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Materials and constructional design for electric vehicles: A review

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ABSTRACT

In this article, electric vehicles (EVs) are generally introduced, and the benefits of shifting from internal combustion engine (ICE) automobiles toward EVs are discussed. Batteries, as the core technology of EVs, are then addressed, and various battery types are reviewed. Next, the critical role of copper as one of the primary materials essential for various EV components, as well as the expected growth in its demand in the near future, are discussed. Following that, the significance of using advanced high-strength steels (AHSSs) in the body structure of EVs to reduce weight while maintaining safety requirements is emphasized, and different types of AHSSs are generally mentioned. Subsequently, common metal forming and joining methods for manufacturing and assembling EV components are reviewed. After that, the importance of proper EV constructional design is highlighted, and the strategic battery pack placement for safety and effective weight distribution is highlighted. The importance of using lightweight materials that offer high strength-to-weight ratios in the body structure of EVs and their benefits for improving the efficiency of EVs through increasing the driving range are also outlined. In addition, the importance of responsible end-of-life actions, including recycling or responsible disposal of EV components after their functional lifespan, is also overviewed. Finally, useful strategies for facilitating wider adoption of EVs are discussed, and alternative options for addressing air pollution and global warming are mentioned.

Keywords: electric vehicle, automobile materials, advanced high-strength steels, copper alloys, constructional design, metal forming, joining, Li-ion batteries.

INTRODUCTION

Air pollution stands out as one of the most serious threats to human health, as it poses short-term and long-term health issues, e.g., respiratory tract infections, cancer, bronchitis, asthma, and other chronic illnesses [1]. It also contributes to global warming and acid rain [2]. A wide range of industrial sectors contribute to air pollution, and among them, the transportation industry stands out as one of the primary contributors to this global problem [3]. Figure 1a shows carbon dioxide (CO_2) emissions from various sources, highlighting the significance of the transportation industry [4]. Since the automotive industry represents a major segment within the transportation sector, addressing the air pollution issue within this domain is crucial. In this regard, electric vehicles (EVs) have been developed as a solution to reduce the production of air pollutants within automotive industry [5, 6]. So far, various environmentally friendly vehicles have been developed, ranging from plug-in hybrids (PHEVs), which have gasoline and electric drivetrains in parallel or serial configurations, to fully battery-powered models (BEVs), as well as fuel cell vehicles (FCEVs), which are primarily powered by hydrogen fuel cells while having battery storage systems [7]. Figure 1(b) presents a comparison

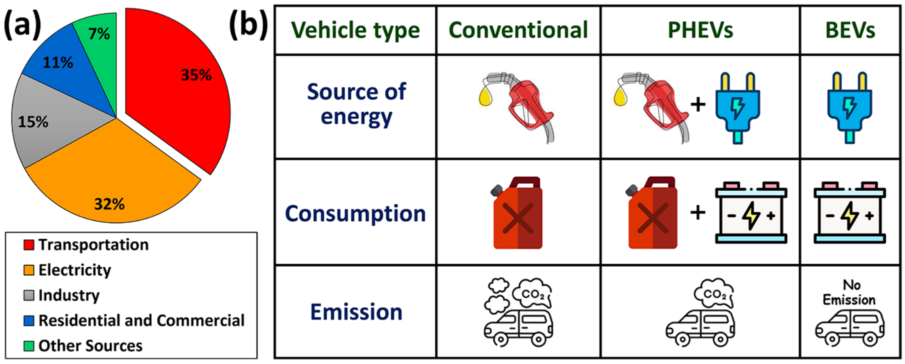

Figure 1. (a) CO_2 emissions from various sources (redrawn based on [4]), and (b) comparison of different vehicle types (redrawn with permission from [8])

of the sources of energy, consumption, and emissions across different vehicle types.

While the concept of EVs has a history spanning over a century, it has recently captured significant attention as a consequence of the growing concern regarding global warming along with the multitude of benefits that EVs offer, notably their capacity to mitigate air pollution and climate change [9]. According to various prediction models, annual sales of EVs are expected to increase in the coming years [10,11]. As an example, it can be referred to the study of Wu and Chen [10], where they predicted the annual sale volume of EVs in the world from 2021 to 2028 using both statistics and machine learning methods, and their findings indicated a projected continuous growth in EV sales during this period, as shown in Figure 2a. In the meantime, the eventual depletion of fossil fuel resources on Earth also necessitates the shift from internal combustion engine (ICE) vehicles towards greener alternatives such as EVs, making this transition to EVs not just an option but also a vital necessity. The benefits of EVs have also attracted the attention of the scientific community, as seen by Figure 2(b), which shows that the number of EV-related publications has notably increased since the beginning of the 21st century, and more research has been committed to EV development every year.

The advantages of EVs go well beyond those listed above. Nonetheless, it is essential to acknowledge that, while EVs offer several benefits, their adaptation is not without challenges. Factors such as battery range limitations, charging infrastructure development, and the environmental impact of battery production all have an impact on consumer adoption and market acceptance. In order to provide a comparison between a typical ICE vehicle and an average BEV, Table 1 has been included to point out that significant improvements are still necessary to enhance EV performance and make them as widely adopted as ICE vehicles. Lightweight vehicle design, battery technology improvements, price reduction, and driving range extension are some of the potential enhancements. By addressing these issues, manufacturers could contribute to narrowing

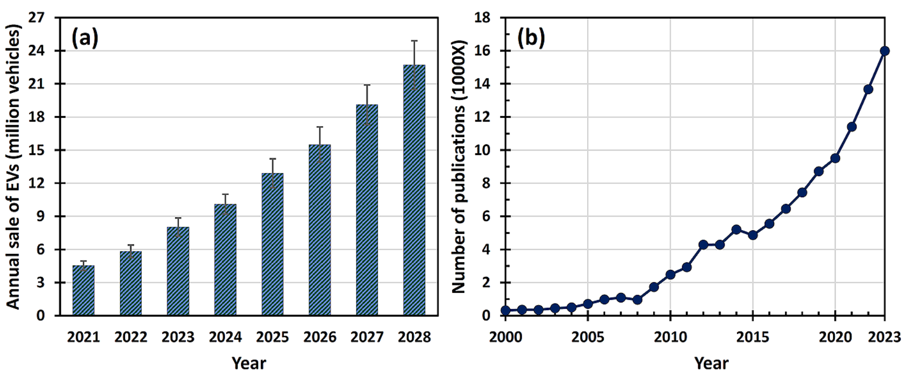

Figure 2. (a) Estimated annual sale volume of EVs from 2021 to 2028 (redrawn based on [10]), and (b) number of EV-related publications since the beginning of the 21st century based on the Scopus database

Table 1. ICE Vehicles vs. BEVs (qualitative assessment)

Parameter	ICE Vehicles	BEVs	Overall Assessment
Mass	Lighter	Heavier	ICE vehicles typically have an advantage in mass
Duration of refueling/ charging	Quick refueling (in scale of minutes)	Longer charging time (in scale of hours)	ICE vehicles offer a clear advantage in refueling time
Price	Generally lower	Generally higher	ICE vehicles are typically more affordable
Driving range	Longer range	Shorter range	ICE vehicles generally provide a better driving range
Efficiency	Lower overall efficiency	Higher overall efficiency	BEVs are significantly more efficient
CO_2 Emissions	Produce direct emissions	Zero operational emissions	BEVs have a clear advantage in emissions
Maintenance cost	Higher maintenance costs	Lower maintenance costs	BEVs generally incur lower maintenance costs

the performance gap and making BEVs a more practical alternative for the typical consumer.

Given the significant impact EVs can potentially have on revolutionizing the transportation industry and reducing the reliance on fossil fuel energy resources, it becomes intriguing to delve into the advanced materials and constructional designs employed in EV manufacturing. This review article addresses critical material considerations and constructional designs essential for EV development, covering topics such as lithium demand, the role of copper and advanced high-strength steels (AHSSs), metal forming and welding technologies, constructional design for heavy batteries, recycling of EV components, and future research opportunities.

Electric vehicles and the battery technologies

Recent advancements in battery technology have also made it more practical to have more EVs on the road. Generally, each EV type incorporates at least one battery as a primary component in its structure. The efficient functioning of EVs predominantly depends on the power and density of the batteries employed as their power source [12]. Therefore, battery technologies for EVs have undergone continuous progress, with multiple enhancements in improving their energy storage capacity, reducing charging time, and enhancing overall performance [13]. There are various types of batteries and battery manufacturing technologies available in the market for equipping EVs [14], including:

- Lead-acid (Pb-acid) batteries, which are a relatively traditional type of battery technology. They have drawbacks like handling acid and containing lead, with low energy stored per weight and volume [14].
- Nickel-cadmium (NiCd) batteries, that offer a relatively long lifespan, typically reaching around 2000 cycles. However, since cadmium is harmful to the health and environment, EU regulations have restricted NiCd battery use [4, 14].
- Nickel-metal-hydride (NiMH) batteries, that share similarities with NiCd batteries in manufacturing and operation. Their primary advantage is that they are not susceptible to the memory effect, but they generally have lower energy storage and higher self-discharge rates compared to high-performance Li-ion batteries [14, 15].
- Sodium nickel chloride (NaNiCl) batteries, which are also known as "Zebra batteries", and use a molten salt electrolyte with an operating temperature of 270–350 °C. While they offer a high stored energy density, their major drawbacks include operational safety concerns and self-discharge during standby [14, 16].
- Lithium-ion (Li-ion) batteries, that have a high power storage capacity and excellent energy density per weight. Although they were initially costly, their price has decreased in recent years, and with improved design and materials, their overheating risks have also been managed effectively [14, 17].
- Lithium-ion polymer batteries, that share similar functionalities and limitations to Li-ion batteries. Their lifespan depends on their chemistry and usage, but it requires proper management to avoid overcharging, overheating, and deep discharge [14, 18].
- Solid-state batteries, which are an emerging technology that use solid electrolytes instead of liquid or gel electrolytes found in conventional

batteries. They have the potential to offer higher energy density, longer lifespans, faster charging times, and improved safety compared to other battery types. However, they are still in the early stages of development and not yet widely used in commercial EVs [19].

