describe the same or similar processes are extrusion casting, liquid metal forging, liquid pressing, pressure crystallization, and squeeze forming. The slow cavity filling minimizes turbulent flow and air entrapment in molten metal. The high applied pressure keeps gases entrapped in the solution and squeezes molten metal from hot spots to incipient shrinkage pores. As a result, the porosity in the squeeze cast component could be eliminated. Moreover, due to the elimination of the air gap at the liquid-mold interface by the high pressure, the heat transfer across die surfaces is enhanced, which increases solidification and cooling rates. Generally, engineering components fabricated by squeeze casting are fine grained with an excellent surface finish and have almost no porosity. They come in a variety of shapes and sizes. The mechanical properties of these parts are significantly improved over those of conventional castings and more sophisticated casting routes of pressure or gravity die-casting [18-21].

A typical process of squeeze casting is shown in Figure 8. Squeeze casting has four main steps, which are preheat, pouring, solidification, and ejection. A suitable die set is installed on the bed of a hydraulic press. The die is preheated to a required working temperature. A commercial graphite lubricant is usually sprayed during the preheat process. Then, a pre-specified amount of molten metal is poured into a female die cavity. The upper male die or punch is lowered, meeting the liquid metal. Thereafter, the pressure is applied shortly after the molten metal begins to solidify and is maintained until all of the molten metal has solidified. Finally, the upper punch is withdrawn back to the original position and the casting component is ejected [22]. Depending on whether the pressure is applied directly on to the solidifying cast product through a punch or the applied pressure is exerted through an intermediate feeding system, squeeze casting can be classified as

"direct" and "indirect". In the direct squeeze casting, the casting component shows higher mechanical properties since the pressure is directly applied to the entire surface of the melting, which gives fully densified components, as well as an extremely fast heat transfer and fine grain structure. In the indirect squeeze casting, a gating system is added, which gives a pressure control on the injection of the material. However, with the indirect system, it is difficult to maintain a high pressure on the casting throughout the solidification, since the pressure is imposed at a distance from the castings. Therefore, alloys with a long freezing range are not preferrable with the indirect squeeze casting [22,23].



Figure 8. Schematic diagram for the direct squeeze casting process. (a) Preheat, (b) pouring, (c) solidification, and (d) ejection [22].

3.3. Sand Casting

Sand casting is one of the oldest casting processes, dating back at least 2000 years. The sand casting molding method was first recorded by Vannoccio Biringuccio in his book Pirotechnia [24], which was published around the year 1540. The technology of sand casting was adapted to aluminum as soon as the metal was available. Sand casting is a metal casting process characterized using sand as the mold material. The term "sand casting" can also refer to an object produced via the sand casting process. Sand castings are produced in specialized factories called foundries. Over 60% of all metal castings are produced via the sand casting process.

Sand casting is a very versatile process and can produce castings of extreme complexity in a wide range of aluminum alloys. Interest in light weighing and improvements in the technology of sand casting has driven the average weight and size of aluminum sand castings upward, with many parts weighing over 50 kg and with some parts as large as 100 m³. Any aluminum alloy can be cast in sand, including alloys that may exhibit hot shortness in metal mold processes.

There are several categories of sand casting, usually defined by the type of binder used to hold the sand together. There are different sands or artificial aggregates in wide use, each of which can be used in multiple sand casting processes. The most common sand is silica, which is an oxide of the element silicon. Silica sands are the most abundant sand in nature and have satisfactory molding characteristics. Other sands that are commonly used include olivine, zircon, and chromite. Zircon and chromite sands have low thermal expansion and high thermal conductivity. The high conductivity can be used to improve the soundness and mechanical properties of castings. Synthetic aggregates, including alumina, bauxite, and mullite are used in few special applications. These materials are hard, wear resistant, and spherical, making them an ideal molding material. Since the cost is higher than natural sands, the recycling efficiency needs to be high to make them economically viable. The principal properties required for the molding media are green strength and flowability, defined as the ability of the material to be compacted to a uniform density. Green strength is required in order that the pattern can be withdrawn from the mold without distortion or collapse. The balance between strength and flowability is determined based on the compaction method used in the molding process [25]. Figure 9 reveals the process of sand casting. The first step is placing a pattern in sand to create a mold, and incorporating the pattern and sand in the gating system to create an excellent mold shape. Then, the pattern

is removed for the preparation of the casting process. Thereafter, the mold cavity is filled with molten metal, and the metal is cooled. In the final step, the sand mold is broken and the casting is removed.



Figure 9. Graphical illustration of sand casting [26].

3.4. Casting Processes for BEVs

The high pressure die casting and sand casting are the two main important processes employed for BEV parts. For certain applications, for example, parts within a BEV, such as a rotor or an inverter, both high strength and high conductivity are desired. Due to the high quality requirement and complex shape of the rotor, it is desirable to form its parts through a high pressure and low velocity metal injection casting process. Moreover, the inadequate castability of an alloy often results in hot tearing, and causes fill issues which typically decrease the mechanical and electrical properties of the end cast part. Therefore, alloys for BEV components should possess good castability, high strength, and high conductivity.

