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Lightweight metals and alloys in electric vehicle manufacturing: enhancing performance and efficiency

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Abstract

Lightweight materials have become a key focus in the manufacturing of electric vehicles (EVs) due to their numerous advantages, including corrosion resistance, excellent formability, and high specific strength. In addition to enhancing performance, these materials contribute to a reduced environmental impact, as they are highly recyclable. This article offers a comprehensive overview of the properties, fabrication methods, and applications of lightweight metals and their alloys in the automotive industry. It also provides a comparative analysis of various lightweight materials, highlighting their relative benefits and limitations. By consolidating scientific knowledge and industry insights, this review aims to guide both the automotive industry and the scientific community in advancing the use of lightweight alloys in EVs, contributing to the development of more sustainable and efficient vehicles.

Keywords: Lightweight materials; Electric vehicles (EVs); Aluminum alloys; Magnesium alloys; Titanium alloys; Sustainable manufacturing

1. Introduction

As the automotive industry moves towards cleaner and more sustainable technologies, electric vehicles (EVs) have become a focal point of innovation. One critical aspect of EV design is the weight of the vehicle, as reducing mass is key to improving energy efficiency, extending range, and optimizing performance.

The transition to green energy and the rapid growth of the electric vehicle (EV) market have placed EV manufacturing companies under significant pressure to secure essential raw materials while ensuring environmental sustainability and cost-effectiveness. One of the most effective strategies to address these challenges is the use of lightweight materials, which can significantly enhance the performance and efficiency of EVs. Lightweight materials, such as aluminum alloys and composites, help reduce vehicle weight, thereby improving energy efficiency and extending driving range. According to studies by Jung et al. (2018) and Redelbach et al. (2012), a reduction of 100 kg in a vehicle's weight can improve energy efficiency by approximately 3.5% or save up to 15 kJ/km in energy consumption. Among various lightweight materials, aluminum alloys are particularly favored in the automotive industry due to their excellent combination of high specific strength, superior thermal conductivity, and strong corrosion resistance. Additionally, aluminum's high recyclability makes it a sustainable choice, aligning with the industry's goals of reducing environmental impact and supporting the circular economy. As a result, aluminum alloys are becoming increasingly integral in the manufacturing of EV components, from body panels to structural elements, offering a sustainable solution that balances performance with environmental responsibility.

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Zhang and Xu (2022) investigated the entire life cycle of automotive materials, physical/mechanical properties, characterization, manufacturing techniques, and potential applications of specific lightweight materials. They outlined the advantages and drawbacks of the reviewed materials, examined specific application scenarios for different lightweight materials. All the major EV manufacturers are increasingly relying on lightweight materials, particularly light alloys, which offer an optimal balance between strength and weight. This article explores the different light alloys used in EV manufacturing and examines their metal strength-to-weight ratios, highlighting their specific application, relative benefits and challenges of each.

2. Lightweight Metal Alloys

Lightweight metals and their alloys are at the forefront of advancements in electric vehicles (EVs), playing a crucial role in the green energy transition and the sustainability of modern automotive manufacturing. Lighter vehicles require less energy to accelerate, making lightweight materials highly effective in improving vehicle efficiency. By replacing traditional materials like cast iron and steel with lightweight alternatives such as magnesium (Mg) alloys, aluminum (Al) alloys, carbon fiber, and polymer composites, vehicle body and chassis weight can be reduced by up to 50%. This reduction not only lowers energy consumption but also increases the vehicle's range. Table 1 below illustrates the mass reduction, expressed as a percentage of the vehicle's gross weight, when these materials are used in manufacturing, as provided by the U.S. Department of Energy.

Table 1 Vehicle mass reduction by using different lightweight metals

Materials	Mass Reduction
Magnesium	30-70%
Carbon fiber composites	50-70%
Aluminum and Al matrix composites	30-60%
Titanium	40-55%
Glass fiber composites	25-35%
Advanced high strength steel	15-25%

2.1. Aluminum Alloys: The Backbone of Lightweight EVs

Aluminum alloys are among the most used materials in EV manufacturing, especially for body panels, frames, and other structural components. Aluminum offers a favorable strength-to-weight ratio, which is essential for improving the overall performance of electric vehicles. Pure aluminum is lightweight, but alloys such as 6000-series (Al-Mg-Si) and 7000-series (Al-Zn-Mg) exhibit enhanced strength properties due to the addition of alloying elements like magnesium, silicon, and zinc.

