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Application of Automotive Closure Parts with Multi-Material Design Concept

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The automotive industry is changing rapidly with the electrification of vehicle powertrains. Many EV platforms have emerged, and the safety issues of battery-pack structures are being studied. The goal of vehicle design is a reasonable compromise between weight reduction and vehicle cost without decreasing vehicle performance or safety. Reducing the impact on global warming is another concern. Automotive industries are making efforts to confront this situation, one of which is using multi-material structures for vehicle bodies. Automotive closure parts account for more than 15% of the total vehicle body weight and have many different components. Therefore, efforts have been made to optimize the structure and material to reduce weight. However, applying different materials to automotive closure parts presents several technical challenges. The combination of dissimilar materials is vulnerable to corrosion, and distortion may occur after the painting process due to the different thermal responses of the materials. From a manufacturing perspective, the use of multi-materials can cause problems in the production line (process conformity). Thus, adaptive solutions to produce closure parts made of multi-materials are needed. This study addressed the design of multi-material closure parts and related manufacturing process issues, such as forming, assembling, corrosion resistance, and dimensional accuracy.

Keywords: *Multi-material structure, Automotive closure, Lightweight design, Manufacturing technology, Life cycle analysis*

1. Introduction

The recent advancements in automotive technology are experiencing a significant industrial transformation that is fuelled by society's demands for new experiences, while also maintaining eco-friendly manufacturing conditions [1]. Due to the significant impact new mobility manufacturers are making in the market, legacy car makers are facing a daunting examination where they must prove their standing once again. The shift towards electric vehicles is moving at a rapid pace, and the market is struggling to keep up with it. New electric vehicle manufacturers are making significant impacts in the traditional automotive industry, which has caused legacy car makers to re-evaluate the value of their technologies. Electric Vehicles (EVs) have a unique position in securing eco-friendliness in driving energy, and are key to future growth, which is unrivaled by existing Internal Combustion Engine (ICE) vehicles.

Electric vehicles (EVs) use a battery to store power sourced by electrical energy instead of using fuel like an internal combustion engine (ICE) vehicle, which is converted into driving power by an electric motor. The plumbing fixtures that provide traditional fluid fuels are replaced with wiring and circuitry to manage electrical energy. The EV drive system includes a motor, reducer, battery, charger, and a power control and management device. Due to the requirements of these components, a different car body layout is necessary compared to existing ICE vehicles. Therefore, car manufacturers are investing heavily in research to enhance the technological competitiveness of this new platform and specially design the car body for EVs.

As the trend continues, the proportion of aluminium alloy applied to the total weight of the electric vehicle structure is increasing in order to reduce greenhouse gas emissions by maximizing energy efficiency through lightweighting. Pursuing energy efficiency to the limit can eventually be considered as a direction to secure eco-friendliness. However, regardless of the power source, it is important to note that this technology which lowers vehicle weight and increases energy consumption efficiency is not

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always effective in terms of eco-friendliness when considering the complete life cycle evaluation. While energy efficiency is essential, it is crucial to consider eco-friendliness throughout the entire life cycle evaluation, including greenhouse gas emissions during manufacturing, production, and recycling stages. Therefore, a design plan that minimizes greenhouse gas emissions in the production, manufacturing, and recycling process should also be regarded as an important technology strategy in order to secure eco-friendliness.

This study discusses the concept of designing parts using multi-material strategies to achieve benefits in weight reduction and life cycle evaluation for automotive closure parts, with a weight ratio of approximately 15% in the car body. Moreover, the study includes the development process, which sheds light on the challenges that might arise during the manufacturing process of structures that use different kinds of materials. Furthermore, potential solutions to these issues and performance testing through prototypes are introduced.