4. Strengthening Mechanisms of Aluminum Alloys

Contributions from different strengthening mechanisms are typically considered additive, assuming that they act independently. In addition, the total strength of alloys might be estimated by Equation (1) [27,28], as follows:

$$S = S_o + S_{gs} + S_{ss} + S_{dis} + S_p$$

$$\tag{1}$$

where S_o is Peierls stress, S_{gs} is grain boundary strengthening, S_{ss} is solid solution strengthening, ening, S_{dis} is dislocation strengthening, and S_p represents precipitation strengthening.

All of these strengthening contributions lead to a degradation of the electrical conductivity, as conductive electrons are scattered by solute atoms and crystal defects. Each scattering event causes an electron to lose kinetic energy and to change its direction, thus increasing electrical resistivity or decreasing electrical conductivities.

4.1. Solid Solutions Strengthening

The solid solutions strengthening works by adding atoms of one element (the alloying element) to the crystalline lattice of another element (the base metal), forming a solid solution. This strengthening can be separated into substitutional solid solution strengthening and interstitial solid solution strengthening. Substitutional solid solution strengthening occurs when the solute atom is large enough (difference in atomic radii between the two atoms is less than about $\pm 15\%$) that it can replace solvent atoms in their lattice positions. A few alloying elements are only soluble in small amounts, whereas some solvent and solute pairs form a solution over the whole range of binary compositions. Interstitial solid solutions form when the solute atom is small enough (radii up to 57% the radii of the parent atoms) to fit at interstitial sites between the solvent atoms. The atoms crowd into the interstitial sites, causing the bonds of the solvent atoms to compress and

4.2. Precipitation Strengthening

thus deform [29].

Precipitation hardening is a form of heat treatment used for certain types of alloys to increase their strength and hardness. This type of strengthening is realized in metals and alloys containing second-phase precipitates which act as obstacles to dislocation glide. The strengthening effect is determined by inter-particle spacing, size, shape of precipitates, coherency of the matrix/precipitate interface, and spatial distribution of the precipitates [30].

4.3. Dislocation Accumulation Strengthening

The dislocation is a linear crystallographic defect or irregularity within a crystal structure that contains an abrupt change in the arrangement of atoms. The movement of dislocations allow the atoms to slide over each other at low stress levels and is known as a glide or slip. Dislocations behave as if they are a distinct entity within a crystalline material, where some types of dislocation can move through the material bending, flexing and changing their shape, as well as interacting with other dislocations and features within the crystal. Dislocations are generated by deforming a crystalline material, such as metals, which can cause them to initiate from the surfaces, particularly at stress concentrations or within the material at defects and grain boundaries [31]. The high density of dislocation in the grain interior and dislocation of dislocation strengthening increases with the increasing dislocation density [32].

4.4. Grain Boundary Strengthening

This type of strengthening increases by changing the average grain size. It is based on the observation that grain boundaries are insurmountable borders for dislocations. In addition, the number of dislocations within a grain have an effect on stress concentration in the adjacent grain, which eventually activates dislocation sources and thus enables deformation in the neighboring grain, as well. According to the well-known Hall-Petch law [33], by changing the grain size, the accumulatio of dislocations taking place inside grains increases yield strength. Hence, a reduction in the grain size results in effectively a high yield strength.

5. Electrical Conductivity of Aluminum Alloys

The electrical properties of metals and alloys are of great practical importance, especially in applications involving heating, temperature measurement, signal and power transmission, switching devices, semiconducting, and thin film devices, etc. [34]. One of their most important electrical characteristics is the ease with which they transit an electric current, which can be described by the electrical properties of materials, i.e., electrical resistivity or electrical conductivity. The formula is written as Equation (2) by virtue of the Matthiessen rule [35,36], where $\rho_{\rm T}$ is a temperature-dependent phonon contribution and $\rho_{\rm D}$ is the contribution from the lattice defects and solutes, which is independent of temperature. Therefore, the resistivity $\rho_{\rm D}$ can be separated into several contributions as Equation (3).

$$\rho = \rho_{\rm T} + \rho_{\rm D} \tag{2}$$

$$\rho_{\rm D} = \rho_{\rm ss} + \rho_{\rm p} + \rho_{\rm dis} + \rho_{\rm v} + \rho_{\rm gs} \tag{3}$$

where ρ_{ss} is the resistivity due to scattering by solute atoms dissolved in the matrix, ρ_p is the resistivity added by the second phase particles, ρ_{dis} and ρ_v are resistivities due to dislocations and vacancies, respectively, and ρ_{gs} is the resistivity due to scattering on grain boundaries. Of note, the ρ_p part, can in turn, consist of several contributions related to various kinds of precipitates in the microstructure (such as Guinier–Preston zones, non-coherent precipitates, and coherent precipitates) [32,37].

