CF-SMC TECHNOLOGY FOR HIGH VOLUME MANUFACTURING

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Abstract

The pressure for increased fuel economy and low CO2 emissions for automotive vehicles continues. In order to satisfy long-term requirements, lightweight materials will need to be deployed as part of a strategy to manage vehicle mass while also incorporating new vehicle content. Glass reinforced composites offer significant potential, but applications can be limited due to their relatively low modulus compared to light metals such as aluminum and magnesium. This has prompted an interest in developing carbon fiber based composites as a means of achieving superior mass reduction when compared to equivalent metallic solutions. However, the challenge associated with implementation of carbon fiber composites is to make them cost effective for high volume production because historically this class of materials has been best suited to low volume production scenarios.

This paper describes development of a new carbon fiber sheet molding compound (CF-SMC) that has been designed to be compatible with conventional high volume compression molding methods. The new material offers a threefold increase in elastic modulus compared to typical glass based SMC solutions. This increase in intrinsic stiffness enables section properties to maintained within the constraints a design package space. This in turn, allows for a low investment pathway to lightweight design using a process that offers the design freedom of compression molding in combination with high utilization of a premium reinforcement fiber. To demonstrate the capabilities of the CF-SMC solution, a rear decklid assembly was designed and tested to confirm performance and suitability for use in a high volume manufacturing scenario.

Introduction

Persistent pressure for improvements in fuel economy, combined with regulations on greenhouse gas emissions, has prompted automobile manufacturers to pursue a broad range of technologies to address these demands. Technologies include hybridization of powertrains, full electrification, plus others affecting vehicle attributes such as aerodynamics. Figure 1 describes recent trends in fuel economy and emissions, indicating that significant progress has been made over the past decade [1]. However, maintaining the year over year improvements, projected in Figure 2, is considered ever more challenging due to market demand for increased vehicle content. Such content includes electronic infotainment systems, autonomous controls, passive and active safety features. While providing additional consumer benefits, these technologies have the potential to negatively impact vehicle mass. This is witnessed in Figure 3 whereby vehicle mass has been held constant over the past decade even though the pace of adoption for lightweight materials is increasing. The implication is that future improvements in fuel economy and greenhouse gas emissions will require execution of ever more aggressive strategies for vehicle mass reduction. A notable example is the 2015 Ford F150, which achieved a 700 lb vehicle weight reduction through increased used of advanced high strength steel, aluminum, and magnesium materials, in turn enabling the use of more efficient powertrain technologies [2].

To match the projected demands for sustained and significant mass reduction, Ford, Dow, DowAksa and CSP (Continental Structural Plastics) partnered to develop a novel carbon fiber

SMC, VORAFUSE™ M6400. The intent of the project team was to deliver industrially relevant composite technology, advanced processing and tooling required to commoditize the processing of light weight components. From a vehicle production volume perspective, this represents a departure from material formats commonly used in low volume niche market applications. Instead, the project team was focused on developing a material system that could accommodate vehicle volumes around 100k/yr, leveraging infrastructure already in position within the Tier 1 supply base.