- Strength-to-Weight Ratio: Aluminum alloys have a density of around 2.7 g/cm^3, significantly lower than steel's 7.8 g/cm^3. The strength of aluminum alloys varies based on the composition and heat treatment, with some high-strength alloys offering tensile strengths upwards of 500 MPa.

- Applications: Aluminum alloys are commonly used in EV body structures, chassis, and battery enclosures due to their excellent corrosion resistance and ability to be easily shaped. Their low weight helps reduce the overall mass of the vehicle, improving cost, range and acceleration.

Recently, Tesla's innovative single-piece casting for the Model Y, as shown in Figure 1, has made significant strides in vehicle design and performance. By using this advanced casting technique, Tesla has successfully reduced the vehicle's weight by 10%, which directly contributes to increased energy efficiency. This weight reduction, coupled with fewer components, has resulted in a 14% increase in driving range.

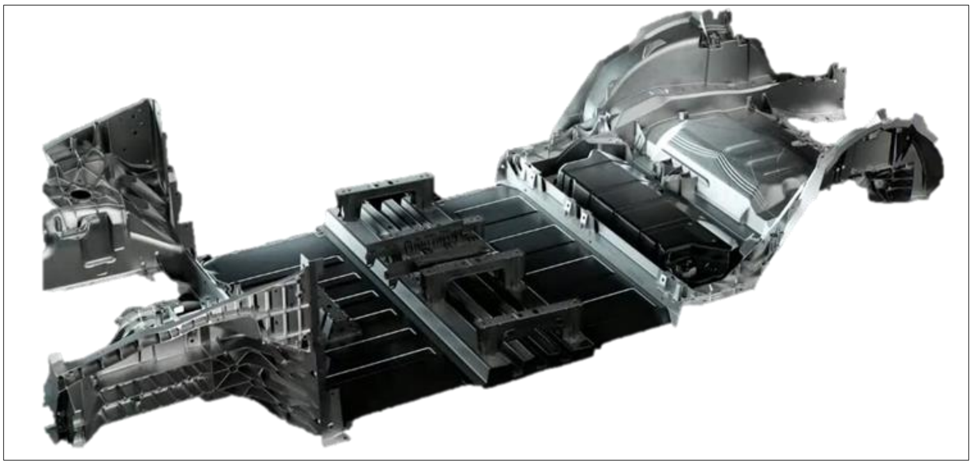

Figure 1 Tesla Model Y front and rear single-piece aluminum castings and structural battery

However, aluminum’s lower stiffness compared to steel can be a limitation in some applications, and the material can be more expensive to process, which may drive up manufacturing costs. Despite these challenges, its benefits in terms of weight reduction make aluminum a top choice for EV manufacturers.

Aluminum alloy development has been a critical area of research and innovation, particularly in industries such as automotive and aerospace, where lightweight materials are essential for improving performance and fuel efficiency. More recently, the development of ultra-high-strength aluminum alloys, including those with heat-treated and cold-worked properties, has enabled the use of aluminum in more demanding applications, such as battery enclosures and chassis in electric vehicles (EVs). Over the years, advancements in aluminum alloy formulations have focused on enhancing the material’s strength, durability, and corrosion resistance while maintaining its low density. Early aluminum alloys were soft and limited in their applications, but the introduction of alloying elements such as copper, magnesium, manganese, silicon, and zinc has significantly improved the material’s mechanical properties. For instance, the 6000-series (Al-Mg-Si) alloys are known for their excellent corrosion resistance and formability, making them ideal for automotive body panels and structural components.

Aluminum alloy wheels, such as AlSi10MgFe, ENAC43400, AlSi9Cu3, and AlSi10MnMg, are increasingly used in small and medium-sized vehicles due to their significant weight reduction—typically 30% to 40% lighter than traditional steel wheels. This reduction in weight contributes to a decrease in the vehicle's overall gross weight, improving fuel efficiency and performance. In the context of electric vehicles (EVs), lighter wheels also help extend driving range by reducing energy consumption.