Electrical conductivity σ is used to specify the electrical character of a material. It is simply the reciprocal of the resistivity or

σ

$$=\frac{1}{\rho} \tag{4}$$

In addition, it is indicative of the ease with which a material is capable of conducting an electric current.

Electrical resistivity and conductivity in metals are an intrinsic property and the result of the movement of free electrons. Table 2 lists the electrical resistivity and conductivity, as well as the density and melting temperatures of the common conductive metals. As well known, metallic atoms are characterized by electrons in the energy level near the Fermi level. These valence electrons located in the outer shell can move under an electric field. When this electric field is applied, a force is brought to bear on free electrons, and by virtue of their negative charge, they migrate in a direction which is opposite to the field [38].

Metal ——	Electrical C	Conductivity	Electrical Resistivity	Density (g/cm ³)	Melting Point	
	(MS/m)	(%IACS)	$(10^{-8}, \text{Ohm m})$	Density (g.em)	(°C)	
Silver	62.1	106	1.6	10.5	961	
Copper	58.5	100	1.7	8.9	1083	
Gold	44.2	75	2.3	19.4	1064	
Aluminum	36.9	63	2.7	2.7	660	

Table 2. Properties of pure metals with the highest electrical conductivity [32].

5.1. Electrical Conductivity of Pure Aluminum

The most effective conductors of electricity are metals that have a single valence electron, which is free to move and causes a strong repelling reaction in other electrons. This is the case in the most conductive metals, such as Ag, Cu, and Au. Al, with three valence electrons, comes as the fourth most conductive metal [32]. Table 2 shows the properties of the top four metals with the best electrical conductivity. Although the silver and gold have the best electrical conductivity, they are not the normal metals used in the industry due to the extremely high cost. Therefore, copper and aluminum are currently the most widely used metals in electrical engineering and electrics. However, pure aluminum and copper, with high electrical conductivity, show very low mechanical strength, and their yield strength is about 10–20 MPa depending on purity. In the electrical automotive industry, the motor with high electrical conductivity and high mechanical strength is necessary. Generally, pure metals can be strengthened by the introduction of obstacles to the motion of dislocations.

5.2. Electrical Conductivity of Wrought Al Alloys

Mechanical strength and electrical conductivity are among the most important properties of conducting materials. However, high strength and high electrical conductivity are mutually exclusive in metals and alloys. In addition, the trade-off between strength and conductivity is always encountered in the development of conducting materials. The properties of coarse-grained pure Al and commercial Al-Mg-Si wires used in overhead power lines are summarized in Figure 10. In all cases, it is clearly seen that alloys exhibit a higher mechanical strength compared to pure metals, but at the expense of the electrical conductivity.



Figure 10. Room temperature electrical conductivity (in % of IACS) versus ultimate tensile strength for coarse grained (CG) pure Al and commercial Al-Mg-Si alloys, as well as their nanostructured counterparts obtained via severe plastic deformation (SPD) processes, including high pressure torsion (HPT) and equal-channel angular pressing (ECAP) [32].

5.2.1. Nanostructure in Wrought Alloys

Achieving an optimal combination of strength and electrical conductivity is still a hot topic in materials science. Recently, new opportunities have appeared with mature technologies that allow the fabrication of nanostructured alloys. Specifically, severe plastic deformation (SPD) appears to be the most promising processing route for manufacturing bulk nanostructured Cu and Al based materials for engineering applications [39]. Depending on the SPD technique and processing parameters, the grain size can be refined down to an ultra-fine scale (0.1–1.0 μ m) or nanoscale (<100 nm). The most popular SPD methods include high-pressure torsion (HPT), equal-channel angular pressing (ECAP) and its modifications, accumulative roll bonding (ARB), hydrostatic extrusion (HE), cryorolling (CR), etc. [32]. Perfect grain boundaries without lattice defects do not usually provide a significant contribution to the electrical resistivity. For example, using SPD processing to enhance the purification of the matrix from solute atoms or to avoid second-phase precipitates that most effectively scatter conducting electrons can dramatically improve the electrical conductivity. Therefore, nanostructuring of metallic alloys by SPD processing appears as an attractive approach to achieve a combination of superior strength and electrical conductivity [40,41].

A significant body of experimental research on nanostructural design, in order to improve the mechanical strength with minimal loss of electrical conductivity in wrought Al alloys materials, exists in the open literature. Table 3 summarizes data regarding the mechanical properties and conductivity of various nanostructured Al-based materials. Published research reports on nanostructuring of Al alloys for the improvement of mechanical strength and conductivity can be classified into two groups: (1) Enhancement of properties in existing commercial Al alloys that are used in electrical engineering; and (2) development of novel nanostructured Al alloys with improved properties.

