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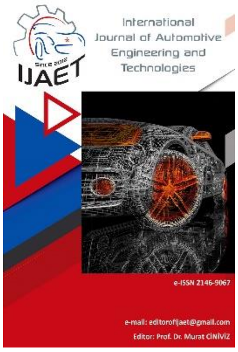

Review Article

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Investigation of changes in body-in-white components and their impact during the transition from internal combustion engine vehicles to electric vehicles

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ABSTRACT

In this study, the impact of improvements and modifications to the chassis framework components, referred to as the Body-in-White (BIW), during the transition from internal combustion engine (ICE) vehicles to electric vehicles (EVs) is examined. Additionally, the material requirements and structural differences compared to ICE vehicles are analyzed. In this context, the literature has been reviewed and presented in a structured flow. The battery requirement of EVs emerges as a factor that increases weight compared to internal combustion engine vehicles. Although advancements in battery technologies have improved the maximum driving range of vehicles, they remain insufficient on their own, necessitating additional efforts towards vehicle lightweighting. The integration of these lightweighting efforts with new technologies has paved the way for the development of new production methods and assembly techniques. Studies examining the compliance of evolving vehicle structures with safety standards, as well as the impact of weight reduction on vehicle emissions, highlight the necessity of addressing this transformation holistically. Therefore, this study investigates the body-in-white structures of vehicles produced by various manufacturers, closely analyzing the changes in materials, weight reduction, and safety considerations during the ICE to EV transition process. Furthermore, the new production methods—such as pressing, welding, and assembly technologies—that companies have integrated into their mass production lines to contribute positively to this transition process and weight reduction have become another focal point of research. These innovations in part manufacturing methods have also played a significant role in the evolution of the body-in-white concept during the ICE to EV transition.

Keywords: Body-in-White; Electrical Vehicle; Internal Combustion Engine; Light weight Design.

1. Introduction

The historical development of EVs can be traced back to the early 19th century. It is known that in 1828, Ányos Jedlik created a model car powered by a small electric motor, followed by Robert Anderson’s prototype electric car in 1832, which ran on nonrechargeable primary batteries and could reach a maximum speed of 12 km/h [1,2]. In 1835, Thomas Davenport produced an electric motor-powered vehicle, which is now considered a cornerstone in the history of electric vehicles [3].

Figure 1.1 Examples of early EVs (A: 1828 Jedlik design, B: 1832 Anderson design, C: 1834 Davenport DC motor) [4,5,6]

Following the development of the electric motor, the idea of using these motors to provide propulsion for vehicles emerged. Between 1897 and 1900, EVs outnumbered ICE vehicles, accounting for 28% of all cars [7]. These early vehicles allowed electric cars to be briefly more popular than fossil fuel-powered engines. However, the advancement of internal combustion engines and the easy access to petroleum caused EVs to fall largely into the background by the early 20th century. General Motors' release of the EV1 prototype in 1996 reignited hope for EVs, gaining significant popularity almost immediately [8]. Other major automakers, including Ford, Toyota, and Honda, also produced electric vehicles. The Toyota Prius, introduced to the Japanese market in 1997, became the world's first mass-produced hybrid electric vehicle (HEV) [9].

EVs have rapidly evolved into a growing global market. Significant progress has been made, particularly in EV powertrain technologies and energy efficiency, which are seen as key components of the evolution and transformation of these vehicles. This increase in efficiency has also been an important factor in extending the maximum driving range of the vehicle [10]. In addition to advancements in powertrain technologies and energy efficiency, improvements and modifications to the chassis framework components, known as the BIW, during the transition from ICE vehicles to BEVs, have been shown to have significant impacts on both road and battery efficiency. This study examines the effects of these systems, as well as the material requirements and structural differences compared to ICE-supported vehicles. The current range of steel used in vehicles addresses safety concerns in the front, side, and rear body designs. However, with evolving technological needs, the use of aluminum and magnesium has been steadily increasing. Furthermore, the development of plastics and composites in body design is encouraged, as they demonstrate good performance in pedestrian collision scenarios, opening the door to research into effective recycling solutions for these materials [11].

2. Materials and Methods

2.1 BIW concept and its role in the ICE to EV transition process

In the literature, BIW refers to the stage in automotive manufacturing where the body structure is assembled before the installation of components such as the engine, chassis, and other subsystems. It is also referred to as the "white body" or "unpainted body" process. This phase involves methods like assembly, welding, riveting, and laser brazing to form the vehicle body [12].

Figure 2.1 BIW design and monocoque structure [12]

As the primary load-bearing structure, the BIW constitutes a significant portion of the vehicle's weight. Reducing BIW weight contributes directly to the overall mass reduction of vehicles. The BIW is a highly complex and extensive system, so its design must take into account various disciplines, such as structural durability, stiffness, noise, vibration, and safety performance. The traditional body design process, including both preliminary and technical design phases, is often complex. During the transition from ICE to BEVs, the automotive industry faces two major challenges:

1. Meeting safety standards
2. Reducing emissions, improving fuel efficiency, and controlling pollution

While some advancements have been made in battery, motor, and control technologies, development continues in light of technological progress. In this context, automotive lightweighting has emerged as an effective and relatively straightforward solution to address these challenges. Lightweight vehicles have taken a prominent position in 21st-century automotive technology development and have become a hot topic of research [13].

Reducing vehicle weight has become a key area of research in the automotive industry. To lower development costs and shorten the time-to-market for new vehicles, it is crucial to optimize BIW design during the concept design phase [14].

In this context, vehicle chassis components are typically divided into three main sections:

1. Front engine compartment
2. Passenger cabin
3. Rear trunk

Each section has its own specific purpose and characteristics. The BIW is produced using sheet metal, which is shaped into the desired form and then joined using spot welding. The resulting structure is highly rigid, and since it operates as a unified system, it is referred to as a monocoque. The monocoque distributes the dynamic loads of normal vehicle operations across its entire surface, making it a highly intricate structure. In the event of a crash, the monocoque transfers forces through side rails or lateral elements to the base and roof structures. In modern vehicles, the engine compartment is used as a crumple zone, designed to absorb energy during a collision and slow down the vehicle [15]. The objectives that automakers aim to achieve as part of the BEV transition can be examined under key themes.

2.2 Meeting safety standards

The expectations from safety regulatory bodies, such as the U.S. National Highway Traffic Safety Administration (NHTSA), the European Safety Council, and other safety oversight organizations, are that vehicles continue to be built in a way that ensures greater safety for passengers. At the same time, automakers are increasingly focused on enhancing the safety of travel. One of the challenges faced by manufacturers of BEVs is protecting the battery with minimal weight increase due to its addition. Typically placed in the lowest part of the vehicle, the battery pack must be shielded from all potential leaks while also maintaining thermal stability in the event of a crash, as any breach could pose a serious fire hazard [16]. In terms of vehicle body designs, the front and rear sections of electric vehicles exhibit several differences when compared to ICE vehicles. These differences can vary depending on the production platform, brand, and model of the vehicle. At the core of these differences are crash tests conducted to ensure safety and the structural integrity of the vehicle body. EVERSAFE conducted frontal crash tests on two first-generation vehicles (Volvo C30 and Toyota Yaris), examining how differences in the design of the front bumper impact vehicle safety.