2. Design of Automotive Closure Prarts

Car bodies are primarily made of sheet materials with varying strength distributions. Each component part is combined using joining techniques such as welding, mechanical fastening, and bonding. Before being assembled into the body, they are first made into module units. At this stage, individual components must be chosen based on their suitable strength and thickness to meet the performance requirements of the body, such as vehicle crash safety, structural rigidity, and suitable materials for manufacturing processes like stamping presses. Table 1 demonstrates some examples of materials and strengths typically applied to automotive closure parts. BH Steel (Bake Hardening) or Al6000 series alloy is mainly used for outer panel materials as they can improve surface quality, and ensure dent resistance. Inner parts require functional designs to fasten internal components, which generally come with complex shapes. Therefore, materials with good formability, such as high ductility low carbon steel or Al5000 series alloy, are used. Parts supporting working mechanisms such as fixed brackets, and those supporting crash impact loads in doors, have various strengths applied, ranging from high-strength carbon steel to ultra-high-strength steel and Al extrusion profile.

These materials emit varying levels of GreenHouse Gas (GHG) during the manufacturing process. Steel, for instance, has a GHG impact level of 2 ~ 3 kg CO_2 per kg of steel in typical blast furnace production, whereas aluminium has an emission of approximately 7 ~ 15 kg CO_2 per kg Al [2], depending on the electricity source used in the refining process. If we know the GHG impact of each material, and the components of the part we want to construct are comprised of numerous materials, as illustrated in Table 1, we can estimate the total GHG emissions resulting from the material composition of the part through a simple summation. Material selection must also take into account the weight effect of other parts, enabling GHG impact calculation from the same perspective during subsequent driving and recycling stages. To streamline the explanation, a simple diagram is presented in Fig. 1. In evaluating the entire process, GHG impact can be expressed as the sum of three primary stages. Stage I encompasses the total GHG emitted from the materials used and the manufacturing process, as

Table 1. The materials and strengths mainly applied to automotive closure parts

Materal	Grade	Thickness	Density	Young’s modulus	Yileld strength	Applications in closure parts
Mild steel	EDDQ	0.7 mmt	7.8 g/cm^3	208 GPa	140 MPa ~	Inner panel, etc.
BH steel	BH340	0.7 mmt			180 MPa ~	Outer panel, etc.
AHSS	DP590	1.2 mt			340 MPa ~	Internal reinforcements, ect.
UHSS	TRIP1200	1.2 mmt			1,000 MPa ~	Door impact beam, ect.
Al5000	Al5182	1.0 mmt	2.7 g/cm^3	70 GPa	110 MPa ~	Inner panel, etc.
Al6000	Al6014	1.0 mmt			110 MPa ~	Outer panel, etc.

*In the table, EDDQ (Extra-Deep Drawing Quality), BH (Bake Hardening), AHSS (Advanced High Strength Steel), UHSS (Ultra High Strength Steel), BH340 (Bake Hardening steel with 340 MPa grade) DP590 (Dual Phase steel with 590 MPa grade), TRIP1200 (Transformation Induces Plasticity steel with 1,200 MPa grade) already mentioned in the production stage. Stage II describes the GHG impact that occurs during the driving phase, including the effect of the material inputs associated with the vehicle's energy consumption and maintenance. Finally, Stage III is simply the sum of the GHG impact from the energy and material recycled during the disposal process of the vehicle at the end of its service life [3]. Usually, this can be explained in a way where an increase in recycling results in a decrease in total GHG emissions.

The ultimate goal of optimizing the environmental impact is to minimize the slope of stage I and stage II while maximizing the slope of stage III, as illustrated in Fig. 1. To achieve this target, various scenarios need to be considered. During stage I, it would be ideal to employ materials that have low greenhouse gas emissions, which can minimize the impact during the manufacturing and assembly processes. This approach ensures that the environmental impact is minimized even before the vehicle is put into use. In stage II, the focus should be on lightweighting, which can reduce the amount of energy consumed during driving. By reducing the weight of the vehicle, less energy is required to power it, thereby reducing carbon emissions. In the final stage, stage III, it is essential to attain the highest possible recycling rate to minimize waste.