Material	Processing: Grain Size d	Ultimate Tensile Strength (MPa)	Elongation (%)	Electrical Conductivity at RT, IACS (%)	References	
	CG T81; d = 65 μm	330	6.1	53.6		
AA6201	HPT at RT; d = 0.13 μm	510	2.5	47.7		
	HPT at RT + HPT at 130 °C d = 0.28 μm + nanoparticles	412	4.9	55.6	[42]	
	HPT at RT + HPT at 180 °C d = 0.44 μm + nanoparticles	365	8.8	58.4		
	CG T6	250	8	53.6		
AA6060	HPT at RT; d = 0.18 μm	525	5	51.8	[43]	
	HPT at 180 °C; d = 0.35 μ m + nanoparticles	347	7	58.1	[10]	

Table 3. Mechanical properties and electrical conductivity of wrought Al alloys AA6201 and AA6060, processed by the thermal treatment and mechanical processing [32].

IACS: International annealing copper standard; CG: Coarse grained; RT: Room temperature; HPT: High pressure torsion.

As reported by Murashkin et al. [32], the Al alloys of 6XXX series which contain Mg and Si are the most widely used in the electrical engineering for power lines. Table 3 compares the mechanical properties and electrical conductivities of CG AA6201 and AA6060 with those of the nanostructured counterparts. The ultimate tensile strength, elongation, and electrical conductivity of CG AA6201, after a standard manufacturing route that consists of solution treatment, water quenching, and cold drawing of wires followed by artificial aging (T81), were 330 MPa, 6.1% and 53.6% IACS, respectively. The HPT processing at room temperature resulted in the formation of nanostructure (0.13 μ m) in AA6201 alloy, which increased the UTS to 510 MPa, and decreased the elongation to 2.5% and IACS to 47.7%. The mechanical processing led to the formation of intragranular second phase precipitates (Mg_2Si). These microstructures show an enhanced precipitation hardening and an increased electrical conductivity due to the partial purification of the Al matrix from Mg and Si solute atoms. For AA6201 alloy, the additional HPT process at elevated temperatures of 130 and 180 $^\circ$ C increased the grain size to 0.28 and 0.44 μ m from $0.13 \,\mu\text{m}$, respectively. The ultimate tensile strength decreased to 412 and 365 MPa from 510 MPa, respectively. The electrical conductivity increased to 55.6% and 58.4% from 47.7% of IACS, respectively. Moreover, the elongation increased to 4.9% and 8.8% from 2.5%. For AA6060, the thermal treatment and mechanical processing slowed the similar effects on the UTS, elongation, and electrical conductivity.

Murashkin et al. [32] pointed out that in Al alloys, insoluble alloying elements were preferred, in order to achieve high electrical conductivity, rather than soluble elements in high-strength alloys. Fe appeared as an attractive alloying element, since its solubility in Al was as low as 0.025 at% at room temperature. Cubero et al. [44] studied the electrical conductivities of Al–Fe alloys processed by high pressure torsion (HPT) and treated by subsequent aging. It was shown that, even with a low Fe fraction (2 wt%), it was possible to achieve interesting combinations of mechanical and electrical properties of Al. The high strength was obtained by high pressure torsion (HPT) processing due to the formation of an ultra-fine grain (UFG) structure with a grain size of 120–130 nm. In addition, original coarse intermetallic particles were fragmented by the severe plastic deformation (SPD) down to 50 nm in size or less. A few of them were dissolved in the matrix leading to a 0.67 wt% Fe supersaturated solution in the Al matrix. Further artificial aging at 200 $^{\circ}$ C led to the decomposition of this solid solution and an additional precipitation hardening due to the formation of nanosized particles, which are homogeneously distributed in the matrix. The resulting yield stress was up to 600 MPa. The relatively poor electrical conductivity (40% of IACS) after high pressure torsion (HPT) processing also improved well above 50% of IACS after the aging treatment due to the recovery of lattice defects and the precipitation of solute Fe dissolved in the matrix. The electrical conductivities of severe plastic deformation (SPD) processed Al–Fe alloys could be further improved with optimized aging treatments.

The study by Chen et al. [45] presented the schematic representation of changes in the grain boundary (GB) energy associated with the formation of a twin "T" inside the grain "A" (Figure 11). Grain boundaries with an high interfacial energy were represented by thick wavy lines, while the thin straight lines 1–4 and 2–3 indicated grain boundaries with a lower interfacial energy, relaxed by twinning. The relaxation of grain boundaries eased the electron movement, and consequently reduced the electrical resistivity and increased the electrical conductivity.



Figure 11. Schematic illustration of changes in GB energy, associated with the formation of a twin "T" inside the grain "A" [45].

5.2.2. Thermal Conductivity in Wrought Alloys

Aksoz et al. [46] measured the thermal and electrical conductivity of the Al-[x] wt% Cu, x = 3, 6, 15, 24, 33, and 52.5 alloys. The change of thermal conductivities (k) with temperatures and copper contents is shown in Figure 12. As can be seen in Figure 12, the Cu addition ranging from 3 to 52.5 wt% reduced the thermal conductivities of the Al-Cu alloy at all of the testing temperatures (373–773 K). Moreover, the thermal conductivity decreased with the increasing temperatures. Figure 13 presents a comparison of thermal conductivities of pure Al and Cu with those of Al-Cu alloys at various temperatures. It can be seen that all of the tested Al-Cu alloys had lower thermal conductivities than pure Al. This observation suggested that the solid solution and the eutectic Al₂Cu phase in Al-Cu alloys might hinder the electron movement, which reduce thermal conductivity.