For the aforementioned battery types, Figure 3a presents the specific energy density versus volumetric energy density and clearly demonstrates the weight and size advantages of Li-ion batteries compared to other currently available options, which makes them favorable choices for EVs, where weight and space optimization are critical design factors. Specific power versus specific energy of the mentioned battery types is also shown in Figure 3b, which again shows the advantage of lithium batteries over other types. The next critical aspect in selecting batteries for EVs is their lifespan, with longer life cycles being the preferable choice. Table 2 outlines the life cycles for the various battery types. Now comes the charge-discharge rate (C-rate), which is another key factor affecting battery lifespan. It dictates the rate at which chemical reactions occur during charging and discharging. Elevated C-rates, which indicate faster charging or discharging, place greater stress on battery materials, speeding up degradation and shortening the overall lifespan. Additionally, higher values of the C-rates can accelerate battery aging, primarily due to the increased internal temperature of the battery cells [20]. It is also important to note that the battery C-rates typically decrease in low-temperature conditions, resulting in reduced performance and efficiency during both charging and discharging processes. To provide an example in the context of EVs, average charging C-rates have been reported as 1.38 for the Volkswagen ID.3 and 1.81 for the Tesla Model 3, respectively [21]. In the meantime, there is also extensive research dedicated to both increasing the life cycle of the existing batteries as well as developing next-generation technologies with higher efficiency, reduced weight and volume, and lower production costs to encourage widespread EV adoption.

It is also important to note that since batteries account for a considerable portion of the cost of EVs, reducing their production costs is essential to lowering the total price of EVs [24]. The manufacturing of Li-ion and Li-ion polymer batteries relies on lithium, and as the market for EVs expands, providing a consistent and sustainable supply of lithium becomes crucial. A simplified approach for the estimation of annual global demand for lithium by EVs can be made by multiplying the number of the annual EV sales by the average lithium content per unit battery capacity. Egbue et al. [25] showed that the lithium demand for plug-in hybrid electric vehicles and battery electric vehicles could potentially grow from 2025 to 2050, as demonstrated in Figure 4a. Batteries account for a significant share of lithium end use (Figure 4b) [25]. Therefore, it is important to optimize lithium extraction methods while also considering recycling and second-life applications of lithium batteries to reduce dependence on primary lithium resources.

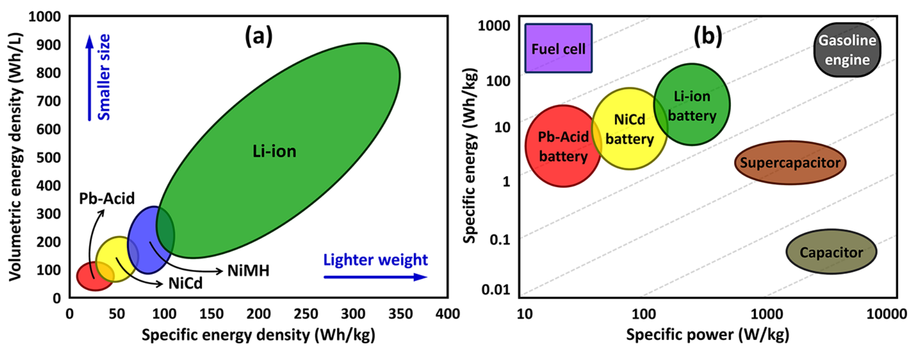

Figure 3. (a) Specific energy density vs. volumetric energy density for different battery types (redrawn based on [22]), and (b) specific power vs. specific energy of various battery types (redrawn based on [23])

Table 2. Typical lifespan of various battery types [4]

Battery type	Pb-Acid	NiCd	NiMH	Li-ion	Li-ion Polymer
Life cycle	1500–5000	2000	<3000	2000	>1200

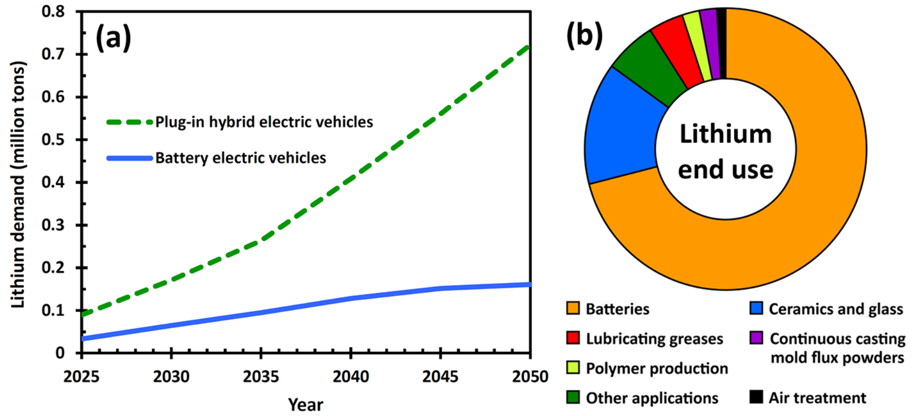

Figure 4. (a) Projected lithium demand for EVs from 2025 to 2050, and (b) various end applications of lithium (redrawn based on [25])

Along with developing battery technology, the improvement of charging infrastructure is equally pivotal for facilitating widespread EV adoption. To address this need, innovative fast-charging technologies as well as wireless charging systems are being developed to meet this requirement, shorten the charging duration, and improve EV user convenience [26]. In addition, implementing good thermal management is also vital for EVs, as effective temperature regulation enhances battery performance, extends its lifespan, and promotes safety [27]. This could potentially be achieved through active cooling methods, such as liquid cooling and refrigerant-based systems, as well as passive methods like phase change materials and heat sinks [28, 29]. The widespread adoption of EVs also relies on a well-developed charging infrastructure network and easily accessible charging stations [5]. To address this issue, governments in many countries, particularly those with a stronger commitment to increasing EV adoption, have invested in promoting EV charging infrastructure. For instance, Figure 5 illustrates the significant rise in the number of EV charging stations in Europe from 2010 to 2021.

Urban development planning is also critical for promoting EV adoption by locating EV charging stations not only in various metropolitan locations but also along intercity routes, which enables drivers to rely on these stations for seamless travel between cities. Moreover, given the variety of EV connectors available on the market [31],

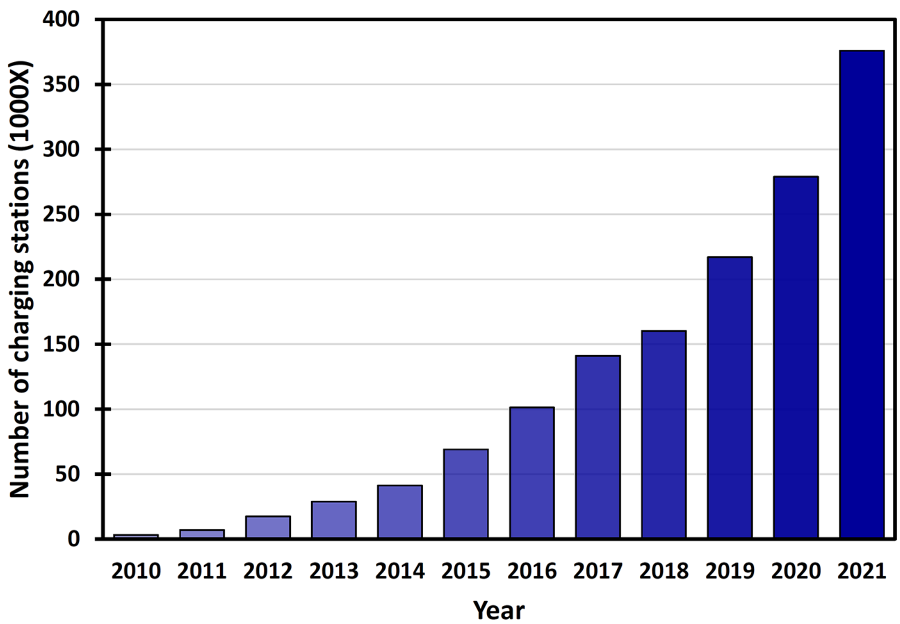

Figure 5. Number of EV charging stations in Europe from 2010 to 2021 (redrawn from [30])

ensuring compatibility between EV connectors and charging station outlets is also critical. Therefore, adopting a worldwide standard connector could be beneficial for eliminating the need for adapters and providing another motivation for drivers to switch to EVs. Furthermore, reducing charging costs would serve as a compelling reason to obtain higher EV adoption rates. In this regard, governments can play a significant role by investing in green technologies such as solar photovoltaic systems, wind turbines, and hydroelectric power plants, specifically designed to supply low-cost electricity exclusively for EV charging stations.

The significance of copper

Copper and its alloys have exceptional electrical and thermal conductivities and play a vital role in the power supply and energy distribution systems of EVs [32, 33]. They also possess good machinability and corrosion resistance, which are desirable features for automotive materials [34]. Notably, due to the presence of more electric gadgets as well as extra wiring systems in EVs, a significantly higher amount of copper is used in EVs compared to typical gasoline-powered vehicles, as shown in Figure 6(a) [35]. Electric motors, wiring systems, electrical contacts, and battery connections all require a variety of copper alloys, ranging from pure copper to advanced high-strength high-conductivity (HSHC) copper alloys. Therefore, the production volume of EVs is directly dependent on the availability of copper and its alloys. In addition, the charging infrastructure required for charging EVs is also reliant on copper and its derivatives. Hence, it is apparent that the demand for copper alloys will increase with the growing prevalence of EVs [32]. In this regard, many models have been developed to predict copper demand in the upcoming decades. One example of the evolution and projection for copper demand for EVs for the current decade is shown in Figure 6b, which suggests a potential rise in copper demand in the upcoming years.

In the meantime, copper extraction, refining, and production processes pose issues related to energy consumption and the release of harmful substances into the environment [36]. These challenges, along with the growing demand for copper, necessitate optimizing copper usage in EVs to lower the risk of copper shortages and the resultant price increase, while also minimizing environmental impact and controlling the depletion of copper natural resources. Another concern with using higher quantities of copper in EVs is its relatively high density, which can lead to increased weight and reduced efficiency and driving range [37]. In order to address weight concerns and reduce the drawbacks of heavier EVs while also maintaining performance levels, researchers are working on developing lighter copper alloys and exploring other conductive alternatives, such as aluminum, that can provide the required electrical conductivity.