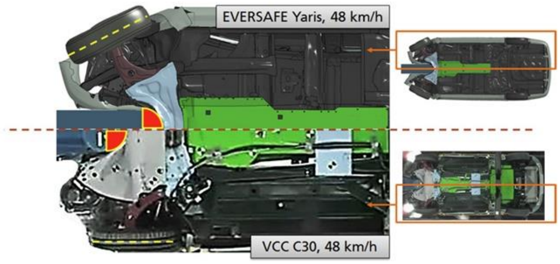

Figure 2.2 Eversafe front crash test (Top: Toyota Yaris, Bottom: Volvo C30) [16]

As part of the test, both vehicles crash into a fixed barrier at a speed of 48 km/h, with the impact directed at the center of the vehicle. Since first-generation EVs were the initial transition from ICE vehicles, their body compositions had significantly more similarities with ICE vehicles compared to the current generation of EVs. Many of these early EVs still had a transmission tunnel underneath the vehicle, and their BIW structures remained largely unchanged. According to this crash test, first-generation EVs converted from ICE vehicles failed to provide adequate stabilization in the front area. The absence of powertrain components and the engine block, which are present in ICE vehicles, resulted in increased deformation. When comparing the two vehicles, it was observed that the front bumper and attached components of the Volvo C30 more effectively transmitted the impact force. This finding indicates that the front bumper designs in EVs need to be improved to enhance protection for the centrally located battery within the vehicle body [16].

2.3 Reducing emissions, fuel efficiency and pollution control

To combat climate change, the Paris Climate Agreement was established in 2015 with the goal of reducing global warming. One approach to lowering greenhouse gas (GHG) emissions is the adoption of BEVs. This can decrease emissions per kilometer by up to 40% when renewable energy is used to power BEVs during their operational phase [17].

Vehicles, particularly in countries where demand for automobiles is growing, are among the most polluting sources globally. Since 2000, China has experienced a rapid increase in automobile usage, reaching a growth rate of 17.5% [18]. Reducing fuel consumption is the only way to control GHG emissions, as 97% of automobile-related GHG emissions stem from the combustion process, which is directly tied to fuel consumption [19].

Figure 2.3 above illustrates the fuel consumption pathways and the outcomes of vehicle technologies for mid-sized sedans. The current technology assesses fuel production and vehicle technologies using existing raw materials and process fuel mixes. Future technologies, on the other hand, represent advanced powertrain technologies and low-emission fuel pathways. In this context:

Black Line: The GHG emissions associated with current technology for the respective pathways.

Red Line: Projected future vehicle efficiency gains. The fuel economy improvement estimates are based on the adoption of advanced vehicle and powertrain technologies within the 2030-2035 timeframe. For electric vehicles, this line represents the state of a vehicle using the U.S. electric grid mix in 2035 with projected future technology gains.

Blue Line: The GHG emissions associated with the production of future technology vehicles, amortized over the vehicle's lifetime. This represents the lifecycle GHG emissions from vehicle manufacturing, assuming the vehicle operates at 0 gCO_2e/mile fuel. The vehicle production assumptions here use baseline assumptions for the electric grid mix, materials, and vehicle production practices from the GREET model, and do not consider additional solutions such as electrification or the use of low-carbon fuels for vehicle manufacturing decarbonization.

Downward Arrows: Potential GHG emissions reductions from low-carbon fuels and electricity in addition to vehicle efficiency gains. The gap between the arrows and lines can be considered the lifecycle emissions associated with fuel cycles or vehicle operation [20].

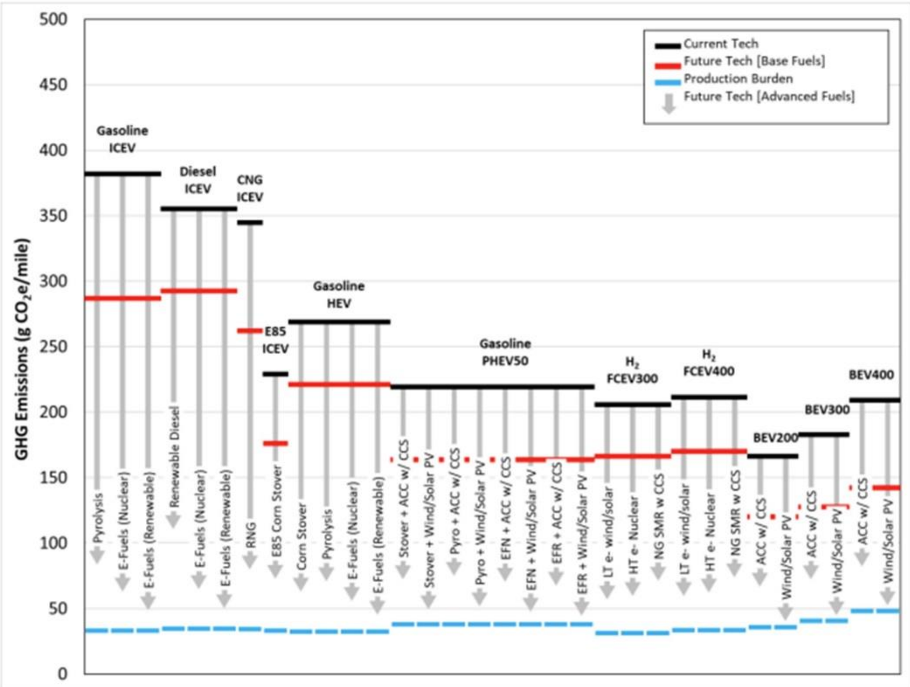

Figure 2.3 Fuel consumption rates for mid-sized sedans according to technological developments [20]

The use of lightweight BIW structures produced from aluminum and advanced high-strength steel, which are increasingly employed in the transition from internal combustion engines to electric vehicles, significantly reduces greenhouse gas emissions. Furthermore, the utilization of aluminum in BIW contributes to substantial reductions in life cycle energy consumption and greenhouse gas emissions, while advanced high-strength steels achieve greater energy savings per unit mass [21]. The substitution of steel with aluminum in automotive bodies demonstrates significant potential for increasing energy efficiency and reducing CO_2 emissions [22]. However, the adoption of aluminum in the automotive industry faces several challenges, including high material costs, the design of safety structures, advanced manufacturing technologies, and supply chain issues [19].

2.3.1 Vehicle dynamics

Vehicle dynamics and behavior are among the characteristics significantly influenced by vehicle weight on performance. Many driving parameters, such as cornering stability, responsive suspension, high-speed stability, acceleration, and braking, are directly dependent on the vehicle's weight [23]. Also, the total vehicle mass has a direct impact on performance by increasing inertia, contributes to environmental effects by accelerating tire and road wear, and affects fuel efficiency due to the higher engine load [24]. Vehicle longitudinal dynamics describe the movement and response of a vehicle along its longitudinal axis. This motion encompasses various factors, including acceleration, deceleration, velocity, position, and the forces influencing the vehicle's behavior [25].