5.2.3. Electrical Conductivity in Wrought Alloys

Aksoz et al. [46] determined the electrical conductivities of Al-Cu alloys based on the measured thermal conductivities with the Smith–Palmer equation (Equation (5)). Figure 13 shows the variation of the calculated electrical conductivities with the Cu contents. As can be seen from Figure 14, the values of the electrical conductivities decreased with the increasing temperatures. The electrical conductivities of the tested Al-Cu alloys exponentially increased with the decreasing Cu content.

$$K_e = 0.909 L \sigma T + 10.5 \tag{5}$$

where K_e is the electronic component of thermal conductivity, T is the temperature, σ is the electrical conductivity, and L is the constant of proportionality which is called the Lorenz number. The value of L is $2.45 \times 10^{-8} \text{ W}\Omega/\text{K}^2$.



Figure 12. Variation of thermal conductivity with the composition of Cu for the Al based Al-Cu alloys [46].



Figure 13. Comparison of thermal conductivities of pure Al and Cu with those of Al-Cu alloys at different temperatures [46].

The temperature dependence of the electrical conductivity of pure Al, which was found in Plevachuk et al. [47], is well described by the following linear equation:

$$\sigma = \sigma_0 + \frac{d\sigma}{dT} \times (T - T_L)$$
(6)

where T_L is the liquidus temperature, $\sigma_0 = 41,400 \ \Omega^{-1} \text{cm}^{-1}$ is the electrical conductivity at the melting point, and the temperature coefficient of the conductivity is given by $d\sigma/dT = -19.36 \ \Omega^{-1} \text{cm}^{-1} \text{K}^{-1}$.



Figure 14. Variations of electrical conductivity with the composition of Cu determined from the Smith-Palmer equation [46].

The electrical conductivity of Al-4 wt% Cu, Al-20 wt% Cu, Al-30 wt% Cu alloys, and pure Al in the liquid state is presented in Figure 15 as a function of the temperature. Plevachuk et al. [47] revealed that the small amount of copper in the Al-4wt% Cu increased the absolute conductivity value as compared with pure Al, while the temperature coefficient of the conductivity was practically the same. An increase in the copper content (20 and 30 wt%) reduced the absolute conductivity values and the temperature coefficient of conductivity as compared with pure Al. The conductivity of all the melts decreased linearly with the temperature, according to Equation (6). The parameters T_L , σ_0 , and $d\sigma/dT$ for the tested alloys and pure Al are given in Table 4.



Figure 15. Temperature dependence of electrical conductivity for liquid Al and Al-4 wt% Cu, Al-20 wt% Cu, and Al-30 wt% Cu liquid alloys [47].

Alloy	T _L (K)	σ_0 (Ω^{-1} cm ⁻¹)	$d\sigma/dT$ ($\Omega^{-1}cm^{-1}K^{-1}$)
Al	933	41,400	-19.36
Al-4 wt% Cu	922	42,600	-19.13
Al-20 wt% Cu	873	37,300	-10.2
Al-30 wt% Cu	836	33,800	-7.34
AlCu ₄ TiMg	931	39,100	-11.72

Table 4. Parameters of the linear fits $\sigma = \sigma_0 + \frac{d\sigma}{dT} \times (T - T_L)$ to the experimental electrical conductivity for liquid Al and Al-based alloys [47].

The electrical conductivity of the liquid Al-4 wt% Cu differed by its behavior, which suggests another mechanism of charge scattering. A 3D shell with high electron density of copper could essentially affect the charge transfer in the melt, resulting in the s-d resonance scattering. Overall, the results of the electrical conductivities indicated that small additions of copper slightly raised the conductivity of liquid pure Al, while the further increase of copper content predictably decreased the conductivity values.

Kaya [48] investigated the crystal growth and morphologies of the directionally solidified Al-Cu alloys, as shown in Figure 16. Figure 16(a_1,a_2,b_1,b_2,c_1,c_2) is the transverse and longitudinal section of Al-6 wt% Cu, Al-24 wt% Cu, and Al-33 wt% Cu, respectively. As can be seen from Figure 16, the characteristics of the microstructures changed with the increasing Cu composition in the Al-Cu alloys. As illustrated in Figure 16, the microstructures of Al-6 wt% Cu and Al-24 wt% Cu were dendritic, whereas Al-33 wt% Cu was eutectic.