To achieve an environmentally-friendly vehicle in each stage, it is necessary to analyze each issue comprehensively

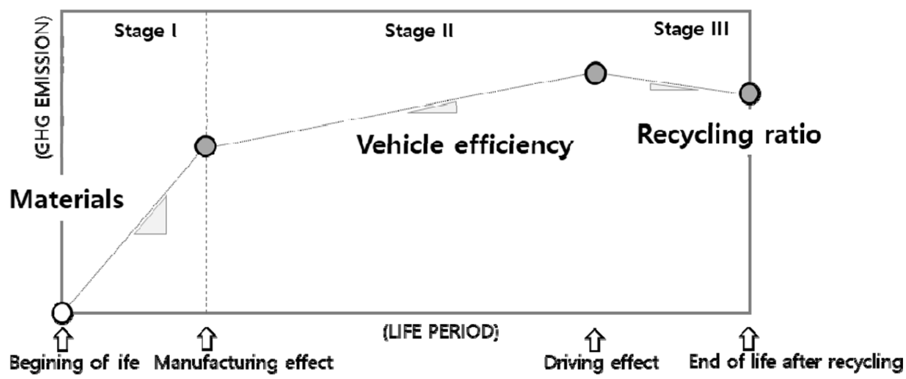

Fig. 1. schematic diagram for LCA (Life Cycle Analysis) effect

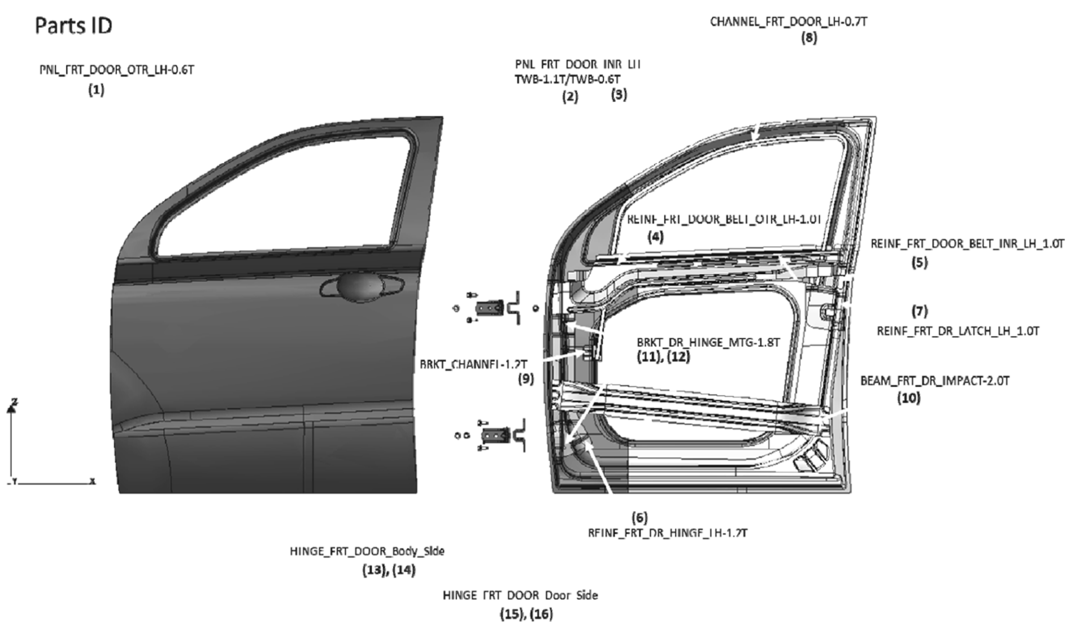

Fig. 2. Automotive front door components

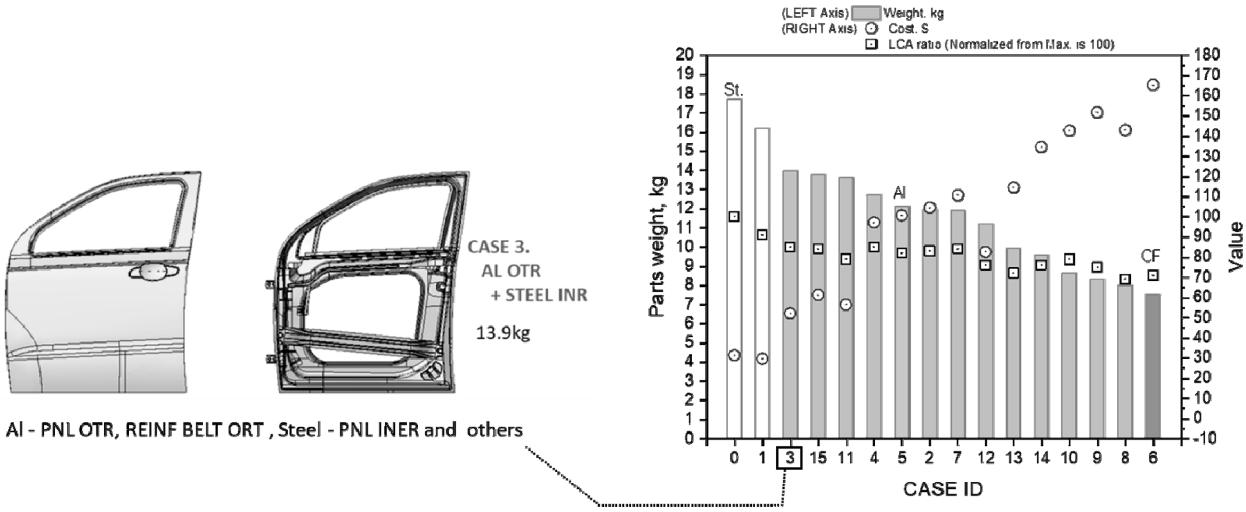

Fig. 3. LCA effect comparison for automotive door (Fig. 2) by World Auto Steel LCA model

and take a comprehensive approach to reduce environmental impact while designing, manufacturing, and operating the vehicle. By considering all the interrelated effects in the design, a sustainable and eco-friendly product can be developed throughout its life cycle.

From this perspective, a design analysis was conducted on the automotive door. Fig. 2 shows an unfolded diagram of the automotive front door used in this design analysis. This particular door is a standard model that consists of 16 components, all of which are assumed to be made of steel. For the analysis, the materials for each component were replaced with steel, aluminium, and polymer composites in order to calculate the equivalent GHG emissions for the manufacturing of individual components and the assembly (Stage I effect). The production volume assumed for the year was 200,000 to 700,000 units, and the production period was compared at 5-year and 10-year intervals to factor in the investment effect for part manufacturing. In addition, the recycling rate was assumed by material type, with 85% for metals such as steel and aluminium, 50% for thermoplastic polymer composites, and 0% for thermosetting polymer composites (Stage III effect). Finally, the calculated results were reflected in the World Auto Steel LCA model[4)], and the final GHG emission effects were analyzed.

In the scenario assumptions regarding the material combination of the target components, Fig. 3 presents the cost, weight, and equivalent CO_2 emissions of the components as various cases. "St." refers to the case in which steel is applied to all components, "Al" refers to the case in which aluminium is used, and "CF" refers to the case made of CFRP composite. The space between them is filled with either a Steel-Al hybrid or an Al-CFRP-Steel hybrid design. The effect on Life Cycle Assessment (LCA) is presented by comparing the proportion it takes in the overall vehicle effect and normalizing the results by defining the basic model, consisting of steel, as 100.

In terms of analysis, the material properties used in the development of these components were precisely re-measured, and stamping die sets for serial production were designed through sheet forming simulations, which were applied to LCA calculations. Additionally, when assembling the components, various material combination characteristics were taken into consideration. As a result, welding options such as RSW (Resistance Spot Welding), mechanical joining methods like SPR (Self-Pierce Riveting), and various adhesives were selected [5]. Furthermore, the utility investments corresponding to the production cycle were also taken into account.

To ensure that the final assembly parts met the functional performance requirements for stiffness, rigidity, strength, and crash safety, their performance was re-evaluated through a performance evaluation based on CAE. Therefore, proper material thickness and strength grades were implemented through redesign.