Advanced high-strength steels

As discussed earlier, a key challenge in the development of EVs lies in their heavy weight due to the presence of batteries and greater copper usage compared to ICE vehicles. While the utilization of lighter materials in the body structure of EVs could potentially compensate for this issue, it is crucial to ensure that these materials meet safety standards by possessing the necessary levels of mechanical properties. To overcome

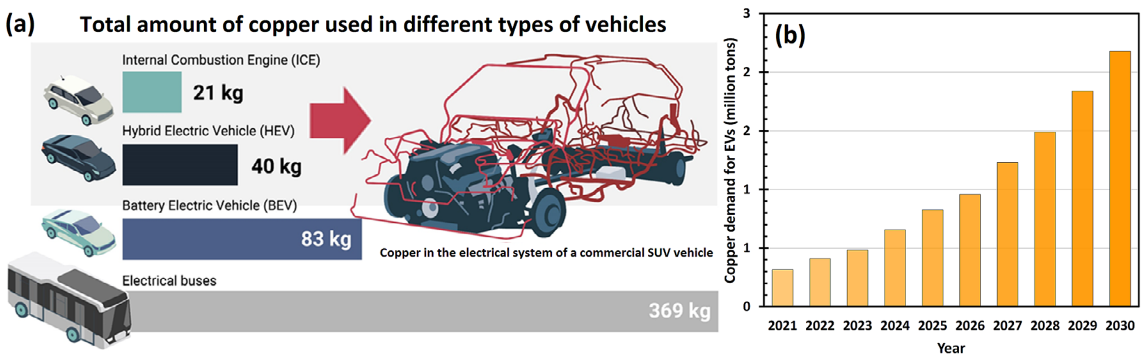

Figure 6. (a) The quantity of copper used in different kinds of vehicles, and (b) the evolution and projection of the demand for copper in EVs by 2030 (redrawn with permission from [35])

this problem, the utilization of AHSSs along with other alloys with a high strength-to-density ratio is crucial [38]. So far, three primary categories of AHSSs have been developed [39]. The first generation of AHSSs includes martensitic steels, dual-phase (DP) steels, complex-phase (CP) steels, and transformation-induced plasticity (TRIP) steels [40]. This generation offers a high level of strength along with low to moderate levels of ductility. Their production methods are relatively easy and cost-effective, which makes them a favorable choice for utilization in the body structures of contemporary automobiles, particularly EVs [41].

The second generation of AHSSs consists of austenitic stainless steels, lightweight steels with induced plasticity (L-IP), and twinning-induced plasticity (TWIP) steels [42]. This generation provides an excellent combination of high strength and high ductility, much better than the first generation; however, there is a drawback, which is their comparatively greater cost. In fact, alloying elements such as chromium and nickel, which are added to the chemical composition of stainless steels, account for their higher price. Additionally, the incorporation of 5-10 wt.% aluminum and silicon in L-IP steels and 15-30 wt.% manganese in TWIP steels not only increases material costs but also presents challenges during casting, hot working, metal forming, welding, and hot-dip galvanizing. Therefore, using these steels in the body structure of mass-production automobiles is not economically efficient [41]. Consequently, the third generation of AHSSs, which includes carbide-free bainitic (CFB) steels, medium-Mn TRIP steels, and quenching and partitioning (Q&P) steels, has been developed to offer a suitable strength-ductility balance between those of the first and second generations, with a lower production cost than the second generation [41,43]. Their good mechanical properties and affordable price make them highly attractive options for integration into the body structure of EVs. Given the critical role of AHSSs in the body structure of EVs, Table 3 has been included to present the typical mechanical properties of various grades of AHSSs. Notably, one unique characteristic observed in most of these steels is the presence of (retained) austenite in their microstructure, which undergoes transformation into martensite during deformation, a phenomenon referred to as the transformation-induced plasticity (TRIP) effect [43,44]. The TRIP effect provides improved strain hardening ability and energy absorption capacity for the material, making it highly suitable for automobile body structure [45]. The strength and ductility of current AHSS grades remarkably rely on the presence of retained austenite in their microstructure [46].

Using AHSSs enables the use of thinner sheets with equivalent (or even greater) strength and energy absorption capacity while reducing total weight as compared to typical steels. Therefore, by using AHSSs, automakers are able to manufacture lighter vehicles while maintaining safety standards [52]. Although AHSSs may come at a higher initial cost for EV manufacturers compared to traditional steels, their lighter weight can bring cost savings for EV customers via increased driving range. Various AHSS grades are anticipated to dominate the vehicle material market in the near future, and by appropriately incorporating them in the body structure of EVs, manufacturers can considerably enhance the performance of their products [53]. Yet, continuous efforts are being made to develop next

Table 3. Typical microstructure and range of UTS and elongation for AHSSs [43,47–50]

Steel	Microstructure	UTS (MPa)	Total elongation (%)	Reference
DP	Ferrite + martensite	500–1100	15–35	[43]
CP	Ferrite + martensite + bainite	500–1100	15–35	[43, 47]
TRIP	Ferrite + austenite + bainite (+ martensite)	550–1150	20–40	[43]
Austenitic stainless	Austenite	550–1050	45–75	[43]
L-IP	Austenite	900–1200	55–75	[43, 48]
TWIP	Austenite	950–1650	35–60	[43, 49]
CFB	Bainitic ferrite + retained austenite	1300–1650	15–25	[43, 50]
Medium-Mn TRIP	Ferrite + austenite (+ martensite)	700–1200	25–55	[43]
Q&P	Martensite + retained austenite (+ ferrite)	1050–1400	15–35	[43, 51]

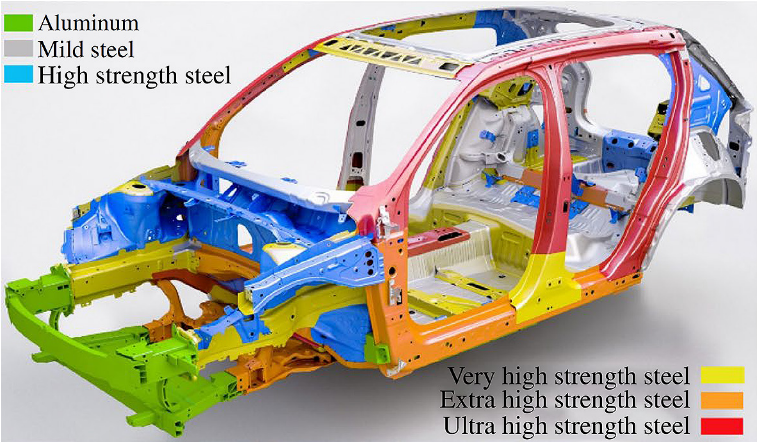

Figure 7. Body structure of a fully electric Volvo XC40 (reprinted from [7] under CC BY 4.0 DEED license)

generations of AHSSs with better strength-ductility balance, higher formability, and affordable prices. Figure 7 displays the body structure of a fully electric Volvo XC40, which shows the utilization of various groups of high-strength steels throughout its body frame.

Advanced metal forming and welding technologies

The EV components made from AHSSs must be formed into desired shapes with a tolerance lower than a certain value. They must also be properly joined together during the assembly process of the body structure. Automakers use a variety of metal forming processes and joining methods to shape and assemble different automobile parts. This section provides a brief review of two critical forming methods, namely hot stamping and hydroforming, as well as two widely used welding techniques, resistance spot welding (RSW) and laser beam welding (LBW). Hot stamping is a high-temperature forming process that operates under non-isothermal conditions, aiming to form complex ultra-high-strength steels with the goal of no springback effect [54]. In general, there are only two simple steps involved in the hot stamping process for steels. In order to get the desired shape of the workpiece, the initial ferritic-pearlitic steel sheet is first heated to an austenitization temperature to transform into austenite, and the hot blank is formed into the desired shape, either before, during, or after the austenitization. Finally, the formed blank is quenched to a temperature below the final martensitic transformation temperature (M_f) to obtain a final product with a martensitic microstructure, which features exceptionally high strength [55]. The hot stamping process is automatic, carried out using robot arms, and is reasonably quick, which makes it an ideal forming method for manufacturing automobile body parts [56]. Hot stamping is used in the manufacture of various automobile components, including A-pillars, B-pillars, side impact protection, sills, frame parts, bumpers, door pillar reinforcements, roof frames, tunnels, and front and rear cross members [57].

The next primary forming method is the hydroforming process, which is a near-net-shape forming process in which complex structures are created by using fluid (water or oil) pressure instead of (or simultaneously with) conventional mechanical forces [58]. Common hydroformed products in automobile body structures include engine cradles and mufflers [59]. The advantages of the hydroforming process can be referred to as reducing the number of welded joints in structures, availability for manufacturing thinner walls, improved dimensional tolerance, and better surface quality. In the automotive industry, aluminum alloys and stainless steels, as well as DP, TRIP, and TWIP steels, are commonly formed using the hydroforming method [59]. Progress in simulation techniques has enhanced the understanding of hydroforming processes and facilitated the efficient and dependable development of hydroformed components today [60]. Yet, still relatively long production cycles and expensive tool costs are drawbacks of this process. Figure 8 shows simplified schematic illustrations of the hot stamping and hydroforming processes.