According to the results of Aksoz et al. [46] and Plevachuk et al. [47], the electrical conductivity of the solid Al-4wt% Cu was lower than the electrical conductivity of the pure Al at the temperatures ranging from 373 to 773 K. However, the electrical conductivity of the liquid Al-4 wt% Cu was larger than the electrical conductivity of the pure Al when the temperature was greater than 933 K. The temperature appeared to considerably affect the electrical conductivity of the Al-based alloys. High temperatures and phase changes resulted in strong vibrations, which acted as irregularities in the lattice. The small decrease in conductivity on the melting of pure metals was due to the loss of long-range crystalline order. The short-range order remained and a strong correlation between the positions of ions led to the coherence between waves that diffracted by the adjacent ions. However, the difference between the electrical conductivity of Al-4 wt% Cu from 773 to 933 still requires further investigation.

5.3. Electrical Conductivity of Cast Al Alloys

Although mechanical deformation processing techniques can be used to produce nanostructured Al alloys with high electrical conductivities, they are only suitable for the fabrication of components with simple geometry and high loss. Since electrical motor components have complicated shapes and even undercut casting processes, including high pressure die casting and sand casting, they should be considered as the most cost-effective route for the massive production of parts in BEVs [49]. To ensure the availability of the casting processes for manufacturing electrical motor components, castable Al alloys with high electrical conductivities are necessary.

5.3.1. Cast Al-Si-Cu-Mg Alloys

The advantages of the cast Al-Si-Cu alloy are good castability, thermal conductivity, and electrical conductivity. Therefore, this class of alloys has numerous applications in aerospace, construction, and the electrical automotive industry. Xia et al. [50] used a design of experiment (DOE) technique to develop as-cast Al-Si-Cu-Mg alloys with high strength and high electrical conductivity. For each factor, three different levels of weight percentages were selected, of which Si was in 3, 4, 5%, Cu was in 0.5, 1.0, 1.5%, and Mg was in 0.3, 0.6,

0.9%. Table 5 shows the design of experiment (DOE) by the Taguchi Method. Table 6 lists the ultimate tensile strength, elongation, hardness (HBS), and electrical conductivity under the as-cast and T6 heat treatment conditions. When the element Si content was 4% (x-2), the ultimate tensile strength was the highest in the as-cast and T6 conditions, which was 190 and 343 MPa, respectively. The electrical conductivity of the T6 x-2 alloy is 23.7 MS/m (39.5% IACS). Comparing the electrical conductivity of A356 (40% IACS) [7], the results were similar. The slight differences in the electrical conductivity might result from the various elements of Cu and Si in the alloys. In the experimental alloys (s1 to s9), when the content of Si was fixed, the electrical conductivity decreased with the increasing Cu content. This was due to the fact that the atom radius for Si, Mg, Al, and Cu was 0.1316, 0.1602, 0.1432, 0.118 nm [42], respectively. The difference between the radius of Cu atom and the radius of Al atom was the largest between Al and Si, as well as Mg. The largest atomic radius difference between Al and Cu significantly influenced the conductivity. Moreover, the electrical conductivities of the T6 treated alloys were higher than the as-cast counterparts. However, Xia et al. [50] failed to report the yield strengths of their DOE Al alloys. Based on the Taguchi method, the optimal combination of the factors and levels was $AlSi_3Cu_{0.5}Mg_{0.3}$ (s-1) and $AlSi_4Cu_{0.5}Mg_{0.3}$ (s-4) for the electrical conductivities of 25.3 and 26.3 ($MS \cdot m^{-1}$) or 42.2% and 43.8% of IACS. In addition, under the as-cast and T6 conditions $AlSi_3Cu_{0.5}Mg_{0.3}$ (s-1) exhibited the highest values of the elongation, 7.46% and 3.92% for the as-cast and T6 condition, respectively. The best chemical combination was $AlSi_4Cu_1Mg_{0.6}$ (x-2) for the strength of 190 and 343 MPa under the conditions of the as-cast and T6 heat treatment, respectively.



Figure 16. Optical micrographs of growth morphologies of directionally solidified (a_1,a_2) Al-6 wt% Cu; (b_1,b_2) Al-24 wt% Cu; (c_1,c_2) Al-33 wt% Cu alloys [48].

Experiment	Si	Cu	Mg
s-1	3%	0.5%	0.3%
s-2	3%	1.0%	0.6%
s-3	3%	1.5%	0.9%
s-4	4%	0.5%	0.6%
s-5	4%	1.0%	0.9%
s-6	4%	1.5%	0.3%
s-7	5%	0.5%	0.3%
s-8	5%	1.0%	0.3%
s-9	5%	1.5%	0.6%

Table 5. Design of experiment for Al-Si-Cu-Mg alloys by the Taguchi Method [50].

Table 6. Mechanical properties and electrical conductivities of Al-Si-Cu-Mg alloys [50].