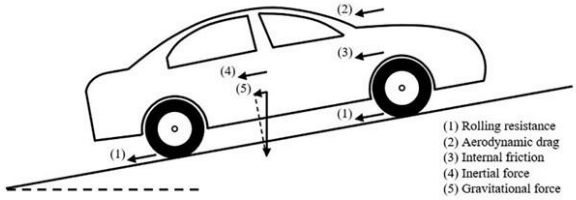

Figure 2.4 Illustration of the different factors affecting vehicle driving resistance [25]

The total tractive force Ft is given by:

$$F_t = F_r + F_a + F_d + F_g \quad (1)$$

In this equation Ft represents total tractive force(N) which sum of F_r rolling resistance force (N) , F_a acceleration resistance force (N), F_d aerodynamic drag force (N) and F_g gravitational force(N)

The rolling resistance at the wheels, is given by:

$$F_r = f \times m \times g \quad (2)$$

Where m represent vehicle mass (kg) and g represent acceleration due to gravity (m/s^2)

The acceleration resistance is given by:

$$F_a = m \times a \quad (3)$$

Where a represent vehicle acceleration (m/s^2)

The aerodynamic drag, is given by:

$$F_d = {}^1/_2\, C_D \times p_{air} \times v^2 \times A \quad (4)$$

Where C_D represent drag coefficient, p_{air} represent air density (kg/m^3), v represent vehicle speed (m/s) and A represent vehicle frontal area (m^2)

Gravitational force is given by;

$$F_g = m \times g \times sin\,(\alpha) \quad (5)$$

Where α represent road grade(°)

Rolling resistance coefficient is given by:

$$f = a + bv + cv^4 \quad (6)$$

In equation (6), the coefficients usually have the following values for passenger car tire [26]:

$a = 0{,}4$

$b = 2{,}5 \times 10^{-5}$

$c = 3{,}5 \times 10^{-10}$

The previous equations clearly indicate that the primary sources of resistance are directly dependent on the mass (m).

This situation leads to improved damping characteristics in roll motions, thereby benefiting driving dynamics. With reduced weight, inertial masses decrease during rolling and yawing movements, positively affecting steering control and the vehicle's overall handling behavior [27].

2.3.2 Passive Safety

Weight reduction through material substitution and compact packaging has significant effects on safety [28]. Detailed CAE (Computer-Aided Engineering) analyses Noise, Vibration, and Harshness (NVH), crash tests, and the durability of structures demonstrate the safety of lightweight structures [29]. Passive safety systems are activated when a crash becomes inevitable. Honeycomb structures have provided lighter and much safer options for advanced vehicles. These structures can be made from aluminum and various thermoplastic materials. The application of honeycomb structures depends on the required level of safety and whether they are used on the exterior or interior of the vehicle. As illustrated in Figure 2.5 below, the use of honeycomb structures clearly shows the advantage of absorbing a large portion of the impact energy [30].

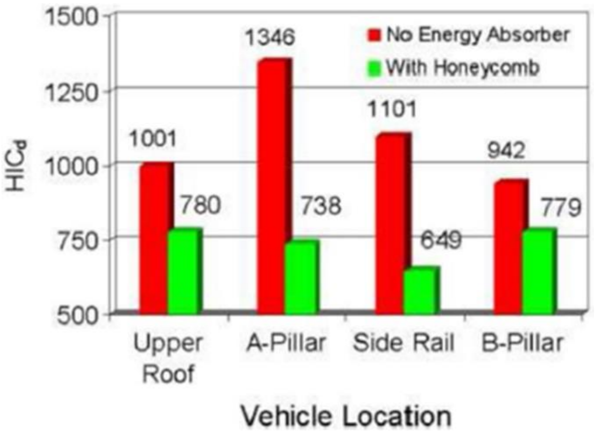

Figure 2.5 Impact absorption responses of honeycomb structures based on vehicle chassis regions [30]

A lightweight material not only reduces the weight of the BIW but also minimizes the risk to both the occupants inside and those around the vehicle [31]. The BIW structure, designed with multi-material usage, has enhanced performance while successfully reducing both weight and cost. By combining aluminum extrusions, castings, and steel press-formed parts, the structure maximizes stiffness while minimizing weight. The selection of multiple materials in BIW manufacturing offers the best optimization in terms of material cost and strength, rather than choosing a single material for the entire body [32]. The adoption of a multi-material approach has led to a 35% reduction in vehicle body weight [19].

2.4 Weight reduction and BEV material usage

Weight reduction in automotive research is not only limited to conventional fossil fuel vehicles but also extends to the rapidly developing electric and FCEV [19]. In recent years, numerous studies on lightweight automotive body components and BIW structures have been conducted and published. Many of these studies have shown excellent potential for reducing mass while maintaining performance. Achieving significant weight reductions in vehicle packaging, while preserving safety and performance, requires substantial changes in the body assembly and paint workshops. To avoid multi-material joints and galvanic corrosion issues, material selection in the design of lightweight vehicle BIW structures is typically limited to a single material, leading to "all-steel" or "all-aluminum" designs [33]. To keep the processing methods as simple as possible and the final product prices as low as possible, special high-strength steels began to be developed in the last decades of the 20th century. Compared to conventional steel, these new materials have much higher strength and meet the required levels for cutting, forming, and weldability [34]. In this context, the percentage of hot-stamped components in BIW structures is steadily increasing. A clear example of this trend can be observed in the evolution of Volvo's BIW design. In 2002, only 7% of the first-generation XC90 SUV was made from hot-stamped steel; these components were particularly used in the B-pillars and bumper beams. By 2015, this figure had risen to 38% in the second-generation XC90, with more parts being produced using Ultra High Strength Steel (UHSS). In 2015, around 360 million hot-stamped steel parts were produced, representing a significant increase from the 124 million parts produced in 2010 [35].

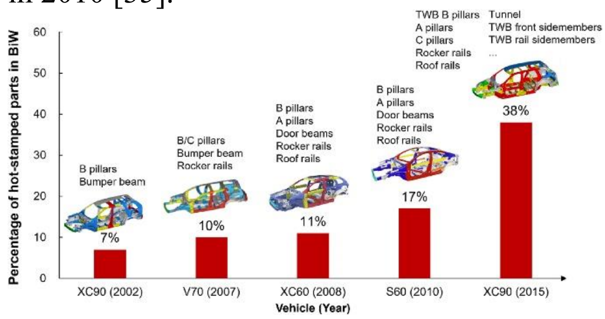

Figure 2.6 Use of hot-stamped components in Volvo [35]