In the manufacturing process of EVs, different components must be joined together to form the body structure. Among all joining technologies,

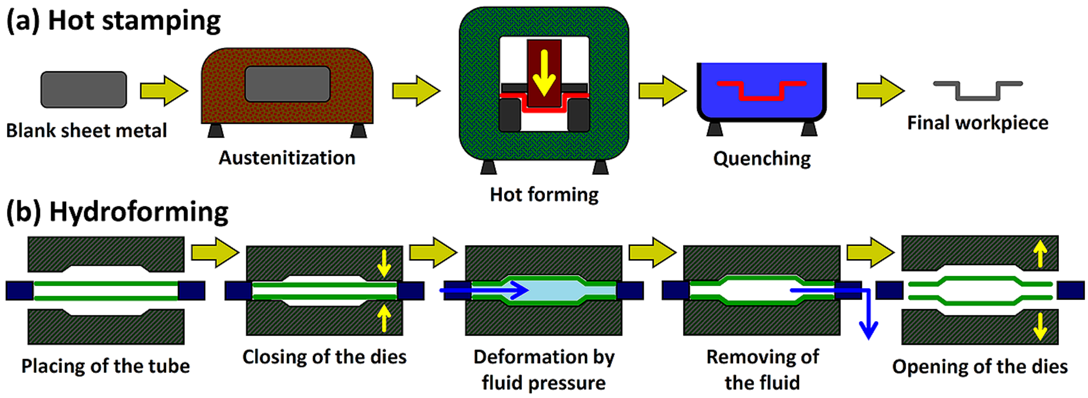

Figure 8. Simplified schematic illustrations of (a) hot stamping, and (b) hydroforming processes

RSW stands out as an excellent method in automotive assembly owing to its advantages in automation, high productivity, and cost-effectiveness [61]. RSW is a dominant technique in the automobile industry, which accounts for a remarkably large proportion of vehicle body assembly tasks [62]. In this process, two (or more) metallic sheets are clamped between two water-cooled electrodes (which are made from copper alloys) and pressed together with a specified electrode force for a designated squeeze time. Then, an electric current, known as the weld current, passes through the clamped joint to generate heat for a predetermined welding time. The high contact resistance at the interface between the sheets facilitates heat generation and their melting, and the molten nugget expands as a result of the bulk resistivity of the materials. Finally, upon termination of the current flow, the weld undergoes cooling and solidification, and the heat primarily dissipates through the electrodes, which remain in contact with the workpiece for a short time after the welding [63].

LBW uses a concentrated laser beam to precisely melt and connect two (or more) pieces of metal. Owing to its precise focusability and high power density, LBW offers numerous advantages, including high welding speed, a narrow and deep weld zone, and a small heat-affected zone (HAZ) [64]. As a result, it stands out as a promising welding technique for joining various components of the automobile body structure, such as door frames, auto hoods, chassis, and trunks, as well as different sub-components such as airbag initiators, motor coil windings, engine parts, transmission components, air-conditioning equipment, and fuel injectors [65]. Moreover, LBW is also a suitable method for manufacturing battery cells and joining cells to create a module, and it also facilitates the process of connecting these modules to construct a comprehensive battery assembly. Owing to its precise and clean welds, LBW is also a desirable approach for creating strong electrical connections within both battery packs and electric motors [65]. Figure 9 presents simplified schematic illustrations of the RSW and LBW processes. It is also worth noting that both methods are environmentally friendly processes characterized by low emissions of fumes and gases compared to other methods. Additionally, the heat is effectively concentrated in a confined welding zone in both methods, which minimizes the thermal impact on the surrounding material and helps preserve the microstructure and mechanical properties of the bulk workpiece. The high hardness of the HAZ of AHSSs can be positively decreased using dual beam laser welding, which enables flexible manipulating with the laser spot geometry and the beam power [66]. It is also worth noting that the AHSSs typically contain a higher quantity of non-metallic inclusions, which results from the higher level of manganese, aluminum, and silicon used in their composition [67, 68].

Constructional design

The constructional design of EVs conveys new challenges different from those encountered in ICE vehicles. For example, since large battery packs necessitate effective space allocation and weight distribution, properly integrating them to ensure optimal weight balance without compromising vehicle performance is crucial in EV design [69]. There are several factors that determine the optimal positioning of a battery pack in EVs. Most importantly, since the EV batteries

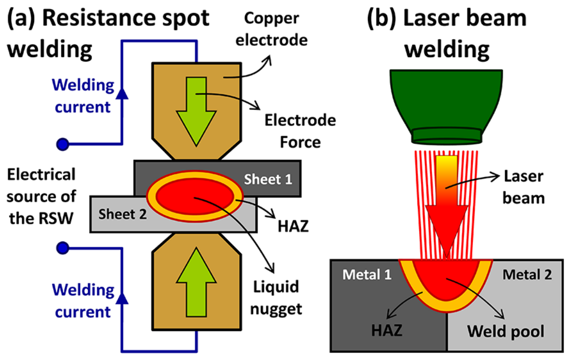

Figure 9. Simplified schematic illustrations of the (a) RSW, and (b) LBW processes

are relatively heavy, the battery pack should be installed in a location that can effectively lower the center of gravity of the vehicle and enhance its weight balance, stability, and handling. Moreover, the battery pack should be located outside the passenger compartment to minimize the risk of high-voltage components compromising passenger safety [70]. In addition, the position of the battery pack should be far enough from the front or back end of the EV body structure in order to protect it from collisions, as impact damage to the batteries might result in fire or explosion [70]. This potential risk is being increased by the continuous growing capacity of the EV batteries, which could potentially release more energy rapidly in the event of a vehicle accident [71]. Furthermore, considering proper thermal management, it becomes beneficial to place the battery pack where sufficient air circulation can occur to boost heat dissipation and prevent the batteries from overheating [70]. Installing the battery pack at the bottom of the vehicle has been found to fulfill all of these requirements. However, relying solely on this approach is insufficient, as under extreme conditions, such as traffic jams on hot days, the radiating heat from the asphalt can contribute to battery pack heating. Therefore, additional cooling mechanisms, such as liquid cooling systems, should also be implemented to prevent potential overheating issues. The electric motor in EVs is typically located on the front axle, rear axle, or both axles, depending on the drivetrain, so placing the battery pack at the bottom of the EV body structure between the front and back of the vehicle is beneficial because it requires a lower wiring system, reducing copper usage. Figure 10 shows an example of the appropriate positioning of the battery pack in the Audi e-tron Sportsback, with the battery pack positioned low within the body structure.

The incorporation of lightweight materials in the design of EVs is also beneficial, as decreasing vehicle weight results in increasing its driving range. In this regard, incorporating light metals like aluminum and magnesium alloys as well as lightweight composite materials such as carbon fiber-reinforced polymers, which offer high strength-to-weight ratios, can significantly contribute to the weight reduction for EVs [73, 74]. Figure 11 shows the potential mass reduction achievable through the utilization of various

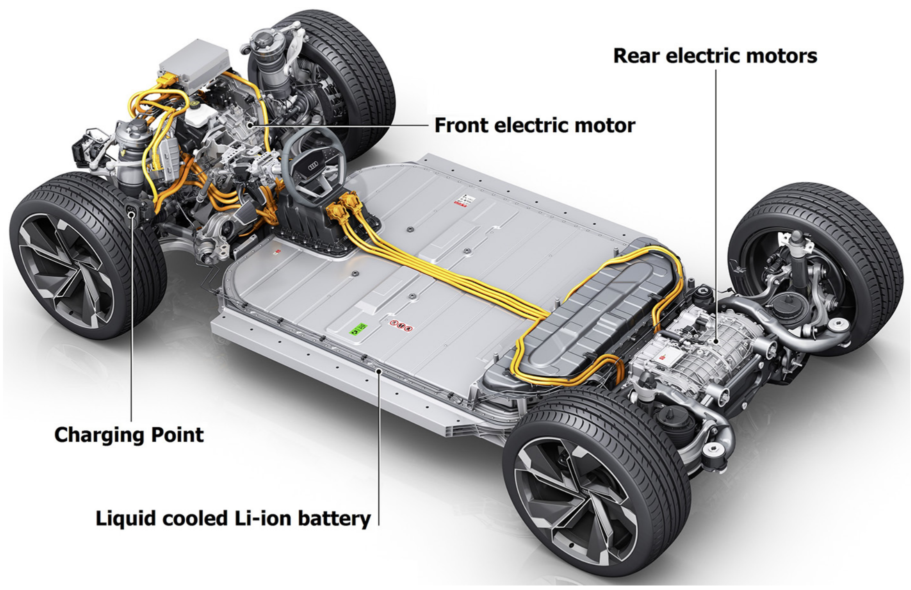

Figure 10. Proper placement of the battery pack in the Audi e-tron Sportsback (reprinted from [72] under CC BY 4.0 DEED license)

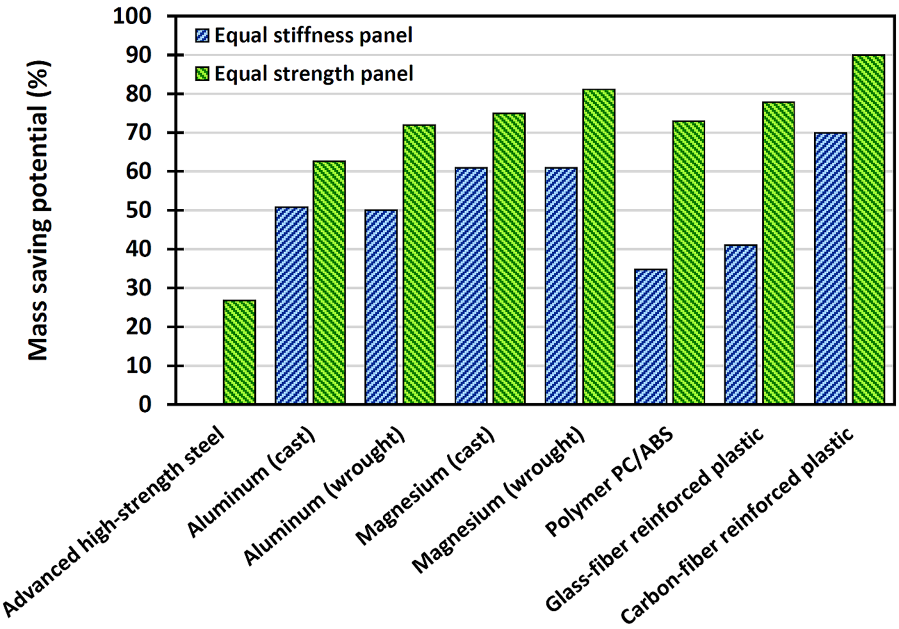

Figure 11. Mass savings in automotive applications for lightweight materials over mild steel in structural panels with equal bending stiffness and bending strength (redrawn based on [7])

lightweight materials instead of mild steel in automotive structural panels while maintaining equivalent bending stiffness and bending strength. Here comes the pivotal role of microstructure engineering for metallic materials, which involves optimizing the processing history in order to achieve an enhanced microstructure that allows for the use of thinner yet equally strong metallic sheets in the body structure of EVs, resulting in considerable weight savings.