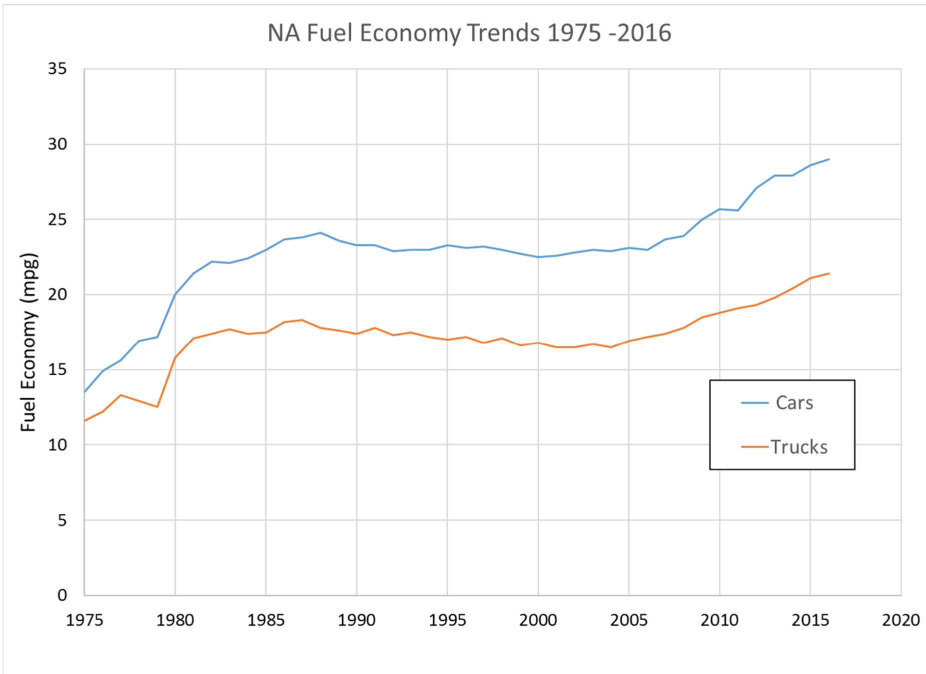

Figure 1. Fuel economy trends

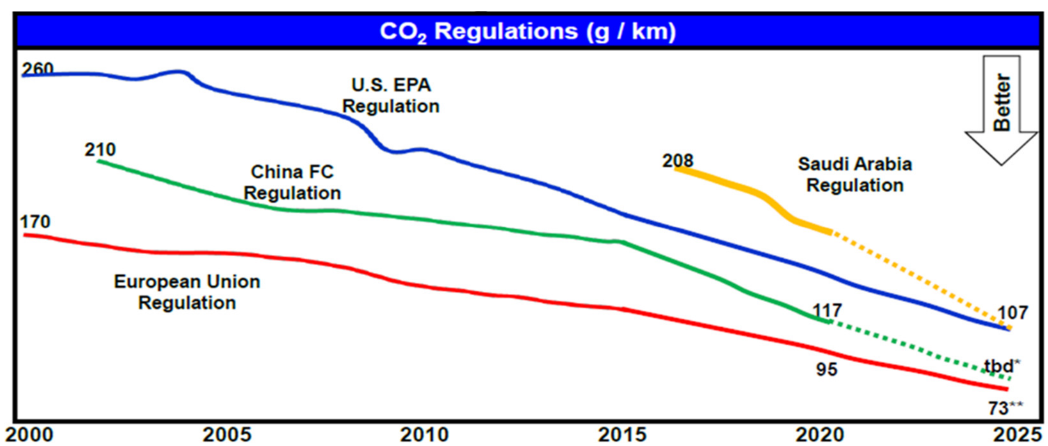

Figure 2: Mandated change in vehicle CO_2 emissions as measured during the New European Drive Cycle (NEDC) as measured in grams of CO_2 per kilometer of travel.

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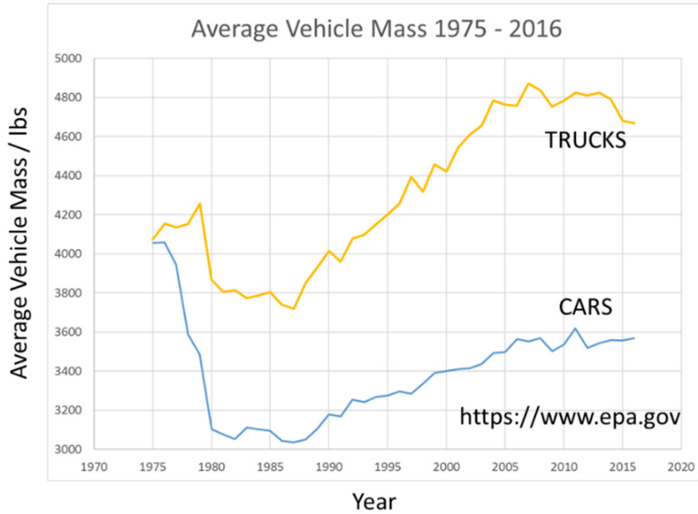


Figure 3: Trends in vehicle mass for the North American car and truck market.

Material & Process Development

Critical to Quality Requirements (CTQ's)

To ensure development of high performance composite materials, ready for high volume manufacturing, detailed Critical-to-Quality (CTQ) metrics were established for processing speed, molded part Tg, and mechanical performance. A few relevant CTQ's are shown in Table I.