The 7000-series (Al-Zn-Mg) alloys, on the other hand, are much stronger and are often used in aircraft and high-performance vehicle applications. Iron (Fe) is a common impurity in aluminum alloys and can form a brittle Fe-rich intermetallic phase known as β-Al5FeSi in cast aluminum, as noted by Luo (2021). To mitigate this, Manganese (Mn) is often added to modify the formation of these intermetallic phases. Recent research has focused on the effects of Mn content and cooling rates on the formation and behavior of these phases (Ceschini et al., 2009; Taylor, 2012). Figure 2 illustrates the effect of cooling rate on the solidification behavior of Al-Si-Mg casting alloys in the presence of high iron content.

Nonetheless, the presence of iron-containing intermetallic phases can improve the ductility of aluminum castings. However, other impurities or voids introduced during forming and casting processes can reduce the ductility of advanced aluminum alloys, such as XTral 728, by as much as 17%, as reported by Rahman et al. (2024). Despite this, XTral 728 is known for its excellent formability and impact resistance, making it well-suited for applications where safety is critical, such as the transportation of hazardous materials.

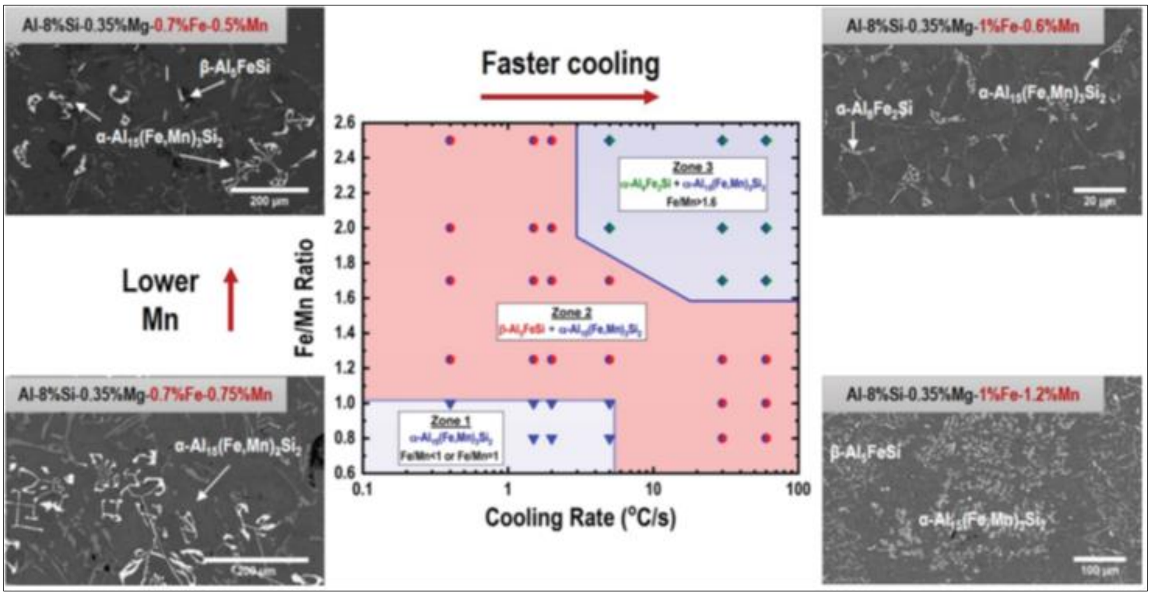

Figure 2 The formation map of Fe-containing intermetallic phases effect of cooling rate on the solidification behaviour of Al-Si-Mg casting alloys with high iron content (Cinkilic et al., 2019)

Aluminum alloy wheels, such as AlSi10MgFe, ENAC43400, AlSi9Cu3, AlSi10MnMg, etc. which are 30%-40% lighter than traditional steel wheels, are used in small and medium-sized vehicles, reducing vehicle gross weight and increasing range.

Another, significant advantage of aluminum in the light of sustainability is that is can be recycled much more efficiently, where the energy required to produce secondary or recycled aluminum is only 5% of the energy used in the production of primary aluminum (Schlesinger, 2013). Such a reduction highlights strong manufacturing sustainability of utilizing recycled aluminum as shown in Figure 3. These innovations in aluminum alloy technology have played a crucial role in reducing vehicle weight, improving fuel efficiency, and meeting the stringent safety standards required in modern automotive manufacturing.