To provide an example of optimizing processing history parameters, DP steels, which are a very common type of AHSSs used in the body structure of contemporary automobiles, can be mentioned, where studies have reported that adjusting the initial microstructure [75], soaking time [76], and intercritical annealing temperature [77] can profoundly affect the resultant microstructure and mechanical properties. For instance, as seen in Figure 12a, using an initial martensitic microstructure for intercritical annealing leads to a DP steel with higher yield strength (YS) and ultimate tensile strength (UTS) compared to DP steels developed from other initial microstructures. In the meantime, applying an appropriate amount of deformation to the initial martensitic steel prior to intercritical annealing can further enhance the resultant mechanical properties. The significance of the influence of soaking time on the mechanical properties is apparent in Figure 12(b), where the existence of an optimal intercritical annealing duration for achieving the best tensile properties can be seen, as short soaking times are insufficient while long annealing durations are detrimental to the tensile properties. Figure 12c highlights the trade-off between strength and ductility as a function of intercritical annealing temperature, demonstrating that lower intercritical annealing temperatures promote higher ductility but come at the cost of lower strength, whereas higher temperatures enhance strength but sacrifice elongation.

Depending on the application, there are optimal intercritical annealing parameters that result in the best balance between strength and ductility. It is also important to note that the processing parameters mentioned above are merely the primary ones. Additional factors, such as prior deformation, heating rate, potential hot rolling parameters, and post-annealing treatments, also play a crucial role in obtaining DP steel with the desired microstructure and mechanical properties. Furthermore, similar parameters are essential in the processing of other AHSS grades, which must be carefully considered during the manufacturing of EV components to optimize the material performance.

Exterior design is also a crucial aspect of EV design, particularly in terms of aerodynamics [78]. Streamlined exterior design, considering aerodynamic features, is essential for maximizing the driving range and efficiency. In other words, by minimizing drag force and optimizing airflow, these designs contribute to reduced energy

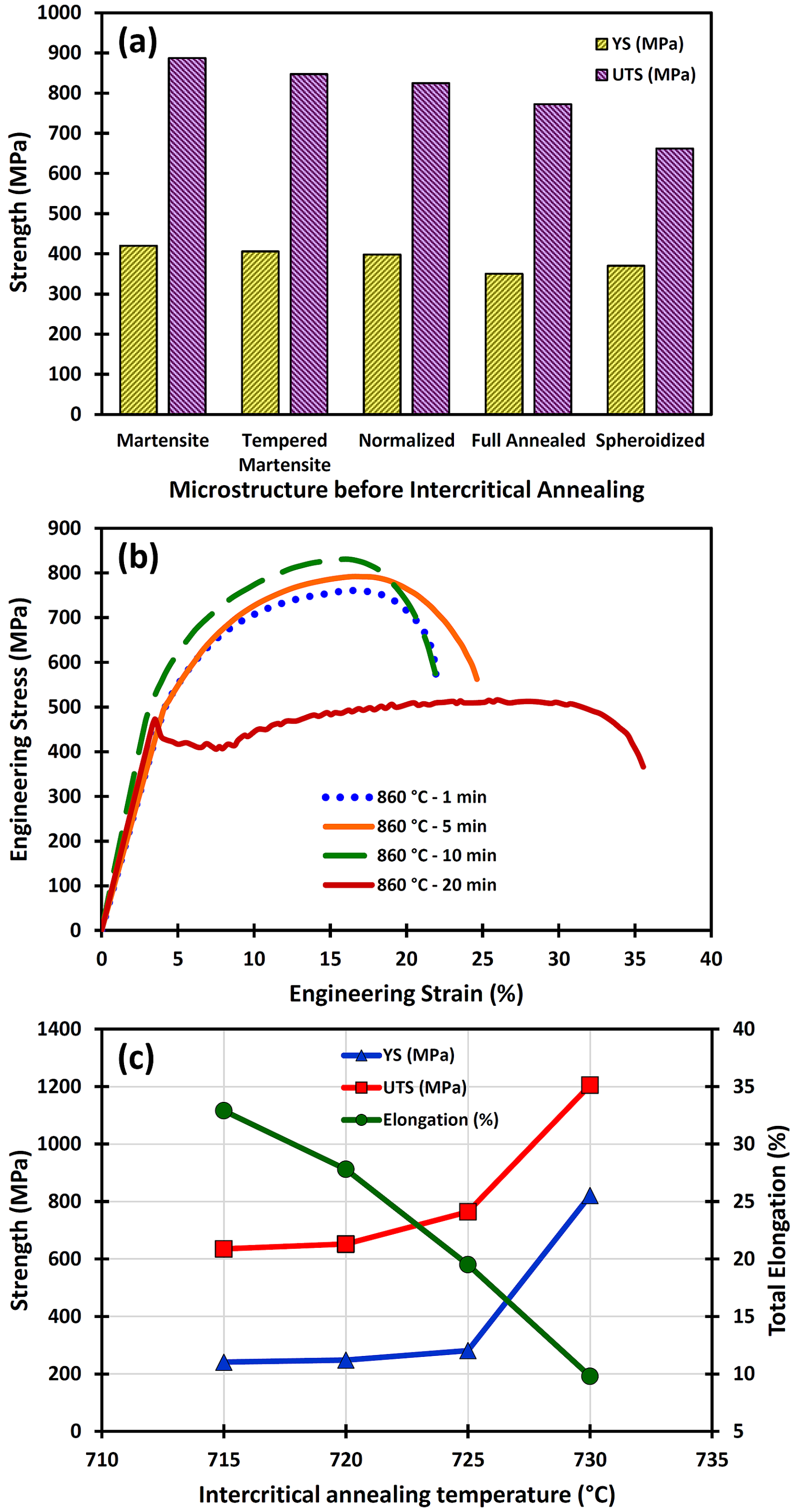

Figure 12. The effect of (a) initial microstructure (redrawn with permission from [75]), (b) soaking time (redrawn with permission from [76]), and (c) intercritical annealing temperature (data collected from [77]) on the tensile properties of the resultant DP steel

consumption and extended driving distances. EVs generally have lower air drag coefficients (C_d) than ICE vehicles. For instance, some C_d values reported for EVs include 0.29, 0.28, 0.24, and 0.31 for the BMW i3, Nissan Leaf, Tesla Model S, and Volkswagen e-Golf, respectively [79]. On the other hand, typical sedans generally possess C_d values ranging from 0.30 to 0.41, depending on their exterior aerodynamic design [80]. These variations highlight the importance of aerodynamic design in EVs, as a lower C_d value enhances the efficiency and driving range of EVs on the road.

In order to achieve an optimized exterior design, employing computational fluid dynamics simulations as well as wind tunnel testing could be useful for fine-tuning the design and optimizing the aerodynamic performance of EVs [81]. EVs also require additional and unique safety considerations due to their distinctive characteristics. For instance, with no engine compartment to absorb impact energy during collisions, the design of crumple zones in EVs needs unique considerations to efficiently absorb and dissipate energy in case of accidents. In other words, thicker sheets are needed for bumpers to compensate for the absence of a classical engine, making AHSSs crucial for minimizing this increase in thickness. The same approach applies to securing batteries, which must remain intact during collisions. Additionally, the absence of certain components in EVs, such as the fuel tank and exhaust system, opens up extra space in the body structure of EVs, which could be used to properly allocate other EV components.

Recycling and disposal strategies

Figure 13 presents a simplified lifecycle flowchart for EV materials. Upon reaching the end of their service life, EV components typically undergo either recycling or responsible disposal. For instance, metallic components typically undergo recycling to fabricate new parts. On the other hand, if recycling is not an option due to technical or economic limitations, responsible disposal methods are implemented to minimize the environmental impact. Optimizing material utilization and the constructional design of EVs also demands strong attention to end-of-service reuse and disposal strategies, which makes recycling a crucial stage in the lifecycle of the vehicle. Effective recycling offers two key advantages. Firstly, it is vital for reducing the environmental footprint of EVs and conserving valuable resources. Secondly, incorporating recycled materials into the fabrication of EVs provides several benefits, including potentially lower production costs. Since EVs introduce new components and technologies, significant changes in vehicle recycling are anticipated in the coming years [82]. In other words, the transition towards EVs necessitates the development of innovative end-of-service strategies, which are crucial for effectively reusing materials and responsibly disposing of those components that cannot be recycled or are economically viable to recycle.

Most of the metallic parts utilized in the body structure of EVs are relatively easier to recycle compared to other components. This advantage comes from the fact that more or less equivalent metallic elements are utilized in other contemporary automobiles, and well-established recycling techniques already exist for them. It is also worth noting that low-alloy metals are typically easier to recycle compared to high-alloy metals, and using them in the body structure of EVs can potentially simplify future recycling operations. On the other hand, EV batteries require unique recycling processes, which are typically more complex. Pyrometallurgical recovery, physical material separation, hydrometallurgical metal reclamation, direct recycling, and biological metal reclamation can be mentioned as the potential recycling methods for Li-ion batteries [83]. Effective battery recycling offers the potential for significant cost reductions in battery production, ultimately lowering the price of EVs [84]. In addition, it reduces the environmental impact by preventing hazardous materials from entering the waste stream.

As shown in Figure 13, optimizing the recycling process also relies on proper material separation beforehand. Incomplete material separation hinders both the efficiency of the recycling process and the quality of the recycled materials.