The rise of BEVs represents another factor in the growth of the hot stamping market. Due to the weight of the battery itself and the increasing demand for the protection of the battery pack, the curb weight of a typical BEV is approximately 10% higher than that of an internal combustion engine vehicle [36]. This increases the need for weight reduction, making hot stamping a more prominent option for BEVs. According to a recent report, automaker Hyundai Motors uses hot-stamped steel in approximately 15% of all steel components in its internal combustion engine vehicles, while this figure rises to 20% for electric vehicles. With the growing need for lightweight solutions in automobile manufacturing, third-generation advanced high-strength steels (AHSS) have been introduced. The design of 3rd Generation AHSS provides both exceptional mechanical properties such as strength and ductility at reduced thickness while maintaining superior safety standards compared to the first-generation AHSS. Additionally, these steels overcome issues such as the high costs associated with using large amounts of alloying elements and the decreased weldability observed in second-generation AHSS. A notable type among these steels is MMn steels, which contain approximately 3-12% Mn, 0.05-0.6% C, 0-3% Si, and 0-6% Al [35]. A lightweight material not only reduces the weight of the BIW but also minimizes the risk for both the passengers inside and those around the vehicle [31]. The BIW structure, designed using multiple materials, has enhanced performance while successfully reducing both weight and cost. By utilizing a combination of extrusion, casting, and pressed aluminum and steel parts, stiffness has been maximized, and weight has been minimized. Selecting multiple materials for BIW production provides the best optimization in terms of material cost and strength, rather than using a single material for the entire body. The use of a multi-material approach has resulted in a 35% reduction in the vehicle body's weight [19].

The use of aluminum in the automotive industry has steadily increased over the years. In the North American market, the use of aluminum per vehicle increased from 154 kg in 2010 to 208 kg in 2020, and it is expected to reach 258 kg by 2030. This increase is primarily due to the growing use of aluminum in areas such as BIW, closures, and chassis components [37].

It is particularly observed that the use of aluminum (alloy, casting, extrusion) and hybrid metals is becoming increasingly widespread. While the use of soft metals is decreasing, the utilization of AHSS steel and composite materials is on the rise.

According to a statement by the World Steel Association (WSA), the types of steel used in BEVs vary depending on technology and needs. It is predicted that in future EVs, 48% of the steel used will be next-generation materials with over 1000 MPa, which will directly impact production methods, and the equipment used [38]. In terms of weight reduction using steel and aluminum materials, the use of hydroformed structures and Tailored Blanks has been shown to provide a 25% weight reduction compared to a standard vehicle. Additionally, lightweight aluminum usage offers a 50% weight reduction [39].

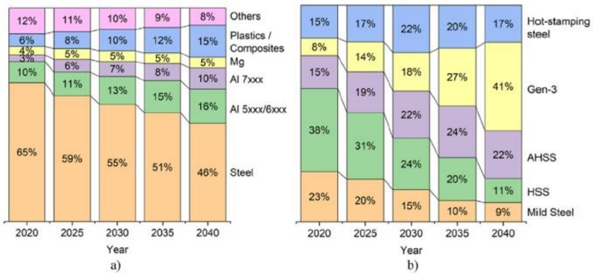

Figure 2.7 General materials used in BIW(a) and the ratio of steel materials over the years (b) [35]

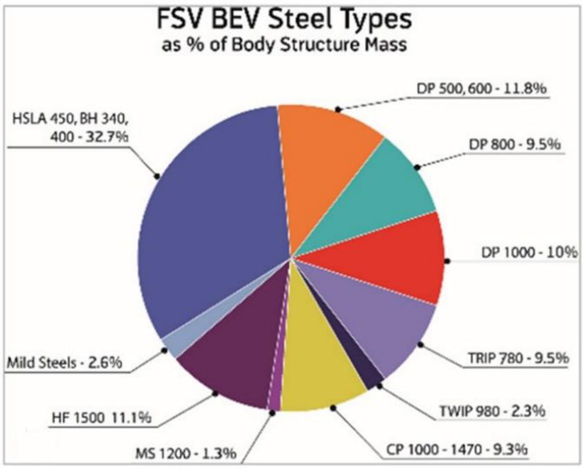

Figure 2.8 Steel types used in BEVs [38]

Studies have explored carbon fiber parts and carbon fiber-reinforced polymers to provide ultra-lightweight solutions, enhance crash performance, and achieve better acoustic properties [40]. The use of polymeric materials, despite a 14% cost increase, has reduced weight by 51% and improved performance by 10%. Carbon Fiber Reinforced Polymer (CFRP) has been successfully investigated for application in lightweight body structures for electric vehicles. The microstructure model of carbon fiber fabric has been examined, and the properties in each axis have been defined. These properties were then applied to the Finite Element Analysis (FEA) package, and the entire body structure was analyzed under various loading and impact conditions, resulting in improved crash resistance. This CFRP structure achieved 28% weight savings compared to Glass Fiber Reinforced Polymer [19].

3.Results and Discussion

3.1. Transition from ICE to BEV platforms

The transition from ICE platforms to BEVs has presented challenges, particularly around battery protection. Passenger safety has always been a priority that drives the scope of engineering improvements. Continuous development has been an ongoing effort across various areas of the vehicle, from the advancement of AHSS for structural components to specially designed crumple zones and airbags.

The addition of batteries in BEVs has introduced the need to protect the battery pack from both overheating and intrusion. Although each automaker has developed its own unique approach, most have positioned the batteries in modules and placed them at the lowest level of the vehicle. Automakers have focused their efforts on reducing the risk of intrusion and crashing in the event of an accident. Manufacturers have implemented various design improvements in line with these primary objectives during the BEVs transition process.

3.1.1 EV body front-end modifications

According to the figure above, 6000 series aluminum extrusion plates are used in region 1, while AHSS is applied in regions 3 and 4. At this point, the modifications made to the front provide a 10% deformation advantage during a collision compared to an ICE vehicle. The front bumper beam has been extended laterally (along the Y-axis) and its cross-sectional width has increased compared to ICE vehicles. Collision boxes have been added to the front bumper attachment to reduce impact during a crash. The connection parts between the front bumper and the upper body have been extended to increase load transmission. Bolt connections have been added to the front door hinge pillar to increase load capacity [41].

One of the efforts to minimize the impact of damage in the front-end sections of ICE and BEVs has been to increase the number of front bumper support barriers. This application has been implemented on the Volvo XC40 model.

Figure 3.1 Ford Mustang Mach-E front support component modifications [41]

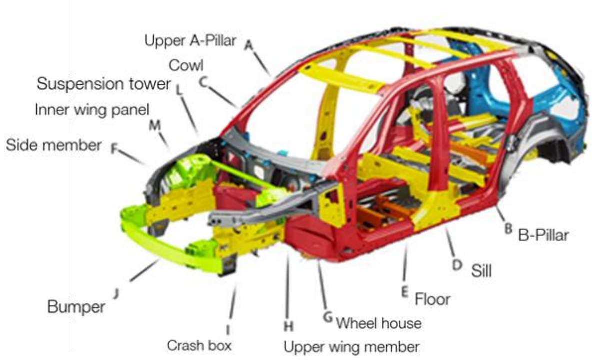

Figure 3.2 Volvo XC40 BIW Representation [10]

Three innovations stand out when compared to ICE vehicles. The front bumper support group extended using aluminum extrusion, the AHSS steel connection group establishing a link between this group and the vehicle's lower chassis frame, and the aluminum extrusion connection brackets. As part of the studies conducted, there are other investigations that directly affect both the vehicle's range and weight.