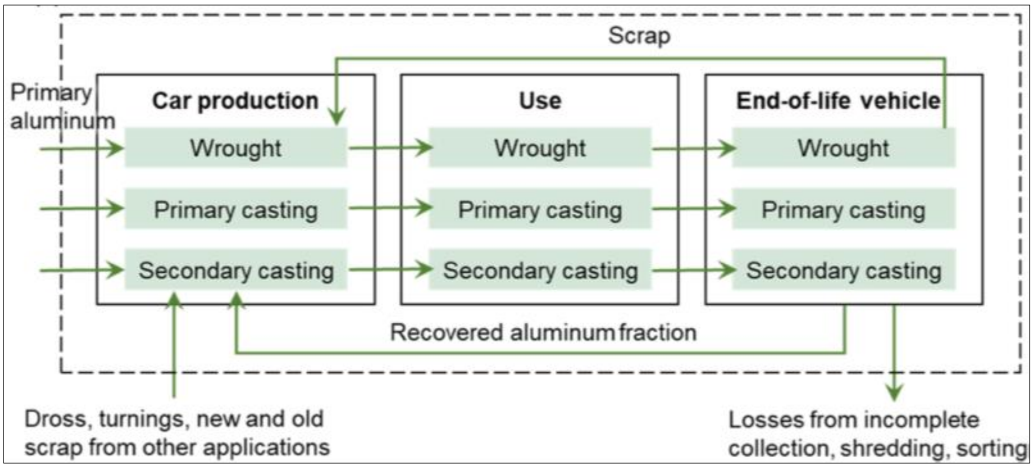

Figure 3 Illustration of recycling aluminum systems in passenger vehicles (Modaresi, 2012)

2.2. Magnesium Alloys: Ultra-Low Weight with High Strength Potential

Magnesium alloys, with a density of about 1.8 g/cm^3, are among the lightest structural materials with high specific strength as mentioned by Luo (2018) used in automotive manufacturing. Magnesium offers an even better strength-to-weight ratio than aluminum, making it a highly attractive option for reducing vehicle weight. When alloyed with other metals such as aluminum, zinc, and manganese, magnesium alloys can achieve impressive strength and stiffness while remaining extremely light.

- Strength-to-Weight Ratio: Magnesium alloys have a density approximately 30% lower than aluminum and 60% lower than steel, but with proper alloying and heat treatment, they can achieve tensile strengths around 350–500 MPa, comparable to high-strength aluminum alloys.
- Applications: Magnesium is used in the manufacturing of components like wheels, seat frames, and transmission cases in some high-performance EVs. Its low density helps reduce unsprung weight, improving handling and ride quality.

Recent advancements in magnesium alloy development have led to the creation of several high-performance alloys with diverse applications. Notable examples include AZ31 (Mg-3Al-1Zn), ZXEM2000 (2Zn-0.3Ca-0.2Ce-0.1Mn), and AE44 (Mg-4Al-4RE). AZ31 is widely used in automotive applications due to its good strength, formability, and corrosion resistance. ZXEM2000, with its enhanced fatigue resistance and higher temperature performance, is suitable for more demanding industrial uses. AE44, which contains rare earth elements, is particularly valuable for applications requiring high strength at elevated temperatures, such as the Corvette engine cradle, which operates at up to 150°C (Luo, 2015). These innovations enhance magnesium alloys' strength-to-weight ratios and thermal stability, making them ideal for lightweight, high-performance components in automotive industries.

Despite its advantages, magnesium is highly reactive and prone to corrosion, especially in automotive environments. Additionally, its high flammability and limited availability complicate its widespread adoption. Researchers are continually working on improving magnesium alloy formulations and protective coatings to overcome these challenges.

2.3. Titanium Alloys: High Strength at a Premium Weight

Titanium alloys, known for their exceptional strength and corrosion resistance, have a higher density (4.5 g/cm^3) compared to aluminum and magnesium, but still lower than steel. Titanium's strength-to-weight ratio makes it ideal for high-performance applications, where strength is critical, and weight reduction is still important. Titanium alloys, typically alloyed with aluminum and vanadium (Ti-6Al-4V), offer excellent mechanical properties.