	UTS/MPa		Elongation (%)		HBS		σ/(MS⋅m ⁻¹)	
	F	T6	F	T6	F	T6	F	T6
s-1	180	298	7.46	3.92	49	90	25.3(42.2%IACS) 25.7(42.8%IACS)
s-2	179	313	3.43	1.68	69	119	24.6(41.0%IACS) 25.1(41.8%IACS)
s-3	188	289	3.14	1.58	77	125	24.0(40.0%IACS) 24.3(40.5%IACS)
s-4	185	338	3.61	1.78	73	112	24.1(40.2%IACS) 26.3(43.8%IACS)
s-5	166	321	2.4	1.68	74	119	23.2(38.7%IACS) 24.5(40.8%IACS)
s-6	183	325	3.92	2.58	64	111	23.7(39.5%IACS) 24.9(41.5%IACS)
s-7	161	287	1.89	1.78	72	116	22.7(37.8%IACS) 25.1(41.8%IACS)
s-8	169	300	3.6	2.59	65	103	23.1(38.5%IACS) 24.8(41.3%IACS)
s-9	180	282	2.8	0.7	75	126	22.4(37.3%IACS) 24.0(40.0%IACS)
x-1	164	316	3.39	1.48	66	110	23.9(39.8%IACS) 23.8(39.7%IACS)
x-2	190	313	4.42	1.55	68	121	22.8(38.0%IACS) 23.7(39.5%IACS)

Moreover, Xia et al. [50] employed a scanning electron microscope (SEM) to investigate the microstructure of $AlSi_4Cu_1Mg_{0.9}$ (s-5) alloy under the as-cast and T6 conditions. Figure 17 presents the SEM micrographs showing the microstructure of the s-5 alloy under the as-cast and T6 conditions. It can be seen from Figure 17a that the primary α -Al dendrites and needle-flake eutectic Si phase were uniformly distributed. The Al₂Cu phase in grey was distributed irregularly around the α -Al dendrites. However, the T6 treatment improved the distribution and morphology of the Al₂Cu and Si phases in the microstructure, as shown in Figure 17b. As a result, the mechanical properties and electrical conductivity of the s-5 alloy improved significantly.

5.3.2. Cast Al-Ni Alloys

Sivanesh et al. [43] invented an aluminum alloy exhibiting high yield strengths and high conductivities, which can be the high pressure die cast to produce electric car parts, as illustrated in Reference 43. This novel alloy, named Tesla alloy, contains about 5 wt% Ni, 0.35 wt% Fe, 0.03 wt% Ti, and the remaining wt% constitutes Al and incidental impurities. The HPDC alloy has a relatively low yield strength of about 90 MPa and an electrical conductivity of about 48% IACS. Figure 18 compares the electrical conductivities and yield strengths between various cast and wrought Al alloys under the as-cast and heat treatment conditions. Based on the yield strength versus the conductivity plot, an alloy design space was proposed by Sivanesh et al. [43]. Cast aluminum alloys were divided into two groups.

One group had high yield strengths but low electrical conductivities, and the other group had high electrical conductivities but low yield strengths. The alloys within the alloy design space possessed an electrical conductivity of about 48% to 55% IACS, and the range of yield strengths was between 90 and 130 MPa, as shown in Figure 18. Aluminum alloy A319, as a representative traditional cast alloy, under the as-cast condition had only a low yield strength of 120 MPa and a low electrical conductivity of 26% IACS. However, both the yield strengths and electrical conductivities of the traditional cast Al alloys were improved by the proper procedure of the heat treatment. The T7 treatment increased the yield strength to about 270 MPa, but little in the electrical conductivity. Figure 19 presents the results of the castability study on the Tesla alloys in comparison with the traditional cast Al alloys. The Tesla alloy had an enhanced fluidity and hot tearing susceptibility, which demonstrated the excellent castability.



Figure 17. SEM micrographs showing the microstructure of the s-5 alloy under the (**a**) as-cast and (**b**) T6 conditions [50].

Figure 20 illustrates the shrinkage of cast Al alloys. It is desirable to design an alloy with as little shrinkage from liquidus to solidus, as possible. As can be observed, the Tesla alloy with 5.4% nickel exhibited only 5.54% shrinkage, which outperformed most of the tested alloys. However, the Tesla alloy had a shrinkage of 5.54% higher than (4.89%) the common HPDC Al alloy A390. The minimization of shrinkage is important for the parts to remain within tolerances during the production.

Table 7 compares the mechanical and electrical properties between the Tesla alloy (Al-5.3Ni-0.35Fe-0.03Ti) and Al-Si-Mg alloys. The alloy with the compositions of 1 wt% Si, 0.4 wt% Mg, and 0.03 wt% Ti had the highest conductivities of 50% and 53% IACS under the as-cast and T5 heat treatment conditions, respectively. The yield strengths under the T5 heat treatment and UTS under the as-cast condition were 110 and 160 MPa, respectively. Meanwhile, the as-cast Tesla alloy exhibited a comparable electrical conductivity of 50% IACS and the relatively low YS and UTS of 90 and 150 MPa, respectively. However, it is impossible to make a comparison of the castability among the three listed cast Al alloys, since there is inadequate information regarding the castability in the open literature.



Figure 18. A yield strength versus the electrical conductivity plot for cast aluminum alloys [43].



Figure 19. Castability of cast pure aluminum and Al alloys, (a) fluidity, (b) hot-tearing susceptibility [43].