Figure 3.3 Magnesium alloy cross bar production via die casting method [42]

The example of a magnesium cross bar produced by "GF Casting Solutions" using the die casting method is shown in Figure 4.3 above. Magnesium alloy provides a lightweight advantage of 37% compared to aluminum [42].

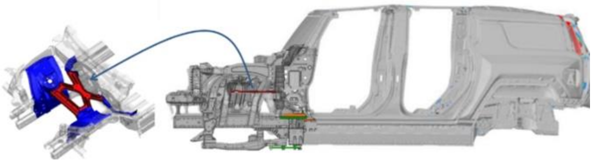

Figure 3.4 Addition of front support bracket for GM

Hummer BEVs [42]

GM has added a "K bracket" in the vacant area on the front engine side of the ICE to enhance the front strength of the Hummer BEV model. This not only provides support for the trunk located at the front of the BEV but also acts as a shock absorber, reducing the impact that may reach the front panel on the driver's side [42].

3.2. EV body mid-side body modifications

Within the scope of BEV, particularly considering impact resistance, side impacts pose a greater threat to the battery group compared to the front and rear sections of the vehicle. New methods and designs that combine lightweight with robustness and safety elements are being applied to vehicles by manufacturers. The traditional material used in the B-pillar of a lightweight utility vehicle is low-carbon steel, which offers strong safety performance at a relatively low material cost. However, steel can be heavy compared to lightweight composites and metals, leading to higher fuel consumption during vehicle operation. Opportunities for reducing the weight of the B-pillar involve replacing steel with alternative materials such as advanced high-strength steel, fiber-reinforced polymer composites, and aluminum [43].

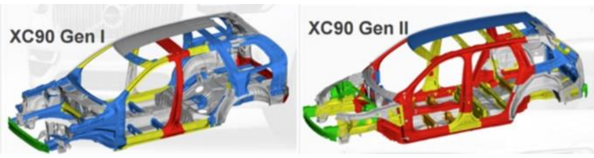

Figure 3.5 Volvo XC90 ICE B-Pillar replacement [10]

Volvo has implemented Tailor Welded material in the Center pillar component of the XC90 vehicle, which is equipped with an internal combustion engine, in its second-generation body design. Sheets with different material properties and thicknesses have been combined to form the B-pillar. This method is also applied in the XC40 model, which is the first-generation EV model.

Audi has implemented a "soft zone" application on the B-Pillar. In this application, the base of the 1500 MPa hot-pressed B-pillar body is made of 550-650 MPa AHSS steel. Due to its ability to dampen side impacts and the weight reduction in the relevant part, this design is also planned for use in future BEVs [44].

Ford has utilized 1500-1700 MPa three-part martensitic roll-formed sheet material in the Mach-E model. This material is connected to the main body using a bolt connection method, positively contributing to energy damping. Additionally, to achieve both lightness and strength, vehicle manufacturers are applying the aluminum extrusion method [41].

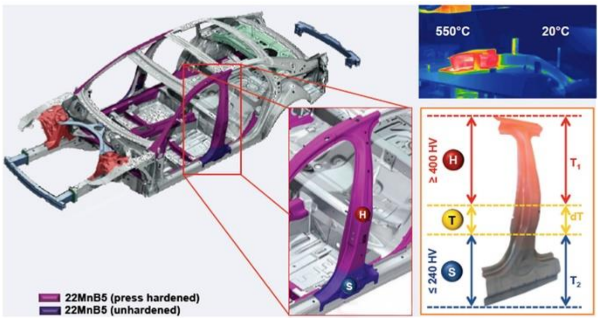

Figure 3.6 Audi soft zone B-Pillar [44]

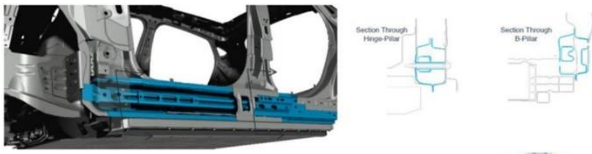

Figure 3.7 Ford Mach-E Rocker design changes [41]

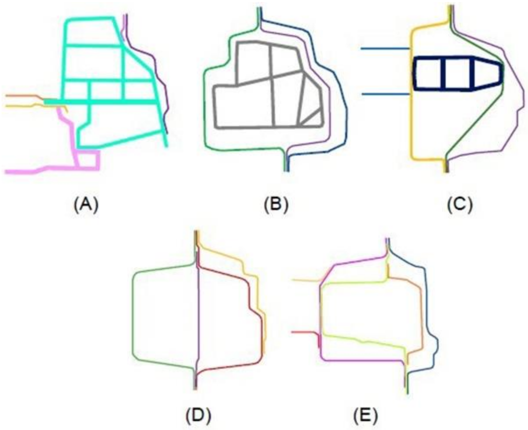

Figure 3.8 BEVs Rocker designs [45]

The above image shows the schematic representations of aluminum extrusion panels used as vehicle rocker panels. The structures indicated by A, B, and C represent multi-chamber aluminum extrusion structures, while D and E illustrate sheets with different thicknesses and strength values that are pressed together. In the component development studies, analyses have shown that the rocker part is examined in two main sections: energy damping and battery protection, depending on the manufacturing method. The homogeneity of structures in aluminum extrusion and the ability to alter pore numbers through design changes provide advantages for vehicle manufacturers. Additionally, the combination of different sheets with various thicknesses and strengths to create damping and protection layers is seen as a continuation of the ICE production method. However, regardless of the method applied, the primary goal is to achieve maximum lightness in the vehicle while ensuring safety [45].

3.3. EV body floor structure modifications

During the transition from ICE to BEV, one of the most notable changes in vehicle body components occurs in the central floor section. With the removal of the driveshaft tunnel in 2nd-generation EVs, which was present in 1st-generation EVs, battery and battery pack designs are playing an increasingly active role in ensuring the structural integrity of the vehicle body.

Figure 3.9 Vehicle floor structure design (Left: Monocoque body, Center: Body-on-frame, right: Skateboard architecture) [12,46,47]

As battery designs have evolved, the vehicle's floor structure has also undergone significant changes. The use of a skateboard-type frame structure has become more prevalent between 1st- and 2nd-generation BEVs. Brands such as Audi e-tron, Nissan Leaf, Chevrolet Bolt, Tesla Model S, and Jaguar I-Pace have started adopting this method as part of their battery protection strategies. Various design modifications have been implemented by manufacturers to integrate the battery into the vehicle and ensure its safety [48].

The most significant difference in the design of the Jaguar I-Pace is the use of a front bumper support block with a 45-degree angled structure, compared to the 90-degree connection to the main body in ICE vehicles. This block also houses the torque box. At the rear, a similarly angled body design helps to evenly distribute the shock across the body in the event of a crash. The rear torque box is integrated into the system from the area indicated in section 2 of the figure. Additionally, the side rocker panels are broader in design.