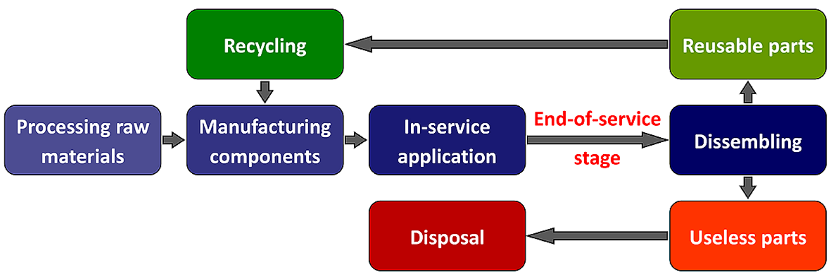

Figure 13. Simplified lifecycle flowchart of EV components

For instance, one significant challenge is when copper and steel are not completely separated from each other. In this case, the occurrence of copper contamination in recycled steel results in various issues, including heightened brittleness and diminished ductility of the recycled steel. Hence, it is more cost-effective to implement efficient separation steps prior to the recycling process to assure high-quality recycled materials.

CONCLUSIONS

An overview of EVs, followed by a discussion on the environmental and economic benefits of switching from traditional ICE vehicles toward EVs, was presented in previous sections. Batteries, being the core technology of EVs, were introduced, and a variety of battery types were overviewed. Then, the importance of utilizing lightweight materials that offer high strength-to-weight ratios in the body structure of EVs, such as fiber-reinforced polymers as well as aluminum and magnesium alloys, and their benefits for improving the efficiency of EVs through increasing the driving range were highlighted. The significance of copper as one of the primary metals essential for various EV components, as well as the expected growth in its demand in the near future, were also discussed. Next, the importance of using AHSSs in the body-in-white of EVs to reduce weight while keeping safety requirements was emphasized, and different types of AHSSs were generally mentioned. After that, the discussion turned to the review of common forming and joining methods for manufacturing and assembling EV components. Subsequently, the importance of effective constructional design in EVs was pointed out, with a particular emphasis on strategically positioning battery packs for optimal weight distribution and safety issues. Finally, the discussion was concluded by highlighting the importance of responsible end-of-life actions, which included a focus on recycling or responsible disposal of EV components after their functional lifespan. The key points of the discussed content can be briefly summarized as follows:

Air pollution is a major health threat, and the transportation sector is a key contributor. EVs are seen as a solution, with lithium-ion batteries being the dominant choice due to their high energy density. However, widespread EV adoption relies on further advancements in battery technology, charging infrastructure, and even urban development planning to make EVs convenient and viable for consumers.

Copper stands as a vital material for EVs owing to its exceptional conductivity. However, careful considerations are imperative due to the escalating demand for EVs. Moreover, advanced materials such as AHSSs find application in the body structure of EVs, enhancing both performance and driving range while maintaining safety standards.

EV components made from AHSSs require precise forming and joining techniques to ensure a strong and lightweight body structure. Two major forming methods are hot stamping, which shapes ultra-high-strength steels without springback, and hydroforming, which uses fluid pressure to create complex structures. Primary welding techniques include RSW, recognized for its automation and cost-effectiveness, and LBW, known for its precision and application in battery and motor assembly. Both RSW and LBW are generally considered environmentally friendly, with minimal thermal effects and pollutants.

Unlike ICE vehicles, EVs require special design considerations. Battery packs are often installed low in the vehicle for better handling, weight distribution, and safety considerations. Lightweight materials like aluminum and carbon fiber composites contribute to increased driving range and overall efficiency. Additionally, AHSSs with optimized processing histories are usually used in the EV body structure for weight reduction. Aerodynamic design is also crucial for EVs in order to increase driving range.

The lifecycle of EV materials involves recycling or responsible disposal at the end of their service life. Metallic components are often recycled into new parts, while more complex components, such as batteries, need specific recycling procedures. Effective recycling reduces the environmental footprint, conserves resources, and can lower production costs. Effective material separation is vital for increasing recycling efficiency and maintaining the quality of recycled materials.

At this point, it is beneficial to briefly explore the future prospects of EVs and discuss strategies that can be used to overcome barriers and accelerate their widespread adoption. Despite the numerous benefits offered by EVs, some challenges still remain in their development and widespread adoption. The primary challenges can be referred to as charging infrastructure, charging time, battery cost and its performance, and the environmental impact of battery production [85]. Another important challenge could be the limited variety of EV models available to customers compared to the wide range of ICE vehicles. In other words, the variety of EV models available, particularly for trucks and sport utility vehicles (SUVs), is still not as broad as ICE vehicles, which limit consumer options and potentially slow down widespread adoption.

In the meantime, in parallel with the development of EVs, there are also alternative transportation concepts emerging in the automotive sector that are independent of fossil fuels as well. For instance, it can be referred to as hydrogen fuel cell EVs, which use hydrogen and oxygen to generate electricity through a fuel cell, with water vapor being the primary byproduct [86]. Another emerging technology includes solar-powered EVs, which are still in their early stages of development and aim toward implementing the application of solar panels to generate electricity and potentially expand the range and efficiency of EVs [87]. These technologies, along with other leading-edge advancements, are revolutionizing the transportation industry and will determine its future, not only for personal vehicles but also for public transportation.

In addition to private sector efforts and investments, governments are also investing in improvements to public transportation systems around the world to control air pollution and global warming. For instance, high-speed trains, magnetic levitation (maglev) trains, and bus rapid transit (BRT) systems offer efficient and environmentally friendly alternatives to traditional individual car ownership [88]. Properly using any of these alternatives has the potential to reduce reliance on private transportation in metropolitan areas and can potentially reduce traffic congestion and air pollution in large cities. In the meantime, establishing dedicated bike lanes could be considered one of the most advantageous strategies, as it offers not only health benefits for cyclists but also promotes environmental sustainability as bicycles emit zero emissions. Building a network of specialized bike lanes in large cities can encourage citizens to cycle for shorter commutes, while in smaller cities, it can make cycling the primary transportation option for the majority of the community.

In the end, it is important to note that tires play a crucial role in the overall performance of EVs, and EV tires are typically designed to address different requirements compared to those demanded in ICE vehicles. Given the high weight of EV battery packs, EV tires must be specifically engineered to support heavier loads and withstand the instant torque produced by EV motors. Moreover, to enhance energy efficiency, EV tires should have specialized tread patterns and materials that minimize rolling resistance. Additionally, since EV motors produce less sound compared to conventional car engines, noise reduction becomes more important in designing and producing EV tires.

In summary, EVs are a relatively new technology with ongoing development to improve their efficiency, range, and affordability. While using proper materials and constructional design are essential for their success, their widespread adoption also depends on factors like suitable charging infrastructure, government support, and consumer preferences. EVs are expected to play a significant role in the future of transportation, but the entire replacement of ICE vehicles with them is still a long-term vision.

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REFERENCES

1. Macharia V.M., Garg V.K., Kumar D. A review of electric vehicle technology: Architectures, battery technology and its management system, relevant standards, application of artificial intelligence, cyber security, and interoperability challenges. IET Electr. Syst. Transp. 2023; 13: e12083. https://doi.org/10.1049/els2.12083.
2. Manisalidis I., Stavropoulou E., Stavropoulos A., Bezirtzoglou E. Environmental and Health Impacts of Air Pollution: A Review. Front. Public Heal. 2020; 8. https://www.frontiersin.org/journals/public-health/articles/10.3389/fpubh.2020.00014.
3. Rigogiannis N., Bogatsis I., Pechlivanis C., Kyritsis A., Papanikolaou N. Moving towards Greener Road Transportation: A Review. Clean Technol. 2023; 5: 766–790. https://doi.org/10.3390/cleantechnol5020038.
4. Verma S., Mishra S., Gaur A., Chowdhury S., Mohapatra S., Dwivedi G., Verma P. A comprehensive review on energy storage in hybrid electric vehicle. J. Traffic Transp. Eng. (English Ed. 2021; 8: 621–637. https://doi.org/10.1016/j.jtte.2021.09.001.