- Strength-to-Weight Ratio: Titanium alloys are significantly stronger than aluminum alloys, with tensile strengths reaching upwards of 900 MPa. However, the material's density means it doesn't offer as high a strength-to-weight ratio as aluminum or magnesium.
- Applications: Titanium is primarily used in specialized components such as fasteners, suspension parts, and high-end engine components. It is also being explored for use in structural parts of the battery pack, where high strength and resistance to fatigue are crucial.

Titanium alloys are becoming increasingly popular in the automotive industry due to their high strength, low weight, and excellent corrosion resistance, making them ideal for high-performance applications. Alloys like Ti-6Al-4V (Grade 5), known for their strength and durability, are used in components such as engine parts, exhaust systems, and suspension components. The Ti-6Al-4V ELI (Grade 23) variant offers increased ductility, making it suitable for critical engine parts and racing applications. Other alloys, such as Ti-3Al-8V-6Cr-4Zr-4Mo, provide superior high-temperature strength, which is ideal for turbochargers and exhaust valves, while Ti-5Al-2.5Sn offers good oxidation resistance, making it suitable for exhaust systems and structural components. Additionally, Ti-10V-2Fe-3Al, a high-strength beta alloy, is being explored for use in hybrid and electric vehicle parts. Titanium Matrix Composites (TMCs), which combine titanium with reinforcing materials, are also being researched for their enhanced strength and stiffness in demanding automotive applications, such as racing car components. High-temperature TMCs can offer up to 50% weight reduction relative to monolithic superalloys while maintaining equivalent strength as mentioned by Hayat et al. (2019). However, the high cost of titanium and its relatively heavier weight compared to magnesium or aluminum mean that it is generally reserved for premium, high-performance applications in EVs, where its mechanical properties justify the expense.

2.4. High-Strength Steel Alloys: Durability and Safety with Weight Trade-offs

While steel is not typically classified as a "light alloy," high-strength steel (HSS) alloys are an essential material in EV manufacturing. These alloys offer a good balance of strength, durability, and cost-effectiveness, although they are heavier than aluminum or magnesium. Advanced high-strength steels (AHSS) such as dual-phase (DP), complex-phase (CP), and transformation-induced plasticity (TRIP) steels provide excellent strength-to-weight ratios.

- Strength-to-Weight Ratio: Steel alloys have a higher density (7.8 g/cm^3) than lighter alloys like aluminum and magnesium, but the strength of modern high-strength steels can reach tensile strengths of up to 1,500 MPa, which is much higher than those of aluminum and magnesium.

- Applications: HSS alloys are often used in critical safety structures such as the vehicle frame, crash zones, and structural reinforcements. While heavier than lightweight alloys, these materials provide superior protection during impact, making them crucial for safety in EV design.

Despite their weight, high-strength steel alloys offer cost-effective solutions for meeting stringent safety standards, and their ability to be easily welded and formed makes them a key material in EVs.

2.5. Relative Comparison

The higher the strength-to-weight ratio of a material, the more desirable it is in the context of automotive manufacturing, as it allows for lighter, stronger components that enhance vehicle performance and energy efficiency. However, it is essential to consider other factors beyond just strength-to-weight ratio when selecting materials for automotive applications. Machining and formability play crucial roles in determining how easily the material can be processed into complex shapes and components. Cost is another important factor, as it directly affects the overall manufacturing expenses and scalability. Additionally, the sourcing of the material, including availability and supply chain stability, is critical to ensure consistent production. While a high strength-to-weight ratio is key, a holistic approach that considers machining, formability, cost, and sourcing is necessary for optimizing material selection in automotive manufacturing.

Aluminum alloys, particularly those like 6000 and 7000 series, offer excellent formability. They can be easily rolled, stamped, and extruded into a variety of shapes, making them ideal for producing complex vehicle body parts and structures. Magnesium alloys, such as AZ31, also exhibit good formability, although they are more sensitive to temperature variations during processing. Titanium alloys, while known for their high strength, are generally less formable compared to aluminum or magnesium alloys, requiring more specialized techniques and higher temperatures to achieve the desired shapes. High-strength steel alloys offer moderate formability, but their higher strength often requires more force during stamping and shaping, potentially adding to manufacturing complexity. In terms of machining, aluminum alloys are generally easy.

Generally, aluminum and magnesium alloys are moderately priced, while titanium alloys are more expensive due to their advanced properties and processing needs. High-strength steel is the most cost-effective option.