A key CTQ for the CF-SMC is a cured Tg higher than the cure temperature when cured for two minutes at ~150 °C. A Tg >150 °C allows a part, compression molded at around 150 °C, to be released while still hot without warping. That is, it enables parts to have sufficient integrity to be de-molded without first cooling the mold and part, which in turn enables shorter molding cycle times. In addition, a Tg >150 °C provides a composite material with the property of high heat distortion temperature which is needed for demanding applications.

Table I. Key processing/property requirements

Process/Property	**Required performance**
SMC storage stability	50 days at ≤ 40 °C
Molding	Compression molding
Mold temperature	145 -155 °C
# of parts molded between applications of external mold release	1000
Cure speed (resin cure kinetics)	< 2 min @ 150 °C (DSC)
Degree of cure after molding	> 95%
Cured Tg	150 – 160 °C (DMA)

From a processing perspective, maintaining a cycle time of 3 minutes per part with 1000 parts molded between applications of an external mold release, is essential for uninterrupted production. Epoxy polymers, being excellent adhesives, bond tenaciously to metals making it necessary to utilize a release agent so that parts can be quickly and easily removed from the metal mold without damage or distortion. Internal mold release agents are preferred because they eliminate the need for frequent application of the release agent to the mold, thereby increasing productivity and reducing part cost. Hence, the CF-SMC formulation developed featured an internal mold release system that achieved the desired mold release characteristics while also providing capability for subsequent bonding and painting.

Novel CF-SMC for Compression Molding

The CF-SMC system developed is based on an epoxy resin formulation designed to be compatible with e-coat process for the vehicle body in white. In practice, this means tolerating the thermal exposure during the e-coating and paint processes. The use of carbon fiber as the polymer reinforcement increases stiffness by approximately three fold over glass based SMC products, while also offering substantial improvement in strength. Figure 4 demonstrates the targets of strength and stiffness for material development.

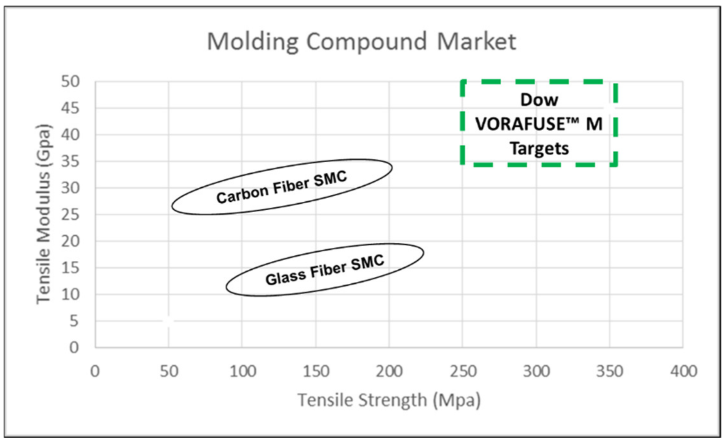


Figure 4. Market for modulus vs strength for SMC systems.

The key challenges for meeting these targets:

- Achieving strength and stiffness while allowing material to flow during the compression molding cycle to create complex 3D geometry
- Infusing the carbon fiber to reduce voids in a high volume production rate
- Defining a repeatable fiber aspect ratio to achieve predictable performance

The aspect ratio of the carbon fiber control both molding flow characteristics and final part strength. Determining the window of fiber aspect ratio providing strength and modulus in the target range, as well as providing enough flow during compression molding to create the complex 3D part geometry in high volume production processes was key to the success of this development. For example, a fiber aspect ratio (defined as length/width) of <10 may provide an excellent flow material with poor physical properties. A fiber aspect ratio of >100 may provide excellent physical properties, but near zero flow. The zero flow material may be useful in low production volume, simple geometry parts, however these designs were not the target of this development. Table II provides a summary of key physical properties for samples extracted from molded flat plaques. Subsequent validation work for material processing and performance of the CF-SMC material was completed with a material system L/W equal to 17.