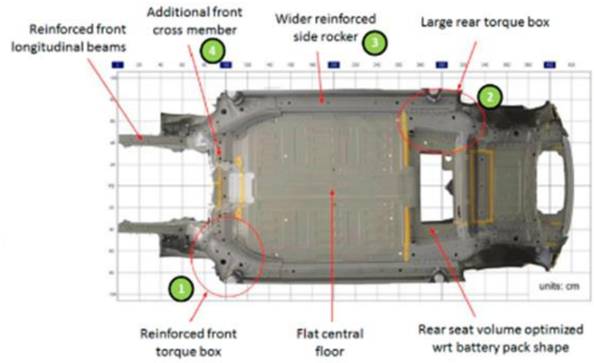

Figure 3.10 Jaguar I-Pace floor structure (Left: ICE, right: BEVs) [48]

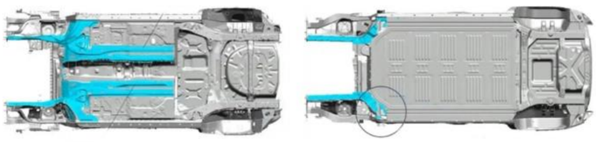

Figure 3.11 Ford Mach-E ICE-BEVs floor structure comparison [41]

The floor geometry used in the Jaguar I-Pace model is also observed in the Ford Mach-E model. The front support panels connect to the rocker panel by enclosing the torque box in a monoblock structure.

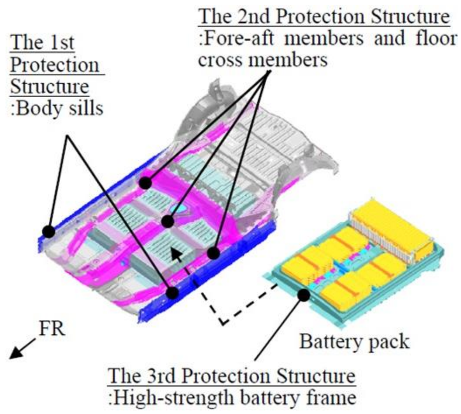

Figure 3.12 Central floor structure connections [49]

When examining the central floor structure connections, it can be seen that protective cross members made of UHSS steel surround the battery. In addition to these connections, the rocker design is also optimized to provide a protective layer for the battery pack. In vehicles with internal combustion engines, the floor structures typically use 600-980 MPa steel sheets; however, for battery protection, these have been replaced with lighter yet stronger 1300-2000 MPa steel materials.

Since 2019, VW's electric vehicle ID.3 has featured two seat cross members made from MBW 1900 steel, as seen in Figure 4.13. These components are part of the MEB platform (Modularer E-Antriebs-Baukasten) and can be used in other electric vehicles in the VW Group. MBW 1900 is the trade name for a press-hardened steel with a tensile strength of 1900 MPa. A properly designed MBW 1900 B-pillar can provide 22% weight savings compared to a Dual-Phase (DP) 600 design and is 9% less costly than the original Dual-Phase design [51].

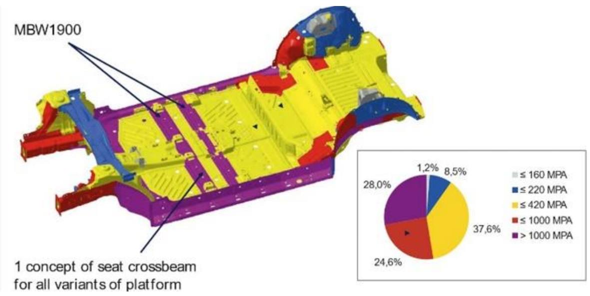

Figure 3.13 Sheets used in the Volkswagen ID.3 platform's floor structure [50]

Ford has also demonstrated that using MBW 1900 instead of PHS 1500 can lead to 15% more weight savings [52]. In line with the design of 2nd-generation BEVs, alternative materials have also been tested in the top and bottom protective plates of battery packs. While 1st-generation BEVs used soft steel battery pack plates, the increasing need for safety and vehicle integrity has shown that Dual-Phase steels make much more positive contributions in 2nd-generation BEVs.

3.4 Production Methods

Advancing technology has positively contributed to the change in manufacturing methods of vehicle chassis parts during the transition from ICE vehicle to BEVs. Some of these methods include aluminum casting, mega casting, patchwork, and new laser welding methods.

3.4.1 Aluminum casting

Aluminum is one of the three most widely used metals in modern society due to its excellent properties such as lightness, good electrical and thermal conductivity, high strength, corrosion resistance, and easy machinability. Aluminum is often alloyed with other elements [53]. Over the past decade, studies aimed at energy savings have revealed that the production of light and economical vehicles plays a significant role in reducing fuel consumption. Aluminum alloys are widely preferred in the construction of passenger cars, buses, and especially maritime applications such as trains [54]. Casting aluminum alloys is quite common and are increasingly finding more applications in modern industry. According to various estimates, 20-30% of all aluminum products produced worldwide are used as aluminum castings [55]. With CO2 emissions becoming a significant issue in the automotive sector, the properties of aluminum alloys, such as energy and fuel savings, as well as lightness, have been emphasized. The largest volume of aluminum components in vehicles includes cast aluminum for engine blocks, cylinder heads, and chassis parts [56]. New aluminum casting techniques offer improved material properties and functional integration to meet the desired requirements. This trend is driven by the need for automotive manufacturers to significantly reduce the weight of powertrain and chassis components. Additional features to improve vehicle performance may lead to an unacceptable increase in vehicle weight [57]. Significant weight reduction can be achieved in smaller but high-volume compact vehicles through the use of aluminum casting, which is already widely used in high-end car engines [56].

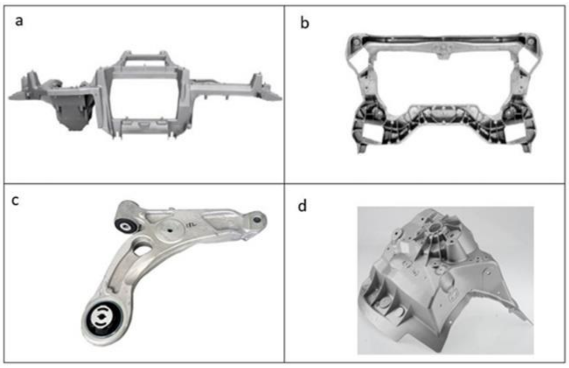

Figure 3.14 Examples of aluminum cast structural parts: cross car beam (a), engine cradle (b), control arm (c), shock tower (d) [58]

Since 1997, high-vacuum aluminum casting technology, which provides weight savings, has been applied in vehicle body structures despite increasing vehicle weights due to market forces beyond fuel economy. Using lightweight aluminum casting technology for net weight reduction is likely to contribute significantly to fuel economy at a reasonable cost. The wider application of aluminum castings and the weight savings achieved through best design practices have been demonstrated in the MMLV (Multi-Material Lightweight Vehicle) program. The MMLV body structure was a good engineering exercise in using commercially available different structural materials, forming operations, and joining techniques for engineers. Overall, high-pressure vacuum aluminum castings offer the possibility of lower mass, part integration, and fewer assembly processes [59].