Table 2 A relative comparison of different lightweight metals, their strength to weight ratio and typical application in automotive industry

Material	**Density (g/cm^3)**	**Tensile Strength (MPa)**	**Strength-to-Weight Ratio ($MPa/g/cm^3$)**	**Formability**	**Cost**	**Typical Applications**
Aluminum	2.7	250 - 500	92.6 - 185.2	Excellent formability, easy to extrude and shape	Moderate to High	Body panels, frames, battery enclosures, chassis
Magnesium	1.8	200 - 350	111.1 - 194.4	Good formability, but more sensitive to temperature variations	Moderate	Wheels, seat frames, transmission cases
Titanium	4.5	900 - 1,200	200 - 266.7	Moderate formability, requires higher temperatures for shaping	Hight	High-performance components, fasteners, suspension
High-Strength Steel	7.8	800 - 1,500	102.6 - 192.3	Moderate formability, requires more force during stamping	Low	Structural reinforcements, safety frames, crash zones

3. The Future of Lightweight Alloys in EV Manufacturing

As the demand for electric vehicles (EVs) accelerates, the adoption of lightweight alloys and sustainable manufacturing practices plays a key role in improving energy efficiency and reducing environmental impact. Lightweight metals such as aluminum, magnesium, and titanium are central to this shift, providing a significant reduction in vehicle weight, which directly enhances performance and range. However, the extraction and processing of these materials come with environmental concerns that need to be addressed through sustainable practices.

Aluminum is one of the most widely used metals in the automotive industry due to its strength-to-weight ratio, corrosion resistance, and high recyclability. However, the production of aluminum from raw bauxite is energy-intensive, contributing significantly to carbon emissions. To mitigate this, automakers are focusing on increasing the recycling of aluminum, which requires only 5% of the energy compared to primary aluminum production. For example, Ford's commitment to using recycled aluminum in their vehicles has helped reduce the environmental impact of aluminum production while maintaining the material's performance characteristics (Ford Newsroom, 2016). Similarly, magnesium, often used in lightweight alloys like AZ31, is another metal that benefits from secondary production processes, which have a much lower environmental footprint compared to traditional mining.

The growing interest in composite materials has also contributed to reducing the weight of EVs while improving their structural integrity. Carbon fiber-reinforced polymers (CFRP) are particularly valued for their exceptional strength-to-weight ratio and are used in high-performance applications. For example, the use of carbon fiber in the Tesla Model S helps reduce the vehicle's weight without compromising on safety or performance. These materials not only lower vehicle weight but also offer superior corrosion resistance, which can extend the life cycle of components, reducing the need for repairs and replacements.

Moreover, 3D printing is emerging as a game-changing technology for producing lightweight components in EV manufacturing. The ability to print complex, lightweight structures directly from digital designs reduces material waste and allows for on-demand production of parts. This is particularly beneficial for producing customized parts that meet specific performance or weight reduction targets. For instance, companies like Local Motors had used 3D printing to produce parts for vehicles, including body panels, which results in reduced manufacturing costs and lower material waste. By printing lightweight alloys like aluminum or titanium, 3D printing offers the opportunity to produce parts with intricate geometries that are both lightweight and optimized for strength.

In addition to these technological advances, automakers are also exploring ways to source metals more sustainably. For instance, BMW's approach to sourcing aluminum involves a commitment to using responsibly mined materials, while also improving the efficiency of the recycling process to create a more circular economy within the automotive industry. This is in line with broader goals of reducing the environmental footprint of EV manufacturing by not only using lightweight metals but also ensuring that they are sourced in an environmentally responsible way.

The future of lightweight alloys in EV manufacturing relies heavily on improving both the sustainability of raw material extraction and the innovative manufacturing processes that minimize waste. By integrating advanced materials like carbon fiber composites and cutting-edge technologies such as 3D printing, the automotive industry can reduce vehicle weight, enhance performance, and make significant strides toward sustainability. As these technologies evolve, the role of lightweight alloys and sustainable manufacturing techniques will continue to be crucial in shaping the future of electric vehicles.