Upon consideration of this graph, it is possible to identify an economical design direction that could potentially lower the component cost while achieving a

Table 2. Parts list for case 3 at automotive front door study models

Part ID	NAME	ASSEMBLE TREE L0	L1	L2	L3	L4	L5	L6	L7	L8	Qt. ea	Material	GRADE	Thickness mm	Net Wgt kg
0	DOOR_ASS'Y_LH	■													13.941
1	PNL_FRT_DDOR_OTR_LH			■							1	AL	AL6014T4	1.0	2.751
4	REINF_FRT_DOOR_BELT_OTR_LH				■						1	AL	AL6014T4	1.5	0.605
	DOOR_INR_COMPL_LH			■											
10	BEAM_FRT_DR_IMPACT_LH				■						1	STEEL	1180CP	1.0	1.134
8	CHANNEL_FRT_DOOR_LH					■					1	STEEL	CQ	0.7	0.442
9	BRKT_CHANNEL_LH					■					1	STEEL	CQ	1.0	0.038
5	REINF_FRT_DOOR_BELT_INR_LH						■				1	STEEL	980DP	1.0	0.850
11	BRKT_DR_HINGE_MTG_LH_UPR						■				1	STEEL	CQ	1.8	0.039
12	BRKT_DR_HINGE_MTG_LH_LWR						■				1	STEEL	CQ	1.8	0.039
6	REINF_FRT_DR_HINGE_LH							■			1	STEEL	1180TRIP	1.2	0.988
7	REINF_FRT_DR_LATCH							■			1	STEEL	590C	1.0	0.440
	PNL_DOOR_INR_COMPL_LH								■			STEEL			
2	PNL_FRT_DR_INR_LH_TWB-1.2T									■	1	STEEL	EDDQ	1.1	2.750
3	PNL_FRT_DR_INR_LH_TWB-0.6T									■	1	STEEL	EDDQ	0.6	3.063
13	HINGE_FRT_DOOR_Body_Side_LH_UPR		■								1	STEEL	CQ	5.0	0.140
14	HINGE_FRT_DOOR_Body_Side_LH_LWR		■								1	STEEL	CQ	5.0	0.140
15	HINGE_FRT_DOOR_Door_Side_LH_UPR		■								1	STEEL	CQ	5.0	0.262
16	HINGE_FRT_DOOR_Door_Side_LH_LWR		■								1	STEEL	CQ	5.0	0.262

*In the table, 1180CP (Complex Phase steel with 1,180 MPa grade), CQ (Commercial Quality low carbon steel), 980DP (Dual Phase steel with 980 MPa grade), 1180TRIP (Transformation Induced Plasticity steel with 1180 MPa grade), 590C (High Strength Low Alloy steel with 590 MPa grade), EDDQ (Extra-Deep Drawing Quality steel)

similar LCA effect as the full Al door. This design direction can be found in case 3 according to Table 2.

3. Fabrication with Multi-Material Design

When applying the multi-material concept to closure component design, the benefits that can be obtained are mentioned as follows:

The first benefit is related to the previously mentioned LCA effect. By reducing GHG emissions during the production process and maintaining the level of lightweighting, it is possible to reduce the total emissions at the end of the lifecycle. The second benefit, which takes into account the overall cost limitations, is that lightweight design can be additionally applied within the cost target, allowing for an increase in the level of lightweighting from the perspective of the entire vehicle. Moreover, using steel allows for the production of parts on existing production lines, which minimizes the investment required for other facilities in order to the utilization of lightweight materials such as aluminium and can reasonably reduce the production cost of parts.

However, a structure consisting of different materials increases the complexity of the manufacturing process, and there may be factors to consider regarding performance when applying production technology. Representative issues that should be taken into account include galvanic corrosion, which can accelerate corrosion behaviour between different metals, and the quality issue of dimensional stability due to thermal stresses experienced