Table II: Representative properties for Novel Carbon Fiber SMC

Property – Molded Plaque Composite	VORAFUSE™ M 6400 Sheet Molding Compound – Typical Molded Properties			
	Method	Units	Fiber Aspect Ratio L/W = 17	Fiber Aspect Ratio L/W = 34
Density	ASTM D792	g/cm3	1.5	1.5
Fiber Content	ASTM D3171 Method 1, procedure B	Wt %	60	60
Resin Content		Wt%	40	40
0º Tensile Strength at Break, Average	ASTM D3039	MPa	275	319
0º Tensile Strength at Break, Std Dev			28	44
0º Tensile Modulus, Average		GPa	42	50
0º Tensile Modulus, Std Dev			2.9	3.7
0º Tensile Elongation, Average		%	0.70	0.64
0º Tensile Elongation, Std Dev			0.06	0.08
0º Compressive Strength, Average	ASTM D6641 Procedure B, Tabbed	MPa	324	347
0º Compressive Strength, Std Dev			31	26
90º Tensile Strength at Break, Average	ASTM D3039	MPa	279	302
90º Tensile Strength at Break, Std Dev			31	69
90º Tensile Modulus, Average		GPa	43	49
90º Tensile Modulus, Std Dev			5.9	8.8
90º Tensile Elongation, Average		%	0.69	0.64
90º Tensile Elongation, Std Dev			0.06	0.05
90º Compressive Strength, Average	ASTM D6641 Procedure B, Tabbed	MPa	331	309
90º Compressive Strength, Std Dev			30	45
ILSS, Short Beam Shear, Average	ASTM D3518	MPa	55	58
ILSS, Short Beam Shear, Std Dev			5.2	5.0
0º Flexural Strength, Average	ASTM D 7264	MPa	482	522
0º Flexural Strength, Std Dev			78	102
0º Flexural Max Strain, Average		%	1.76	1.56
0º Flexural Max Strain, Std Dev			0.36	0.30
0º Flexural Chord Modulus, Average		GPa	32	39
0º Flexural Chord Modulus, Std Dev			5.1	6.9
Onset Tg (pk storage modulus)	ASTM D 5418	°C	127	132
Tg (peak tan delta) by DMA			159	160

Material Validation & Testing

To validate the performance of the new carbon fiber SMC system, a rear closure was selected for re-design using the CF-SMC material. Target CTQs were used as input into engineering analysis to develop a final design for comparison against the incumbent material system. Figure 4 shows the vehicle selected for this study, a Lincoln MKS, with the corresponding decklid assembly.