5. Sun X., Li Z., Wang X., Li C. Technology Development of Electric Vehicles: A Review. Energies. 2020; 13. https://doi.org/10.3390/en13010090.
6. Satjabut P., Kalhor A., Uthaisangsuk V., Mirzadeh H. Microstructure and Mechanical Properties of Dual-Phase Steels by Combining Adjusted Initial Microstructures and Severe Plastic Deformation. Steel Res. Int. 2022; 93: 2100596. https://doi.org/10.1002/srin.202100596.
7. Lipman T.E., Maier P. Advanced materials supply considerations for electric vehicle applications. MRS Bull. 2021; 46:1164–1175. https://doi.org/10.1557/s43577-022-00263-z.
8. Adnan N., Nordin S.M., Rahman I., Vasant P.M., Noor A. A comprehensive review on theoretical framework-based electric vehicle consumer adoption research. Int. J. Energy Res. 2017; 4: 317–335. https://doi.org/10.1002/er.3640.
9. Mohanty A.K., Vivekanandhan S., Tripathi N., Roy P., Snowdon M.R., Drzal L.T., Misra M. Sustainable composites for lightweight and flame retardant parts for electric vehicles to boost climate benefits: A perspective. Compos. Part C Open Access 2023; 12: 100380. https://doi.org/10.1016/j.jcomc.2023.100380.
10. Wu M., Chen W. Forecast of Electric Vehicle Sales in the World and China Based on PCA-GRNN. Sustainability. 2022; 14. https://doi.org/10.3390/su14042206.
11. Li Y., Liang C., Ye F., Zhao X. Designing government subsidy schemes to promote the electric vehicle industry: A system dynamics model perspective. Transp. Res. Part A Policy Pract. 2023; 167103558. https://doi.org/10.1016/j.tra.2022.11.018.
12. Meissner E., Richter G. The challenge to the automotive battery industry: the battery has to become an increasingly integrated component within the vehicle electric power system. J. Power Sources. 2005; 144: 438–460. https://doi.org/10.1016/j.jpowsour.2004.10.031.
13. König A., Nicoletti L., Schröder D., Wolff S., Waclaw A., Lienkamp M. An Overview of Parameter and Cost for Battery Electric Vehicles. World Electr. Veh. J. 2021; 12. https://doi.org/10.3390/wevj12010021.
14. Manzetti S., Mariasiu F. Electric vehicle battery technologies: From present state to future systems. Renew. Sustain. Energy Rev. 2015; 51 1004–1012. https://doi.org/10.1016/j.rser.2015.07.010.
15. Jha M.K., Choubey P.K., Dinkar O.S., Panda R., Jyothi R.K., Yoo K., Park I. Recovery of Rare Earth Metals (REMs) from Nickel Metal Hydride Batteries of Electric Vehicles. Minerals. 2022; 12 (34). https://doi.org/10.3390/min12010034.
16. Kebede A.A., Kalogiannis T., Van Mierlo J., Berecibar M. A comprehensive review of stationary energy storage devices for large scale renewable energy sources grid integration. Renew. Sustain. Energy Rev. 2022; 159: 112213. https://doi.org/10.1016/j.rser.2022.112213.
17. Wen J., Zhao D., Zhang C. An overview of electricity powered vehicles: Lithium-ion battery energy storage density and energy conversion efficiency. Renew. Energy. 2020; 162: 1629–1648. https://doi.org/10.1016/j.renene.2020.09.055.
18. Zeng Y., Wu K., Wang D., Wang Z., Chen L. Overcharge investigation of lithium-ion polymer batteries. J. Power Sources. 2006; 160: 1302–1307. https://doi.org/10.1016/j.jpowsour.2006.02.009.
19. Lim H.D., Park J.H., Shin H.J., Jeong J., Kim J.T., Nam K.W., Jung H.G., Chung K.Y. A review of challenges and issues concerning interfaces for all-solid-state batteries. Energy Storage Mater. 2020; 25: 224–250. https://doi.org/10.1016/j.ensm.2019.10.011.
20. Basma H., Mansour C., Haddad M., Nemer M., Stabat P.A novel method for co-optimizing battery sizing and charging strategy of battery electric bus fleets: An application to the city of Paris. Energy. 2023; 285: 129459. https://doi.org/10.1016/j.energy.2023.129459.
21. Schneider J., Teichert O., Zähringer M., Balke G., Lienkamp M. The novel Megawatt Charging System standard: Impact on battery size and cell requirements for battery-electric long-haul trucks. ETransportation. 2023; 17, 100253. https://doi.org/10.1016/j.etran.2023.100253.
22. Nkembi A.A., Simonazzi M., Santoro D., Cova P., Delmonte N. Comprehensive Review of Energy Storage Systems Characteristics and Models for Automotive Applications. Batteries. 2024; 10. https://doi.org/10.3390/batteries10030088.
23. Iqbal M., Benmouna A., Becherif M., Mekhilef S. Survey on Battery Technologies and Modeling Methods for Electric Vehicles. Batteries 2023; 9. https://doi.org/10.3390/batteries9030185.
24. Kapustin N.O., Grushevenko D.A. Long-term electric vehicles outlook and their potential impact on electric grid. Energy Policy. 2020; 137: 111103. https://doi.org/10.1016/j.enpol.2019.111103.
25. Egbue O., Long S., Kim S.D. Resource Availability and Implications for the Development of Plug-In Electric Vehicles. Sustainability 2022; 14. https://doi.org/10.3390/su14031665.
26. Panchal C., Stegen S., Lu J. Review of static and dynamic wireless electric vehicle charging system. Eng. Sci. Technol. an Int. J. 2018; 21: 922–937. https://doi.org/10.1016/j.jestch.2018.06.015.
27. Lyu Y., Siddique A.R.M., Majid S.H., Biglarbegian M., Gadsden S.A., Mahmud S. Electric vehicle battery thermal management system with thermoelectric cooling. Energy Reports. 2019; 5: 822–827.

https://doi.org/10.1016/j.egyr.2019.06.016.

28. Thanigaitambi R., Ramesh S., Arulprakasajothi M., Devarajan Y., Sundaram M., Subbaiyan N. Thermal management using nano coated heat sink for electric vehicle battery cooling. Environ. Qual. Manag. 2023; 33: 139–148. https://doi.org/10.1002/tqem.21996.
29. Zhang N., Lu Y., Ouderji Z.H., Yu Z. Review of heat pump integrated energy systems for future zero-emission vehicles. Energy 2023; 273: 127101. https://doi.org/10.1016/j.energy.2023.127101.
30. Tucki K., Orynycz O., Dudziak A. The impact of the available infrastructure on the electric vehicle market in Poland and in EU countries. Int. J. Environ. Res. Public Health. 2022; 19. https://doi.org/10.3390/ijerph192416783.
31. Hemavathi S., Shinisha A. A study on trends and developments in electric vehicle charging technologies. J. Energy Storage. 2022; 52: 105013. https://doi.org/10.1016/j.est.2022.105013.
32. Huang C.L., Xu M., Cui S., Li Z., Fang H., Wang P. Copper-induced ripple effects by the expanding electric vehicle fleet: A crisis or an opportunity. Resour. Conserv. Recycl. 2020; 161 104861. https://doi.org/10.1016/j.resconrec.2020.104861.
33. Kalhor A., Rodak K., Tkocz M., Myalska-Głowacka H., Schindler I., Poloczek Ł., Radwański K., Mirzadeh H., Grzenik M., Kubiczek K., Kampik M. Tailoring the microstructure, mechanical properties, and electrical conductivity of Cu–0.7Mg alloy via Ca addition, heat treatment, and severe plastic deformation. Arch. Civ. Mech. Eng 2024; 24: 71. https://doi.org/10.1007/s43452-024-00890-0.
34. Li Y., Hu A., Fu Y., Liu S., Shen W., Hu H., Nie X. Al alloys and casting processes for induction motor applications in battery-powered electric vehicles: A Review. Metals (Basel). 2022; 12. https://doi.org/10.3390/met12020216.
35. Souza Filho I.R., da Silva A.K., Büyükuslu Ö.K., Raabe D., Springer H. Sustainable Ironmaking Toward a Future Circular Steel Economy: Exploiting a Critical Oxygen Concentration for Metallurgical Cu Removal from Scrap-Based Melts. Steel Res. Int. n/a 2024; 2300785. https://doi.org/10.1002/srin.202300785.
36. Nikolić I.P., Milošević I.M., Milijić N.N., Mihajlović I.N. Cleaner production and technical effectiveness: Multi-criteria analysis of copper smelting facilities. J. Clean. Prod. 2019; 215: 423–432. https://doi.org/10.1016/j.jclepro.2019.01.109.
37. Miller W.S., Zhuang L., Bottema J., Wittebrood A.J., De Smet P., Haszler A., Vieregge A. Recent development in aluminium alloys for the automotive industry. Mater. Sci. Eng. A. 2000; 280 37–49. https://doi.org/10.1016/S0921-5093(99)00653-X.
38. Morawiec M., Opara J., Grajcar A. Nanobainite formation in high-Al medium-Mn steels: thermodynamic approach. J. Therm. Anal. Calorim. 2024. https://doi.org/10.1007/s10973-024-13441-9.
39. Zhang M., Sun L., Liu Y., Feng Y., Xu N., Chen H., Wang Y.D. In-situ investigation of strengthening and strain hardening mechanisms of Cu-added medium-Mn steels by synchrotron-based high-energy X-ray diffraction. J. Mater. Res. Technol. 2023; 24 2952–2964. https://doi.org/10.1016/j.jmrt.2023.03.209.
40. Kalhor A., Karimi Taheri A., Mirzadeh H., Uthaisangsuk V. Processing, microstructure adjustments, and mechanical properties of dual phase steels: a review. Mater. Sci. Technol. 2021; 37: 561–591. https://doi.org/10.1080/02670836.2021.1944524.
41. Zhao J., Jiang Z. Thermomechanical processing of advanced high strength steels, Prog. Mater. 2018; Sci. 94, 174–242. https://doi.org/10.1016/j.pmatsci.2018.01.006.
42. Kalhor A., Soleimani M., Mirzadeh H., Uthaisangsuk V. A review of recent progress in mechanical and corrosion properties of dual phase steels. Arch. Civ. Mech. Eng. 2020; 20: 85. https://doi.org/10.1007/s43452-020-00088-0.
43. Soleimani M., Kalhor A., Mirzadeh H. Transformation-induced plasticity (TRIP) in advanced steels: A review. Mater. Sci. Eng. A. 2020; 795: 140023. https://doi.org/10.1016/j.msea.2020.140023.
44. Kozłowska A., Morawiec M., Petrov R.H., Grajcar A. Microstructure evolution of medium-manganese Al-alloyed steel manufactured by double-step intercritical annealing: Effects of heating and cooling rates. Mater. Charact 2023; 199: 112816. https://doi.org/10.1016/j.matchar.2023.112816.
45. Kozłowska A., Stawarczyk P., Grajcar A., Radwański K., Matus K., Samek L. Microstructure evolution and strain hardening behavior of thermomechanically processed low-C high-manganese steels: an effect of deformation temperature. Arch. Civ. Mech. Eng. 2023; 23: 184. https://doi.org/10.1007/s43452-023-00722-7.
46. Skowronek A., Grajcar A., Sozańska-Jędrasik L., Radwański K., Matus K., Opara J. Retained austenite grain size as a strength-plasticity relationship indicator in Al-alloyed medium-Mn steel processed by intercritical annealing. J. Mater. Res. Technol. 2023; 26: 3201–3213. https://doi.org/10.1016/j.jmrt.2023.08.114.
47. Li X., Ramazani A., Prahl U., Bleck W. Quantification of complex-phase steel microstructure by using combined EBSD and EPMA measurements. Mater. Charact. 2018; 142: 179–186. https://doi.org/10.1016/j.matchar.2018.05.038.
48. Zhang W., Xu J. Advanced lightweight materials for automobiles: A review. Mater. Des. 2022; 221: 110994. https://doi.org/10.1016/j.matdes.2022.110994.