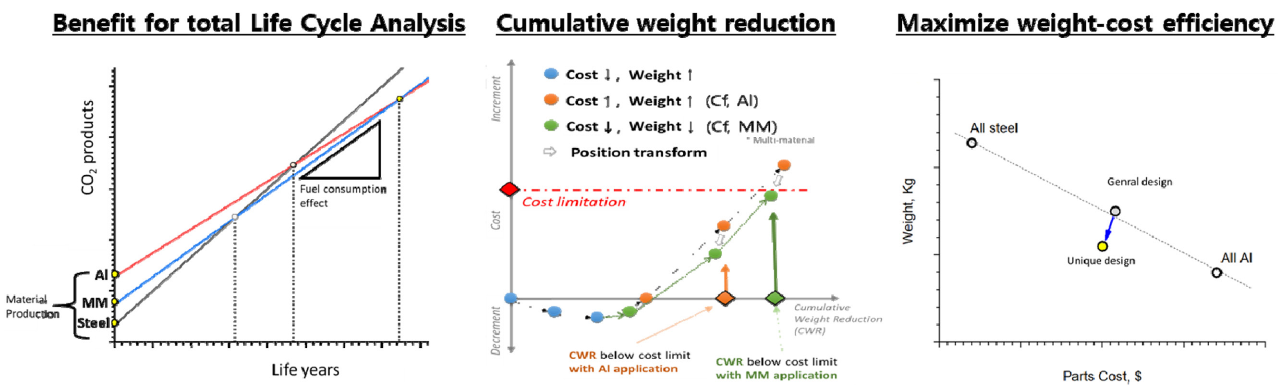

Fig. 4. Benefits of applying multi-material design concepts in automotive closure

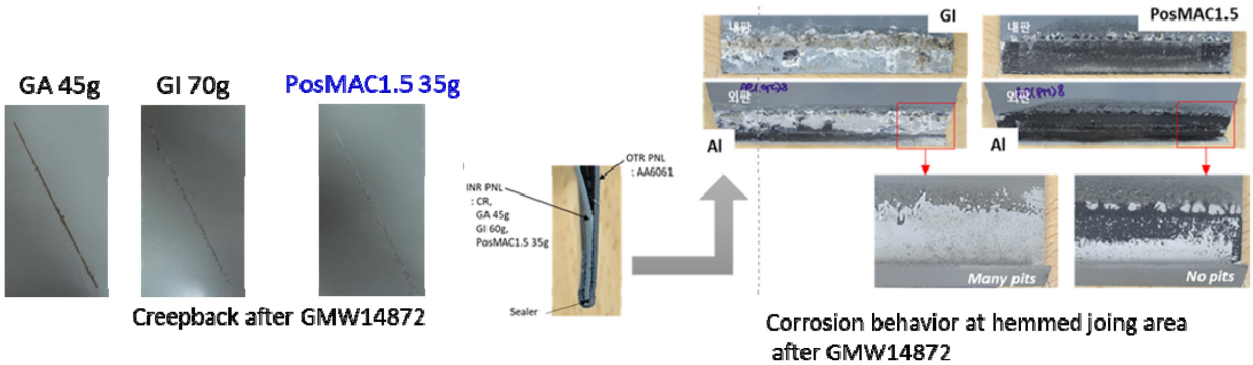

Fig. 5. Corrosion behaviour at three kinds of galvanized steel and hemming area after CCT with GMW 14872

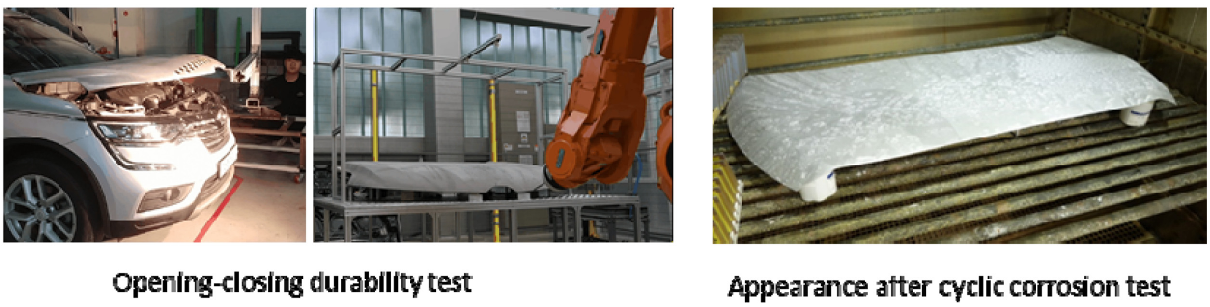

Fig. 6. Functional assessment for prototype hood made by Al outer panel and Steel inner panel

during manufacturing processes.