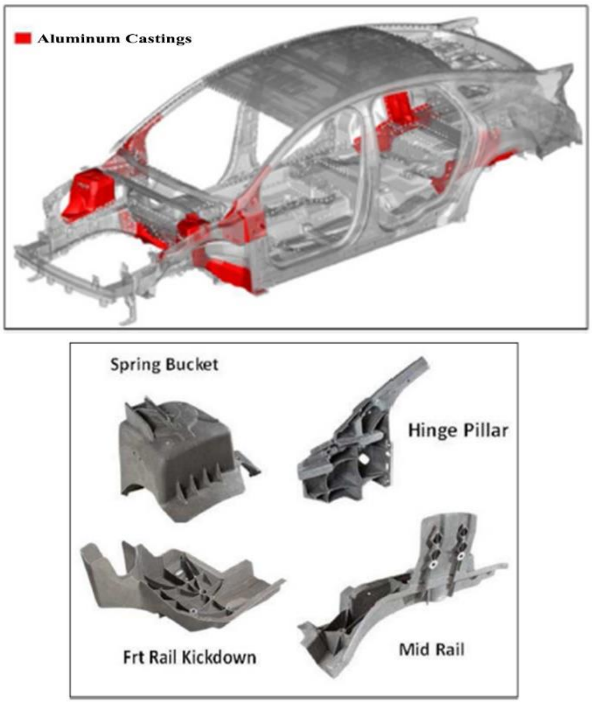

Figure 3.15 MMLV body aluminum casting parts [33]

The eight castings in the MMLV consist of the front shock tower, hinge pillar, kick-down rail, and rear mid-rail castings on the left and right sides. Most of the aluminum castings in the MMLV are mechanically joined to steel materials using a structural adhesive. The most commonly used method for such connections is SPR (Self-Piercing Rivets).

Figure 3.16 Example of a SPR [33]

SPR is a cold mechanical joining process in which a rivet passes through the top sheet or both the top and intermediate sheets and locks into the bottom sheet with the help of a suitable die. SPR is currently the primary method used in the assembly of lightweight automotive structures made from aluminum and composite materials. SPR emerged half a century ago but has made significant progress in the last 25 years due to the automotive industry's need to join lightweight materials, especially aluminum alloy structures, aluminum-steel structures, and other composite materials [59]. The automotive industry is the largest consumer of aluminum casting alloys, where they are used in various components such as engine blocks and transmissions in ICE vehicles and BEVs. Additionally, the urgent need for the transition to carbon neutrality is accelerating trends in weight reduction (lightweighting) that contribute to energy savings and the reduction of greenhouse gas emissions in the automotive industry. The application of lightweight materials in automobiles, combined with increasing electrification, will lead to changes in the demand for processed and cast alloys in the near future [60].

3.4.2 Mega-giga casting

Numerous studies have demonstrated that the use of aluminum in lightweight vehicles has been increasing for decades. Specifically, it has been observed that aluminum usage per vehicle has surpassed 227 kg in North America and 180 kg in Europe. Although casting has been the dominant product form until now, in recent years sheet and extrusion applications are expected to show the highest growth rates [61]. The primary reason for using aluminum has always been to achieve weight reduction. However, higher aluminum content, particularly in sheet metal and extrusion assemblies, also translates into higher costs. Moreover, if primary aluminum is being used, it results in a higher carbon footprint. Original equipment manufacturers (OEMs) and their suppliers are working to reduce the material and processing costs of their components, improve production quality, and enhance sustainability—meaning, increasing the recycled content in all types of aluminum parts [62].

In the automotive industry, trends have emerged among OEMs toward producing Mega-Cast body components. As of May 5, 2024, Tesla and Volvo have shown on their websites that they are adopting approaches to producing Mega-Cast aluminum components in the underbody of their vehicles [63]. In 2018, the electric car manufacturer Tesla patented Mega-Casting, making it possible to produce an entire car body in one operation using aluminum high-pressure die casting (HPDC) in the future [64]. The aim of this invention is to reduce operating, production, and tooling costs, along with cycle time. Other companies planning to use Mega-Casting include Mercedes-Benz, which refers to this technology as "Bionic Cast," as well as Chinese OEMs XPeng and Nio [63].

In recent years, with the trend initiated by Tesla, giga-castings (referred to as "mega-castings" by some OEMs) have started to be used in BEVs components. With this method, it is possible to combine many parts used in the vehicle body into a single component [61]. Examples of this application can be seen in Tesla's Model Y. In Figure 3.17 below, the design of the front and rear body parts of the Tesla Model 3 and Model Y is shown.

Figure 3.17 Giga casting example: TESLA Model 3 (left) – Model Y (right) [58]

Compared to the Model 3, these two castings replaced 171 parts and 1,600 welds, removing 300 robots from the assembly line, which significantly reduced the necessary capital investment and floor space. Additionally, it made a significant contribution to lowering the logistical costs and carbon footprint associated with the 171 parts [58].

Recently, Volvo and the premium electric vehicle brand Polestar have adopted giga-presses, also referred to as mega-castings, and begun using this technology. As shown in Figure 3.18, Volvo plans to use this technology to create a single-piece mega-cast aluminum base [58].

The mega-cast bases for Volvo's next-generation BEVs will already be designed to include mounting points for parts like suspension arms and electric motors, which will eliminate the need for a rear subframe. Compared to using methods like welding multiple small parts in chassis production, mega-casting is expected to enable the production of monolithic chassis components. This way, many additional steps in the assembly phase are removed, aiming to reduce costs and provide energy-efficient vehicles. German automaker Mercedes-Benz is targeting maximum cost and weight reduction (enabled by mega-casting) to extend the electric vehicle range by managing energy consumption [58].

There are several brands that either following this method or have announced plans to do so. Among these brands are Mercedes-Benz, Volkswagen, Toyota, General Motors, Hyundai, and Chinese BEVs manufacturers Nio and Xpeng.

Figure 3.18 Volvo mega-casting example [58]

3.4.3 Patchwork and BEVs relationship

Today, reducing the weight of components in the aerospace and automotive industries has become a crucial step toward lowering gas emissions and fuel consumption. One of the most commonly used manufacturing processes is sheet metal forming, and in this process, continuous optimization is carried out regarding the weight, strength, and thickness of the formed sheets. For this purpose, designers need to predict the strain limits and localized necking of the formed part; this subject has been extensively studied in the scientific literature [65]. With environmental issues becoming increasingly severe, energy conservation and environmental protection have become two critical problems that need to be addressed in the automotive industry. Patchwork hot forming technology can be used to produce lightweight and high-strength parts, and it is increasingly being applied in the production of automotive body components. Since the main sheet and the patchwork sheet must be joined with spot welds before forming, the arrangement of these weld points has a significant impact on the formability of part [66].