4. Conclusion

In conclusion, the selection of lightweight alloys is pivotal in advancing electric vehicle (EV) manufacturing, significantly impacting performance, energy efficiency, and safety. Materials such as aluminum, magnesium, titanium, and high-strength steel alloys each offer distinct advantages based on their strength-to-weight ratios and suitability for specific automotive applications. As EV technology continues to evolve, ongoing research and development of new materials and processing techniques will be essential to meet the growing demand for vehicles that are lighter, stronger, and more energy efficient. This review has provided a comprehensive examination of the properties of these alloys, offering valuable insights into their role in automotive manufacturing and guiding the selection of the most appropriate material for different applications. By optimizing the use of lightweight alloys, manufacturers can not only enhance vehicle performance but also contribute to the sustainability and cost-effectiveness of EVs in the long term.

Compliance with ethical standards

Disclosure of conflict of interest

The author declares that there are no conflicts of interest regarding the publication of this paper.

References

[1] Ceschini, L., Boromei, I., Morri, A., Seifeddine, S., & Svensson, I. L. (2009). Microstructure, tensile and fatigue properties of the Al–10% Si–2%Cu alloy with different Fe and Mn content cast under controlled conditions. Journal of Materials Processing Technology, 209(15–16), 5669–5679. https://doi.org/10.1016/j.jmatprotec.2009.05.030

[2] Cinkilic, E., Ridgeway, C. D., Yan, X., & Luo, A. A. (2019). A formation map of iron-containing intermetallic phases in recycled cast aluminum alloys. Metallurgical and Materials Transactions A, 50 (12), 5945–5956. https://doi.org/10.1007/s11661-019-05469-6

[3] Ford Newsroom, Ford Recycles Enough Aluminum to Build 30,000 F-150 Bodies Every Month. Online. Available: https://media.ford.com/content/fordmedia/fna/us/en/news/2016/04/22/ford-recycles-enough-aluminum-to-build-30000-f150-bodies.html

[4] Hayat M., Singh, H., He Z., Cao P., Titanium metal matrix composites: An overview, Composites Part A: Applied Science and Manufacturing, Volume 121, 2019, Pages 418-438, ISSN 1359-835X, https://doi.org/10.1016/j.compositesa.2019.04.005

[5] Jung H.; Silva R.; Han M. Scaling trends of electric vehicle performance: driving range, fuel economy, peak power output, and temperature effect. World Electric Vehicle Journal, 2018, 9(4): 46.

[6] Luo, A. A. (2015). Material design and development: From classical thermodynamics to CALPHAD and ICME approaches. CALPHAD, 2015(50), 6–22. https://doi.org/10.1016/j.calphad.2015.04.002

[7] Luo, A. A. (2018). Magnesium: The lightest structural metal. International Magnesium Association.

[8] Luo, A. A. (2021). Recent advances in light metals and manufacturing for automotive applications. CIM Journal, 12(3), 79–87. https://doi.org/10.1080/19236026.2021.1947088

[9] Modaresi, R., Müller, D.B. The role of automobiles for the future of aluminum recycling, Environ. Sci. Technol. 46 (16) (2012) 8587–8594.

[10] Rahman, M.A., Uddin, M.M. and Kabir, L. 2024. Experimental Investigation of Void Coalescence in XTral-728 Plate Containing Three-Void Cluster. European Journal of Engineering and Technology Research. 9, 1 (Feb. 2024), 60–65. https://doi.org/10.24018/ejeng.2024.9.1.3116

[11] Redelbach M.; Klötzke M.; Friedrich H. E. 2012. Impact of lightweight design on energy consumption and cost effectiveness of alternative powertrain concepts. EEVC European Electric Vehicle Congress, Brüssel, Belgien: DLR, 2012: 1-9.

[12] Schlesinger, M. E. (2013). Aluminum recycling (2nd ed.). CRC Press.

[13] Taylor, J. A. (2012). Iron-containing intermetallic phases in Al-Si based casting alloys. Procedia Materials Science, 1, 19–33. https://doi.org/10.1016/j.mspro.2012.06.004

[14] US Department of Energy, Lightweight Materials for Cars and Trucks. Available online: https://www.energy.gov/eere/vehicles/lightweight-materials-cars-and-trucks

[15] Wen Zhang, Jun Xu, Advanced lightweight materials for Automobiles: A review, Materials & Design, Volume 221, 2022, 110994, ISSN 0264-1275, https://doi.org/10.1016/j.matdes.2022.110994