Galvanic corrosion between steel and aluminium is a well-known intrinsic property. However, it is important to explore and utilize this phenomenon in a way that satisfies the performance and quality conditions of an automotive manufacturer from an engineering perspective. The most fundamental technology used to prevent corrosion in steel is galvanizing, which involves applying a plating layer, such as GI or GA. These coatings not only prevent corrosion of steel but also aid in preventing galvanic corrosion when formed into an electrical bridge with aluminium components. When utilizing galvanized steel, it is crucial to consider the impact of the plating material on corrosion resistance for decision-making in engineering design regarding material application.

The evaluation results of Cyclic Corrosion Test (CCT) with GMW 14872 [6] are presented in Fig. 5. Even though the plating weight on the steel sheet was lower, the PosMAC1.5 [7] plating sheet demonstrated better creep back corrosion performance. Moreover, it was confirmed that the PosMAC1.5 plating steel exhibited superior corrosion resistance in samples subjected to the hemming process, which is the primary assembly method for closure parts that combine Al outer panel and steel inner panel. The samples were produced using a conventional method, with ED-painting and adhesive glues such as hemming sealer and paint sealer that are commonly used in the assembly process of closure parts in the automotive industry. The CCT results of samples fabricated using the same process revealed that the corrosion resistance level depends on the plating material. Thus, it can be expected that using PosMAC1.5 plating steel sheet will result in more stable corrosion resistance effects.

To verify the corrosion behaviour in an automotive hood, a prototype was fabricated by using PosMAC1.5 plated steel sheet for the hood's inner panel and Al6014T4 sheet for the hood's outer panel. The entire part was then inserted into a CCT chamber, and an accelerated corrosion evaluation was conducted according to the GMW14872 standard. Fig. 6 shows the durability evaluation of the prototype component and its appearance after the CCT evaluation. Throughout this corrosion evaluation test, no corrosion phenomena were observed, and it was confirmed that the prototype parts have stable corrosion resistance.

The dimensional stability of the closure components is

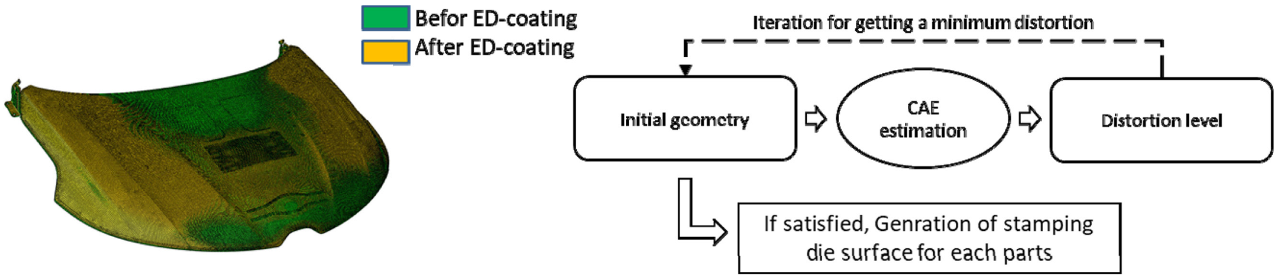

Fig. 7. Thermal distortion analysis results in the hood without geometry optimization and the schematic diagram for geometry correction strategy