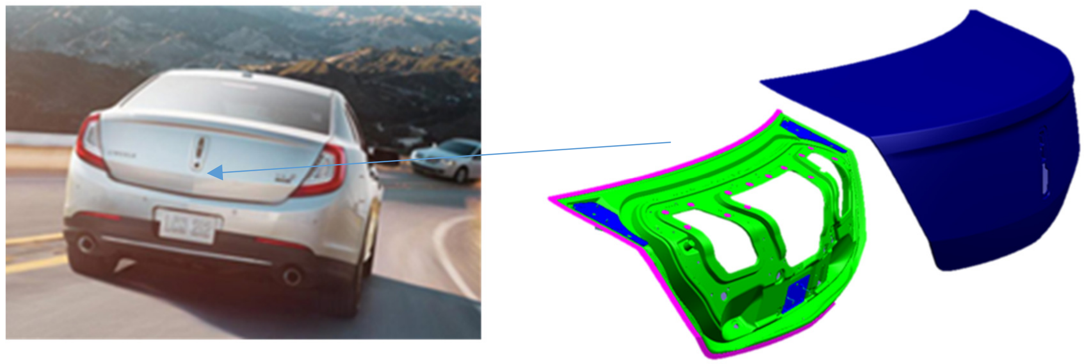


Figure 4: Lincoln MKS with decklid assembly

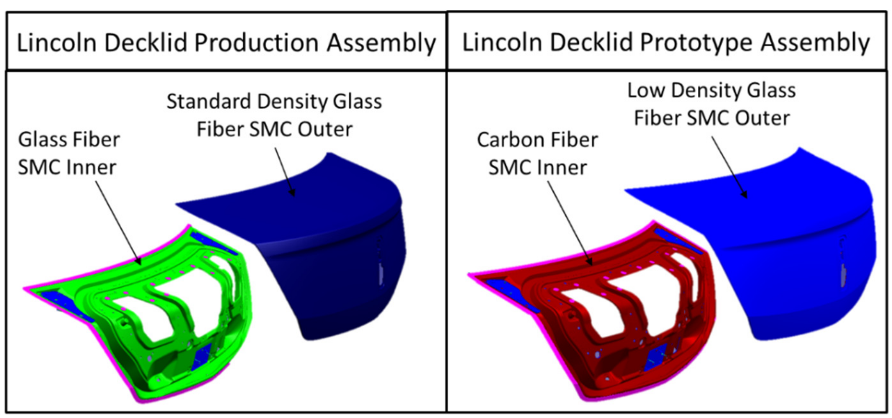


Figure 5. Comparison of production vs. prototype carbon fiber SMC decklid assembly

As Figure 5 indicates, the production release version of the decklid was manufactured from a glass fiber SMC inner and outer combination. Localized steel reinforcements were attached to the inner panel to provide attachment locations for the hinges and latch, with common hardware and reinforcements for all design variants. For the case of the non-production, re-designed decklid, CF-SMC was selected for the inner panel material, in combination with a low density glass fiber SMC outer panel. The transition from a 1.9 g/cm^3 standard density outer to a 1.3 g/cm^3**Error! Not a valid bookmark self-reference.** low density outer, providing additional opportunity for reduction in overall assembly mass.

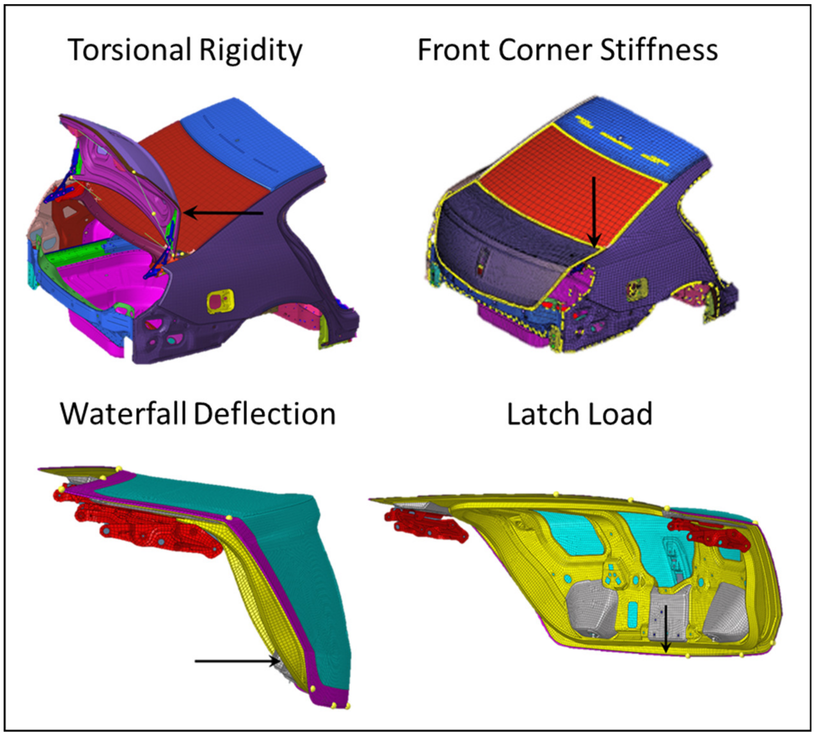


Figure 6: Lincoln MKS decklid base-line design in comparison to a carbon fiber inner / glass fiber outer concept.

To guide the design and development of the carbon/glass hybrid decklid, a series of key load cases were selected to assess overall function versus the baseline design. CAE representations of these load cases are shown in Figures 6. While it should be noted that these load cases are only a sub-set of analysis performed as part of a regular vehicle production program, the analysis can still be used to project the estimated weight savings potential and performance against the incumbent. For the selected load cases, the carbon/glass hybrid design was able to take full advantage of the increase in intrinsic stiffness. Specifically, combining the existing inner panel geometry with a threefold increase in modulus for the carbon fiber translated to a significant improvement in overall performance of the decklid assembly.