49. An X.H., Lin Q.Y., Sha G., Huang M.X., Ringer S.P., Zhu Y.T., Liao X.Z. Microstructural evolution and phase transformation in twinning-induced plasticity steel induced by high-pressure torsion. Acta Mater. 2016; 109: 300–313. https://doi.org/10.1016/j.actamat.2016.02.045.
50. Wang K., Gui X., Bai B., Gao G. Effect of tempering on the stability of retained austenite in carbide-free bainitic steel. Mater. Sci. Eng. A. 2022; 850: 143525. https://doi.org/10.1016/j.msea.2022.143525.
51. Kozłowska A., Skowronek A., Grzegorczyk B., Grajcar A. Thermodynamic approach for designing processing routes of 4Mn quenching and partitioning steel. J. Therm. Anal. Calorim. 2024. https://doi.org/10.1007/s10973-024-13577-8.
52. Kaczmarczyk J., Grajcar A., Kozłowska A., Banuelos J.S.C., Opara J., Tatke N. Modelling of strain-induced martensite formation in advanced medium-Mn automotive sheet steel. Contin. Mech. Thermodyn. 2023; 35: 1841–1858. https://doi.org/10.1007/s00161-023-01202-2.
53. Czerwinski F. Current Trends in Automotive Lightweighting Strategies and Materials. Materials (Basel) 2021; 14. https://doi.org/10.3390/ma14216631.
54. Naderi M., Ketabchi M., Abbasi M., Bleck W. Analysis of microstructure and mechanical properties of different high strength carbon steels after hot stamping. J. Mater. Process. Technol. 2011; 211: 1117–1125. https://doi.org/10.1016/j.jmatprotec.2011.01.015.
55. Wróbel I., Skowronek A., Grajcar A. A review on hot stamping of advanced high-strength steels: technological-metallurgical aspects and numerical simulation. Symmetry (Basel). 2022; 14. https://doi.org/10.3390/sym14050969.
56. Skowronek A., Wróbel I., Grajcar A. Design, simulation and experimental evaluation of hot-stamped 22MnB5 steel autobody Part. Symmetry (Basel). 2022; 14. https://doi.org/10.3390/sym14122625.
57. Karbasian H., Tekkaya A.E. A review on hot stamping. J. Mater. Process. Technol. 2010; 210 2103–2118. https://doi.org/10.1016/j.jmatprotec.2010.07.019.
58. Bell C., Corney J., Zuelli N., Savings D. A state of the art review of hydroforming technology. Int. J. Mater. Form. 2020; 13: 789–828. https://doi.org/10.1007/s12289-019-01507-1.
59. Kucharska B., Moraczyński O. Exhaust system piping made by hydroforming: relations between stresses, microstructure, mechanical properties and surface. Arch. Civ. Mech. Eng. 2020; 20 141. https://doi.org/10.1007/s43452-020-00142-x.
60. Hartl C. Research and advances in fundamentals and industrial applications of hydroforming. J. Mater. Process. Technol. 2005; 167: 383–392. https://doi.org/10.1016/j.jmatprotec.2005.06.035.
61. Dong W., Lei M., Pan H., Ding K., Gao Y. Role of the internal oxidation layer in the liquid metal embrittlement during the resistance spot welding of the Zn-coated advanced high strength steel. J. Mater. Res. Technol. 2022; 21: 3313–3326. https://doi.org/10.1016/j.jmrt.2022.10.154.
62. Zhou K., Yao P. Overview of recent advances of process analysis and quality control in resistance spot welding. Mech. Syst. Signal Process. 2019; 124: 170–198. https://doi.org/10.1016/j.ymssp.2019.01.041.
63. Patel M., Shojaee M., Sherepenko O., Midawi A.R.H., Ghassemi-Armaki H., Biro E. Mitigating the influence of industrially relevant disturbances on LME severity of dissimilar resistance spot welded advanced high-strength steels. J. Mater. Res. Technol. 2023; 26: 22–31. https://doi.org/10.1016/j.jmrt.2023.07.176.
64. Xiao R., Zhang X. Problems and issues in laser beam welding of aluminum–lithium alloys. J. Manuf. Process. 2014; 16: 166–175. https://doi.org/10.1016/j.jmapro.2013.10.005.
65. Biswas A.R., Banerjee N., Sen A., Maity S.R. Applications of laser beam welding in automotive sector-A review BT-advances in additive manufacturing and metal joining. In: N. Ramesh Babu, S. Kumar, P.R. Thyla, K. Sripriyan (Eds.), Springer Nature Singapore, Singapore, 2023: 43–57.
66. Morawiec M., Rózański M., Grajcar A., Stano S. Effect of dual beam laser welding on microstructure-property relationships of hot-rolled complex phase steel sheets. Arch. Civ. Mech. Eng. 2017; 17: 145–153. https://doi.org/10.1016/j.acme.2016.09.007.
67. Grajcar A., Różański M., Kamińska M., Grzegorczyk B. Study on non-metallic inclusions in laser-welded TRIP-aided Nb-microalloyed steel. Arch. Metall. Mater. 2014; 59: 1163–1169.
68. Opiela M., Fojt-Dymara G. Effect of Non-Metallic Inclusions on the Hot Ductility of High-Mn Steels. Adv. Sci. Technol. Res. J. 2023; 17: 19–30. https://doi.org/10.12913/22998624/162702.
69. Pierri E., Cirillo V., Vietor T., Sorrentino M. Adopting a Conversion Design Approach to Maximize the Energy Density of Battery Packs in Electric Vehicles. Energies. 2021; 14. https://doi.org/10.3390/en14071939.
70. Arora S., Shen W., Kapoor A. Review of mechanical design and strategic placement technique of a robust battery pack for electric vehicles. Renew. Sustain. Energy Rev. 2016; 60: 1319–1331. https://doi.org/10.1016/j.rser.2016.03.013.
71. Kulkarni S.S., Hale F., Taufique M.F.N., Soulami A., Devanathan R. Investigation of crashworthiness of carbon fiber-based electric vehicle battery enclosure using finite element analysis. Appl. Compos. Mater. 2023; 30: 1689–1715. https://doi.org/10.1007/

s10443-023-10146-4.

72. Arora S., Kapoor A., Shen W. Application of robust design methodology to battery packs for electric vehicles: Identification of critical technical requirements for modular architecture. Batteries 2018; 4. https://doi.org/10.3390/batteries4030030.
73. Kumar S., Bharj R.S. Emerging composite material use in current electric vehicle: A review. Mater. Today Proc. 2018; 5: 27946–27954. https://doi.org/10.1016/j.matpr.2018.10.034.
74. Habrat W., Lisowicz J., Tymczyszyn J., Skroban A. simulation and experimental study of the termomechanical effect of the milling process of 7075 aluminium alloy. Adv. Sci. Technol. Res. J. 2024; 18: 58–66. https://doi.org/10.12913/22998624/185680.
75. Kalhor A., Mirzadeh H. Tailoring the microstructure and mechanical properties of dual phase steel based on the initial microstructure. Steel Res. Int. 2017; 88: 1600385. https://doi.org/10.1002/srin.201600385.
76. Khorasani F., Jamaati R., Jamshidi Aval H. Effect of intercritical annealing time on the microstructure and mechanical properties of dual-phase steel processed by large-strain asymmetric cold-rolling. Steel Res. Int. 2023; 94: 2300086. https://doi.org/10.1002/srin.202300086.
77. Siyahtiri A., Hossein Nedjad S., Hamed Zargari H., Ito K. Medium-carbon dual-phase steels with spheroidized ferrite matrix. J. Mater. Res. Technol 2024; 30: 4692–4701. https://doi.org/10.1016/j.jmrt.2024.04.184.
78. Czyż Z., Karpiński P., Koçak S. Numerical analysis of the influence of particular parts of the high efficient electric vehicle on the aerodynamic forces. Adv. Sci. Technol. Res. J. 2019; 13: 1–7. https://doi.org/10.12913/22998624/112835.
79. Sanguesa J.A., Garrido P., Martinez F.J., Marquez-Barja J.M. Analyzing the impact of roadmap and vehicle features on electric vehicles energy consumption. IEEE Access. 2021; 9: 61475–61488. https://doi.org/10.1109/ACCESS.2021.3072979.
80. Gao J., Hong X., Li Z. Optimization design of auto shell model structure, In: 2020 7th Int. Forum Electr. Eng. Autom., 2020: 958–961. https://doi.org/10.1109/IFEEA51475.2020.00201.
81. Afianto D., Han Y., Yan P., Yang Y., Elbarghthi A.F.A., Wen C. Optimisation and efficiency improvement of electric vehicles using computational fluid dynamics modelling. Entropy 2022; 24. https://doi.org/10.3390/e24111584.
82. Elwert T., Goldmann D., Römer F., Buchert M., Merz C., Schueler D., Sutter J. Current developments and challenges in the recycling of key components of (hybrid) electric vehicles. Recycling 2016; 1: 25–60. https://doi.org/10.3390/recycling1010025.
83. Harper G., Sommerville R., Kendrick E., Driscoll L., Slater P., Stolkin R., Walton A., Christensen P., Heidrich O., Lambert S., Abbott A., Ryder K., Gaines L., Anderson P. Recycling lithium-ion batteries from electric vehicles. Nature 2019; 575: 75–86. https://doi.org/10.1038/s41586-019-1682-5.
84. Wang L., Wang X., Yang W. Optimal design of electric vehicle battery recycling network – From the perspective of electric vehicle manufacturers. Appl. Energy 2020; 275: 115328. https://doi.org/10.1016/j.apenergy.2020.115328.
85. Kumar S., Usman A., Rajpurohit B.S. Battery charging topology, infrastructure, and standards for electric vehicle applications: A comprehensive review. IET Energy Syst. Integr 2021; 3: 381–396. https://doi.org/10.1049/esi2.12038.
86. Handwerker M., Wellnitz J., Marzbani H. Comparison of hydrogen powertrains with the battery powered electric vehicle and investigation of small-scale local hydrogen production using renewable energy. Hydrogen 2021; 2: 76–100. https://doi.org/10.3390/hydrogen2010005.
87. Reddy V.J., Hariram N.P., Maity R., Ghazali M.F., Kumarasamy S. Sustainable vehicles for decarbonizing the transport sector: a comparison of biofuel, electric, fuel cell and solar-powered vehicles. World Electr. Veh. J. 2024; 15. https://doi.org/10.3390/wevj15030093.
88. Janić M. Advanced transport systems. Springer, 2014.