In recent years, to enhance crash safety, it has become necessary to design special components with segmentation of strength and toughness in some structural parts made of boron steel. Patchwork hot forming technology is a new method that offers good applicability and low-cost advantages, and it is being increasingly used in the production of such special components. Currently, the primary welding methods used in patchwork hot forming are resistance spot welding, laser welding, and arc welding [67]. Considering automotive manufacturing costs and efficiency, resistance spot welding is a widely used joining method. In the patchwork sheet hot forming, the main sheet and the patchwork sheet are first joined by spot welding, and then both are heated and hot-formed together. As a result, patchwork parts with a specific segmentation of strength and toughness are obtained [66]. In patchwork sheets, one or more “patch sheets” (reinforcements) are superimposed on a “main sheet” and joined by spot welding. These spot-welded sheets are then heated in a furnace and hot-formed in a single operation. The final part will have increased thickness in the areas of interest. As shown in Figure 5.6, patchwork sheets can reduce the need for reinforcement assemblies after forming.

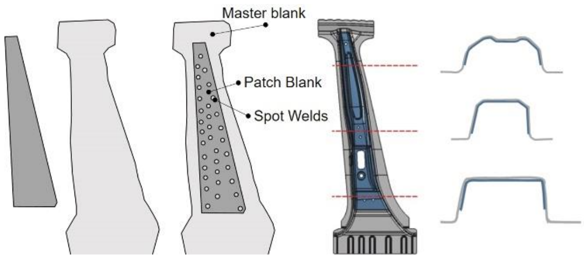

Figure 3.19 Geometries of the main blank and patch for the B-pillar: (a) before, (b) after the spot welding process, (c) after hot forming [68]

Since the spot welds in the patchwork process are also austenitized and annealed, the hardness distribution is generally better than that of spot welds made after hot forming [68]. Overlap patch blanks are a subset of patch sheets. As shown in Figure 3.20, instead of a shaped main sheet and bracket, two (or more) flat sheet sub-parts are joined over the “overlap zone” using the spot welding method, creating a structure like a specially laser-welded part. This technology was initially applied to cold-formed components [69].

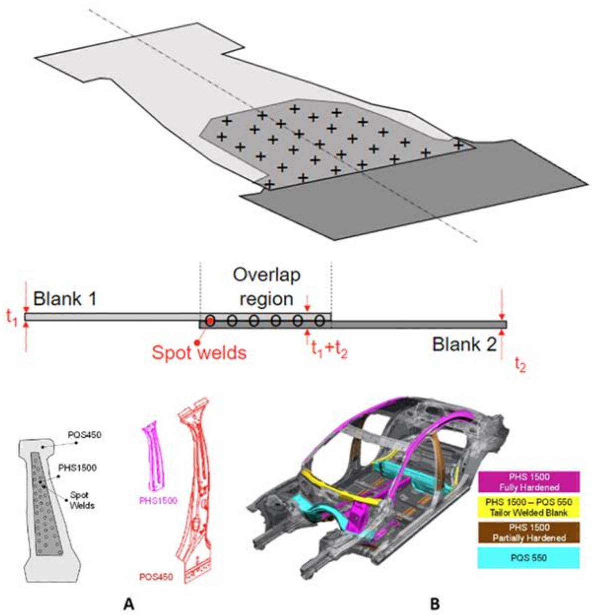

Figure 3.20 Overlapped patch sheet welding (a) and Jaguar I-Pace B-pillar (b) [70,71]

The B-pillar reinforcement of the Jaguar I-PACE, an aluminum-intensive electric SUV introduced in 2018, was made from a patchwork sheet. Unlike previous applications, the main sheet was made of PQS450, which can be easily added to the rest of the vehicle through mechanical joining. The patch was made of PHS1500, improving side impact and roof crush performance [71].

In the automotive sector, many companies, including Honda, Volvo, Jaguar, Ford, and Mercedes, are known to apply the patchwork method to produce high-strength lightweight body parts, reducing the need for spot welding processes, thereby achieving cost and equipment savings. This method also plays a significant role in the global reduction of greenhouse gas emissions.

3.4.4 Laser screw welding

Elements such as formsty, reliability, and chassis stiffness, which form the basis of vehicle performance, play a crucial role in the assembly of the vehicle body’s structure. Most of these assembly processes are carried out with spot welding. However, due to current distribution, it is not possible to shorten the welding intervals, limiting the number of joining points, and it is difficult to fully reveal the strength and stiffness of the structural components. The LSW (Laser Screw Welding) technology developed by Toyota was introduced to resolve the problem of narrow plate gap tolerance, which was previously an issue with laser welding technology. By applying laser welding to the vehicle body's structure, the goal is to enhance vehicle performance [72].

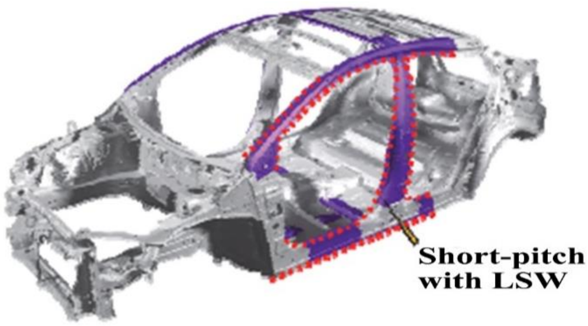

Figure 3.21 Toyota factory Lexus LSW application method [73]

In 2011, the LSW process was integrated into Toyota's Lexus production factory, adding approximately 150 LSW welding points, thus commercializing this technology as a means to enhance driving stability and comfort. From the early stages of development, the primary purpose of LSW has been to renew the structural integrity and improve vehicle performance, such as crash safety [73].
LSW is approximately three times faster than traditional spot welding and can be applied throughout the vehicle. Replacing some of the thousands of spot welds in a vehicle structure with LSW can increase productivity. The welding process in the vehicle chassis with LSW can be shortened by up to 40% by replacing the spot welds with LSW. The main objective of LSW development is to enhance the fundamental performance of the vehicle structure. LSW is also used flexibly between aluminum and steel materials on assembly lines. Toyota claims that thanks to the versatility and speed of this technology, assembly line length has been reduced by approximately 50%. This also brings with it a reduction in factory CO2 emissions [73].

4. Conclusions

The ongoing efforts to generate and store electrical energy from renewable energy sources, combined with advancements in automotive technology, have played a significant role in reducing fossil fuel consumption and carbon footprints. These developments have contributed greatly to the transition from ICE vehicles to BEVs. Efforts to reduce the weight of electric vehicles, driven by the added weight of batteries, have opened the door to new technologies and the use of innovative materials in the automotive industry. It can be concluded that vehicle lightweighting is not only important for increasing battery range but also for enhancing fuel efficiency by reducing emissions and controlling pollution. The trend toward producing lighter vehicles has also necessitated changes in materials and manufacturing methods in the vehicle's welded underbody parts to meet safety standards. In particular, the integration of aluminum casting methods with giga-mega presses and the use of hot-formed sheet materials have demonstrated that electric vehicle dynamics can yield better results than the monocoque body structures of internal combustion engine vehicles. Emerging technologies, such as LSW, Patchwork, and Giga-Mega aluminum casting methods, are expected to facilitate the transition from internal combustion engine vehicles to electric vehicles by offering advantages in lightness, durability, cost efficiency, and safety, while also enabling longer ranges and more environmentally friendly features.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Murat Onat: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing.

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