A summary of predicted performance versus the baseline production decklid is shown in Table III. In terms of a test response, a reduction in deflection for each load case is shown as a percentage improvement. All four tests outperformed the baseline by significant margins, providing considerable potential for design optimization. Subsequent design studies focused on topology optimization assumed a minimum gage thickness of 2.0mm. While flat plaque and small part molding studies had previously demonstrated flow down to 1.5mm, a more conservative approach was taken for the decklid due to the size and shape complexity.

Table III: Comparison of carbon fiber hybrid decklid design to baseline performance.

Test	Result units	Baseline vs CF SMC	Baseline vs Optimized CF SMC	Pass/ Fail
Front Corner Deflection	Displacement -Z (mm)	35.8%	28.3%	Pass
Waterfall Deflection	Displacement Z (mm)	47.5%	24.0%	Pass
Latch Loads	Displacement Normal to Surf. (mm)	45.6%	36.3%	Pass
Torsional Rigidity	Angle / meter (degrees/m)	55.0%	30.5%	Pass

The mass of the baseline design and carbon/glass hybrids is shown in Figure 7. As expected, the assembly mass reduces, initially due to a straight density change, followed by optimization of part thickness. On the left-hand side of the figure, the inner and outer panel mass for the production release decklid is listed as 10.5kg. A straight substitution of the inner panel with a carbon fiber SMC and outer panel to the LD-SMC, reduces the mass by 3.17kg. Further optimization of panel thickness within the limits of manufacturing feasibility resulted in a final design weight of 6.81 kg. It should be noted that following design optimization, confirmation of performance was established through physical testing of prototype components, as is described later.

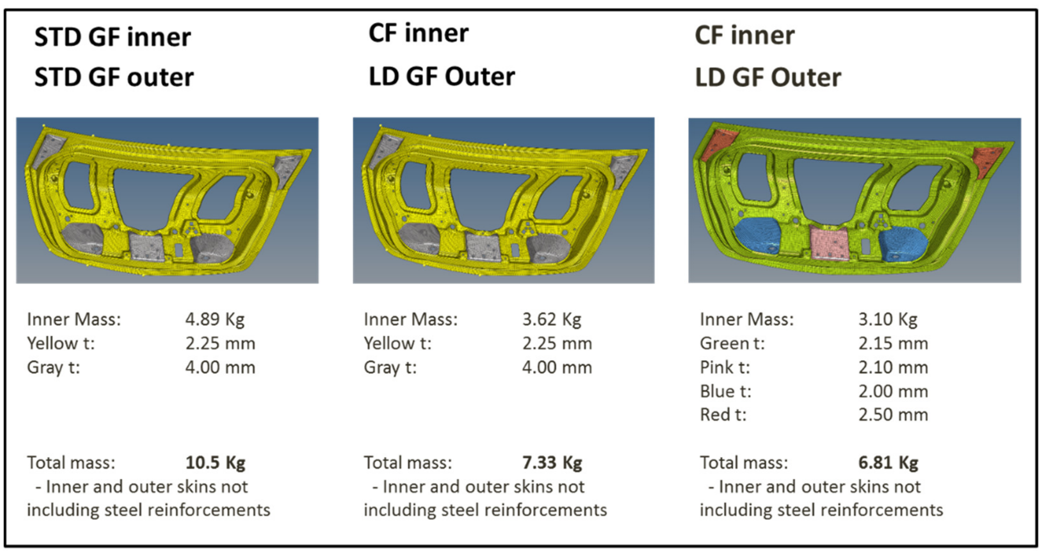
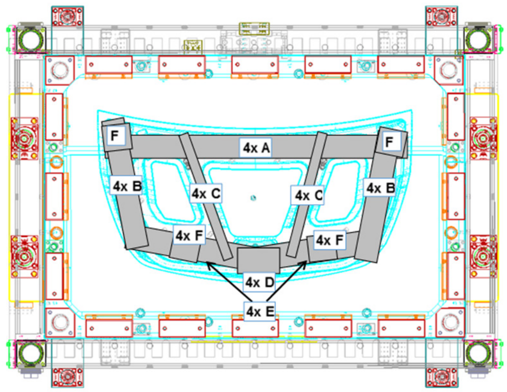


Figure 7. Comparison of decklid masses for baseline and carbon/glass hybrid designs.