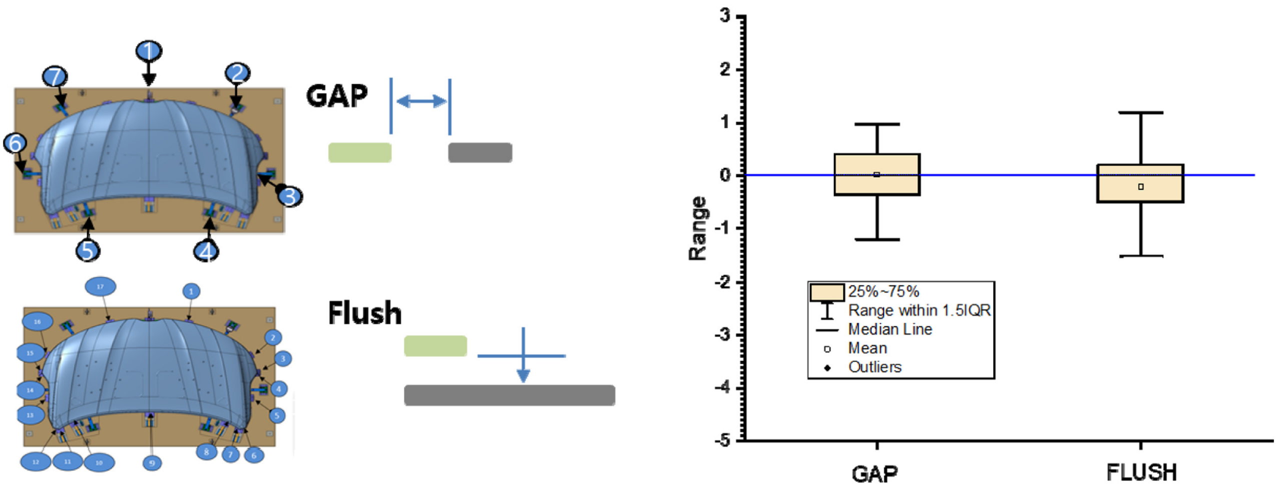

Fig. 8. Gap and flush level measured in checking fixture after geometry optimization for multi-material hybrid hood

a critical quality factor as it relates to gaps and flushes in the vehicle's surface. These features serve as indicators of the manufacturing quality of the product. If the components experience severe distortion, it can lead to vehicle assembly failures. To minimize these problems, manufacturers enforce strict tolerances during the manufacturing phase. Therefore, the thermal deformation that occurs in multi-material hybrid-designed components is essential to consider. When different materials combine to form a structure, the difference in thermal expansion coefficient levels results in different deformation behaviour for each material. This imbalance can cause distortion of the geometry in a way that minimizes residual stress due to thermal deformation across the entire part. This ultimately contributes to weakening the dimensional stability of the final product.

While the development of the multi-material hybrid hood, a maximum flush of 12 mm occurred in the prototype fabrication stage. This was attributed to a thermally distorted geometry that resulted after the painting process was applied to the original part's shape. To address this issue, FEM analysis was conducted as an optimization strategy to reconfigure the initial part's geometry, with the goal of minimizing thermal deformation after the ED-coating process. Subsequently, the predicted deformation was embedded back into the initial conditions, and the process was repeated to accurately estimate a revised parts geometry that could minimize thermal distortion. This procedure follows a similar approach to the press die build-up process for spring back correction in stamping components, but it requires additional heat treatment processes and measurement of dimensional changes to predict the effects accurately. To overcome these challenges, physical phenomena should be considered with FEM calculation by analyzing temperature history in the process.

After manufacturing stamped dies by applying the optimized part geometry, individual parts were fabricated. These fabricated parts were used to produce a prototype hood by assembly. Following this, the multi-material hybrid hood underwent ED-coating, a common process in the automotive parts production industry, where the maximum temperature in the line was 185 degrees. A one-part sealer was applied for hemmed assembly, which is typically utilized in general car body production. The prototype hood made with the optimized parts geometry showed good dimensional quality which has a measuring level of 1 mm or less for gaps and flushes at the checking fixture. It is considered to have satisfactory dimensional stability, taking into account the prototype part generation.

4. Summary

This is a time that requires various procedural and technological efforts to strengthen environmental performance. In the development of vehicles, lightweighting is important not just for the purpose of reducing weight but also for securing environmentally friendly performance. Among various technological development directions to achieve this goal, the multi-material design concept that applies various materials can be a noteworthy option.

By applying the concept of multi-material design to automotive closure parts, benefits can be gained in terms of LCA effects by considering the entire lifecycle of the vehicle. Additionally, utilizing existing production lines can rationalize production costs. However, specialized manufacturing processes for handling different kinds of materials require new efforts and attempts to ensure the quality and performance of the components. As part of these development efforts, the manufacturing technology for serial-producing multi-material hybrid components is anticipated to be achieved by applying PosMAC1.5 plating to provide galvanic corrosion resistance and an optimization strategy to reconfigure the initial part's geometry to minimize thermal distortion.

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