5.4. Advantages and Disadvantages of Potential Wrought and Cast Al Alloys

As a prospective material for applications in BEVs, Al alloys exhibit the advantage of lightweight over Cu for use in electric motors. Potential light Al alloys should have both high mechanical properties and electrical properties, as well as low materials and manufacturing costs. Although nanostructured wrought Al alloys possess both high mechanical properties and electrical conductivity, the multiple process steps involved in their fabrication increase the cost of final products significantly. With these wrought alloys, it is almost impossible to produce components with complex geometries. Cast Al-Si-Cu-Mg alloys exhibit excellent castability for the production of complex castings, that require high mechanical properties. However, low electrical conductivities of cast Al-Si-Cu-Mg alloys prevent their direct application from electric motors. The experimental Al-Ni alloy demonstrates both high mechanical properties and electrical conductivity. However, the high cost of Ni addition may limit its usage. Moreover, its castability is still questionable and requires verification.



Figure 20. Shrinkage of cast pure aluminum and Al alloys [43].

Table 7. Comparison of mechanical and electrical properties between the Tesla alloy and the other two Al-Si-Mg alloys [43].

Property -	Alloy				
	Al-1Si-0.4Mg-0.03Ti	Al-3.6Si-0.4Mg-0.03Ti	Al-5.3Ni-0.35Fe-0.03Ti		
Conductivity (as cast, %IACS)	50	47	50		
Conductivity (T5—225 °C/2 h, %IACS)	53	50	Not applicable (NA)		
Yield strength (as cast, MPa)	110	110	90		
Yield strength (T5—225 °C/2 h, MPa)	160	150	Not applicable (NA)		
UTS (as cast, MPa) 160		170	150		

6. Summary

Aluminum alloys are extremely attractive for BEV applications due to their great potential for improved specific strengths, high electrical conductivities, and good castability. In BEVs, Al alloys are excellent lightweight metallic materials for electrical components, such as rotors and inverters that require both high strength and conductivity. The present research work focuses on the development of nanostructured Al-based alloys, which possess both the excellent strengths and high electrical conductivity. The nanostructure of the Al alloys is primarily produced by mechanical deformation processes, which are relatively expensive and incapable of cost-effectively manufacturing electrical motor components with complex shapes.

For the massive production of complex electrical components, casting processes including high pressure die casting, sand casting, and squeeze casting appear alluring to the automotive industry due to the low cost, flexibility, and versatility. Table 8 summarizes the effects of strengthening mechanisms and common chemical elements, Si, Mg, Cu, Ni, and Sr on the strengths and electrical conductivities of cast Al alloys. Both the strengthening mechanisms and the chemical addition improve the strength of Al alloys. However, they adversely affect the electrical conductivity. Since high strength and high electrical conductivity are mutually exclusive for metallic materials, the balance between strength and conductivity is a challenging task in developing castable Al-based alloys. In particular, as-cast high strength and conductive Al alloys with no thermal treatment are highly desired, since extra processing steps are avoided. As a result, the understanding and establishment of the relation between the microstructure and mechanical and electrical properties of castable Al alloys are essential for the success in the massive implementation of light weight Al in BEVs, as a substitute for heavy metal Cu.

Table 8. Effects of strengthening mechanisms and common chemical elements on the strengths and electrical conductivities of cast Al alloys.

Strengthenin	Strengthening and Element		Electrical Conductivity	References
	Solid Solutions Strengthening	Good	Poor	
Strengthening	Precipitation Strengthening	Good	Poor	[40-50]
Wiechanism	Dislocation Strengthening	Good	Poor	
	Grain Boundary Strengthening	Good	Poor	
	Silicon (Si)	Good	Limited	
	Magnesium (Mg)	Good	Limited	
Elements	Copper (Cu)	Good	Poor	[16,43,50]
	Nickel (Ni)	Good	Unknown	
	Strontium (Sr)	Limit	Unknown	

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Nomenclature

- BEV Battery-powered electric vehicle
- S Strengthening
- So Peierls stress
- S_{gs} Grain size strengthening
- S_{ss} Solid solution strengthening
- S_{dis} Dislocation strengthening
- S_p Precipitation strengthening
- ρ Resistance
- $\rho_{\rm T}$ Temperature resistance

- $\rho_{\rm D}$ Lattice defects and solutes resistivity
- $\rho_{\rm ss}$ Solute atoms resistivity
- $ho_{
 m p}$ Resistivity added by second phase particles
- $\rho_{\rm dis}$ Dislocation resistivity
- $\rho_{\rm v}$ Vacancies resistivity
- $\rho_{\rm gs}$ Grain boundaries resistivity
- σ Electrical conductivity
- σ_0 Electrical conductivity at melting point ($\sigma_0 = 41,400 \ \Omega^{-1} \text{cm}^{-1}$ for pure aluminum)
- K_e Thermal conductivity of free electrons
- L Lorenz number (L₀ = $2.445 \times 10^{-8} \Omega W/K^2$)
- T Temperature
- T_L Liquidus temperature

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