Prototype Production

For prototyping activities, carbon fiber SMC decklid inners and low density glass fiber SMC outers were manufactured using series production compression molding tools. For the carbon fiber SMC decklid inner, an initial charge pattern was developed based upon the production glass fiber SMC and then modified to account for the lower carbon fiber SMC areal density and material distribution in various regions of the component (Figures 8 and 9).



Figures 8 and 9. Decklid inner charge pattern and Lincoln MKS decklid inner molding tool.

A standard tool closure profile combined with a mold temperature of 150 °C resulted in a component cure time of less than 3 minutes. Clamp tonnage on the compression press was also typical for SMC processing at approximately 1500 psi (~100 Bar). Incorporation of an internal mold release agent within the epoxy matrix also eliminated the need for coating the production steel tooling. Following part ejection, decklid inners were placed on cooling fixture ahead of de-flashing and trimming in preparation for assembly.

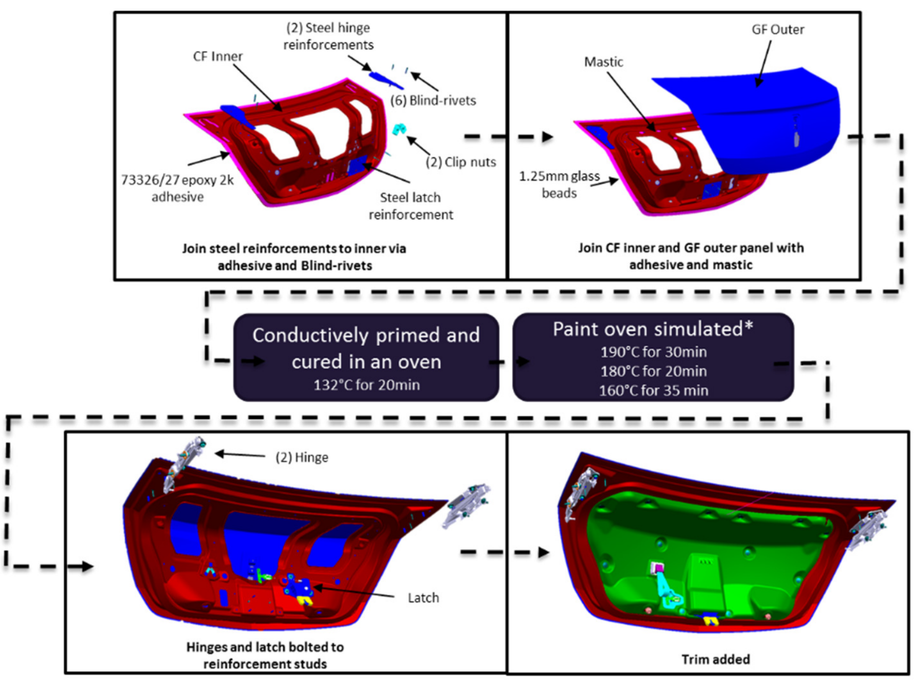


Figure 10. Bill of Process for Decklid Assembly

Decklid assemblies, comprised of low density glass fiber SMC outers and carbon fiber SMC inner panels, were fabricated per the bill of process given below in Figure 10. Localized steel reinforcements at the hinge and latch areas were attached using blind rivets and a structural adhesive. The decklid inner and outer were joined using the same structural adhesive. For prototype assemblies, the two component adhesive was cured at room temperature prior to the assembly being subjected to the standard paint process including all oven cure cycles (conductive primer, e-coat, primer, paint). Following the paint cycles, the latch and hinges were installed along with interior trim items.

Design Verification Testing

Prior to any formal verification studies, a series of assembly teardowns was completed to ensure adequate adhesion of the structural adhesive to the carbon fiber inner and a continuous bond along the perimeter. Figure 11 show an example inner panel and corresponding low density SMC outer. It should be noted that throughout the bond line, the adhesive bond strength is shown to be sufficient to promote fiber tear out of the outer panel around the entire perimeter. This is confirmation of good adhesion between the inner and outer as no evidence of cohesive failure or adhesive failure to the inner was present.

Figure 11. Decklid assembly teardown for validation of adhesive placement and bond strength

Figure 12. Physical testing of prototype decklid assemblies.

Following the teardown study, physical testing of decklid assemblies was performed to verify performance versus requirements. Figures 12 shows the physical representation of the load cases described as part of the CAE design optimization process above. As is observed, the latch pull and waterfall deflection test were performed at the component level, whereas the front corner deflection and torsional rigidity were performed on vehicle. Per the CAE predictions, the carbon/glass hybrid design was observed to be stiffer than the production version of the decklid (Table IV). This resulted in lower displacement, far exceeding requirements for each of the load cases.

Table IV. Pass/Fail results for prototype decklid physical testing

Test	Result units	Pass/Fail
Front Corner Deflection	Displacement -Z (mm)	Pass
Waterfall Deflection	Permanent Set (mm) Displacement Z (mm)	Pass
Latch Loads	Permanent Set (mm)	Pass
Torsional Rigidity	Angle / meter (degrees/m)	Pass

Manufacturing Robustness

As an initial evaluation of manufacturing robustness, an assembly dimensional study was performed for a small (n=5) sample of prototype parts. The intent was to understand repeatability of both the molding and bonding assembly process. Figure 14 shows a dimensional map of 3D scanned parts compared to engineering CAD data. The standard deviation, point to point, shows a consistent trend, part to part. The largest deviation from nominal appeared to be at the leading upper edge of the decklid, at a mid-point between the hinges. However, this is not surprising as these points are the furthest from any mounting locations. While it was not within the scope of this exercise, it is anticipated that improvements in dimensions could be achieved through charge placement development and revisions to the cooling fixtures.

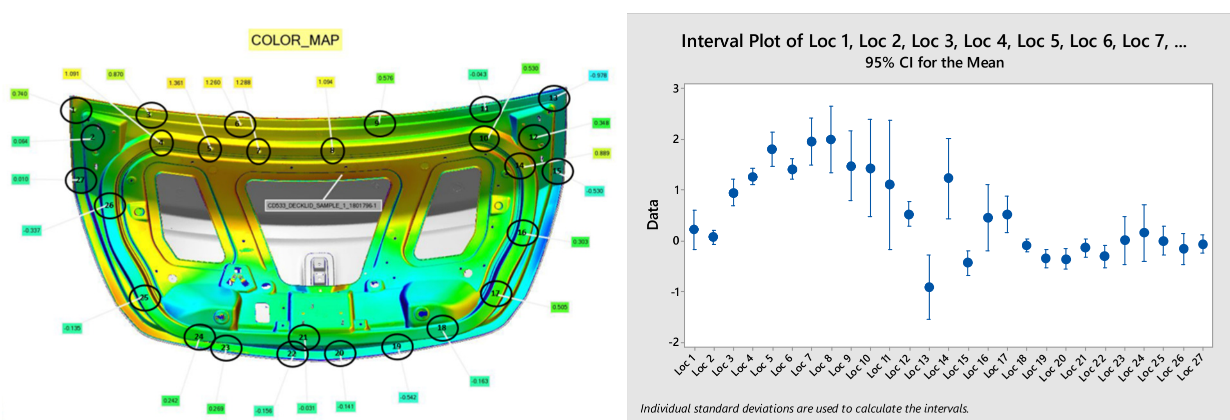


Figure 14. Dimensional variation of prototype decklid assemblies (n=5)

Summary and Conclusions

The on-going drive for improvements in vehicle fuel economy continues to spur new innovations in a wide array of vehicle technologies with vehicle mass reduction considered a critical element to achieving this goal. The latter has prompted renewed interest in lightweight body systems that take advantage of advances in materials such as high strength steel, light metals and composites. This report summarized a joint project undertaken through the Institute for Advanced Composites Manufacturing Innovation. The project partners consisted of Dow Automotive, Ford, DowAksa, Purdue, University of Tennessee, Michigan State and Oak Ridge National Lab. Research was focused on the development of a carbon fiber material system that could be adopted to support high volume manufacturing. A result of this joint development has yielded an epoxy based SMC that features room temperature shelf stable technology and a threefold increase in modulus compared to comparable glass based products. Following, laboratory prove-out, operations were scaled to enabled large part molding and component assembly. Subsequently, decklid assemblies were subjected to validation testing to confirm performance against original design predictions.

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References

1. Fuel Economy and Mass Trends, US Environmental Protection Agency Report, 2017
2. Ford Motor Company. Ford Sustainability Report 2014/15.