

THE INFLUENCE OF SMC FORMULATION, INNER PANEL THICKNESS, AND BOND STAND-OFFS ON BOND-LINE READ-THROUGH SEVERITY

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Abstract

Bond-line read-through (BLRT) is a distortion in a Class “A” surface that has no impact on the structural performance of automotive body panels, yet it diminishes the customer’s perception of the quality of a vehicle. The root causes of this distortion are poorly understood. When a panel is discovered to exhibit BLRT in production, the most straightforward solution is to increase the thickness of the outer panel – essentially adding weight for appearance. The Automotive Composites Consortium (ACC) has a multi-year project targeted at developing a better understanding of the causes of this distortion so that OEMs can use minimum thickness body panels and still meet customer expectations for surface appearance quality.

In the first phase of this project, the ACC developed a tool for quantifying the visual severity of BLRT-induced distortion. The ACC then partnered with Meridian Automotive Systems to complete a series of experiments to understand the relationship between material and process factors and BLRT severity. In addition, these experiments are intended to demonstrate how to minimize the severity of this distortion without increasing the thickness of the outer panel. Experiments reported previously investigated the effect of bond fixture temperature, outer panel material, and type of adhesive on BLRT severity. In addition, the influences of adhesive squeeze-out and adhesive volume on BLRT severity have also been previously reported.

Two experiments will be discussed in this paper. In the first experiment, the impact of SMC outer panel formulation, SMC inner panel formulation, and inner panel thickness on BLRT severity was investigated. That data showed that the SMC formulation used to mold the inner and outer panels of an assembly has an effect on BLRT severity. The material properties that best explain the experimental variation in this experiment were outer panel coefficient of linear thermal expansion (CLTE), outer panel bending stiffness, the interaction between the outer panel and inner panel CLTE, and the interaction between the outer panel and the inner panel bending stiffnesses. In the second experiment, bond gap standoffs were molded into the bond flange of the inner panel. These standoffs were removed from half of the inner panels prior to bonding. The other factors included in that experiment were inner panel thickness, type of adhesive, and bond gap. The addition of standoffs was found to create a significant amount of distortion in the outer panel directly above the standoffs. The other factors were found to have a statistically significant impact on BLRT severity as well.

Introduction

The exterior appearance of an automobile is one of the most important factors a customer considers when making a purchase decision. Consequently, manufacturers work hard to ensure that the surfaces produced are the Class "A" surfaces intended. While there are many benefits to using adhesives in automotive body components, their use can cause distortion in a Class "A" surface. This distortion has been termed "bond-line read-through" (BLRT).

There have been previous efforts to determine what causes this distortion [1-4]. Unfortunately, the results of experiments can contradict each other. This is most likely due to the fact that an instrument capable of objectively quantifying the severity of BLRT did not exist. The Automotive Composites Consortium (ACC) first collaborated with Visuol Technologies and EOS Technologies to develop a measurement system capable of providing an objective measure of this distortion. The basic principle of that methodology was reported previously [5].

Once the measurement system had been demonstrated to correlate to visual assessments of these distortions, the data the system provides could be used to quantify the severity of BLRT in experiments designed to identify the root causes of this distortion. The team first established a list of potential factors that were believed to contribute to BLRT. Since there were too many potential factors to investigate in a single experiment, a series of experiments was planned to investigate the impact that the proposed factors have on BLRT severity. These experiments have been completed with assistance from Meridian Automotive Systems at their plants in Shelbyville, IN and Rushville, IN. The results of the first experiments completed as part of this project have been reported previously [6-7].

The first of the two experiments that will be discussed in this paper investigated the relationship of SMC outer panel formulation, SMC inner panel formulation, and inner panel thickness on BLRT severity. The data from this experiment also showed that differences in surface roughness of the different SMC formulations used to mold outer panels can confound BLRT severity data. In the second experiment, small bond standoffs were molded into the bond flanges of the inner panels. These standoffs were then sanded off the bond flanges prior to bonding for half of the assemblies. That experiment then investigated the impact of the standoffs, inner panel thickness, adhesive, and bond gap on BLRT severity.

The ultimate objective of the ACC BLRT project is to develop a finite element (FE) model capable of predicting the occurrence of BLRT. As of this writing, preliminary modeling work had been completed and was reported in a companion paper by Fuchs and Deslauriers [8]. The data from the experimental studies discussed here is being used to develop and validate that model. In particular, the data collected from the assemblies from the standoff experiment was used to evaluate the correlation between the model's prediction and experimental results.

Bond-Line Read-Through Measurement

The BLRT measurement tool developed as part of this project is based upon the ONDULO technology. A detailed description of how the ONDULO technology works is available in [5]. The reader should note, however, that the BLRT measurement described in that publication is not the version of the algorithm that was used in this work. An updated description of the format of the algorithm and a demonstration of the correlation of the BLRT scores to visual assessments will be published at a later date.

The basic output of the ONDULO technology is a graphical representation of the curvature values at each point in a surface (i.e. a "curvature map"). The process used to convert the

curvature values to a quantitative measure of BLRT severity first filters the curvature data. The data is filtered twice to remove features that do not affect an observer's perception of BLRT. The first filter removes short wavelength defects such as paint induced waviness (e.g. orange peel) and high frequency surface roughness. The second filter removes long wavelength deformations such as panel warp or twist. An example of a filtered curvature map is shown in Figure 1. If the filtered curvature map contains defects that are not related to BLRT (e.g. paint pops, molding defects, ejector pin mark-offs, etc.) these defects can be removed from the data by a masking operation so that they do not affect the BLRT severity score. The green regions in Figure 1 are masked pixels.

The scale used to display curvature maps after completion of the two filtering operations is fixed to allow one to easily compare BLRT severity on different assemblies. In ONDULO curvature maps, curvature values close to zero are displayed as a medium gray color. As the curvature values increase in magnitude, the pixels become lighter (for large, positive curvature values) or darker (for large, negative curvature values). Pixels that are red or blue have a curvature value greater than the limit of the scale. The data in Figure 1 was collected on an assembly after bonding, but prior to priming or painting. The "background" curvature variation in the data from assemblies at this point can be due to general surface waviness, fiber read-through, or changes in surface reflectivity on the SMC. After assemblies are painted, "orange peel" and other irregularities in the paint result in additional "background" curvature variation.

To convert curvature data to a BLRT severity score, pixels with a curvature value above the limit found to correspond with visible distortions were isolated. Adjacent pixels were then grouped into potential individual defects. Groups of pixels were retained as an individual defect if the group was larger than the specified pixel count and had a mean curvature above the required threshold. An example of the BLRT score map derived from the filtered curvature map in Figure 1 is shown in Figure 2. Note that the ONDULO technology is more sensitive than the human eye, so even though the curvature map appears to show a distortion along all the bondlines, the bondlines on the upper left and lower right of the panel are not visible to the unaided eye.

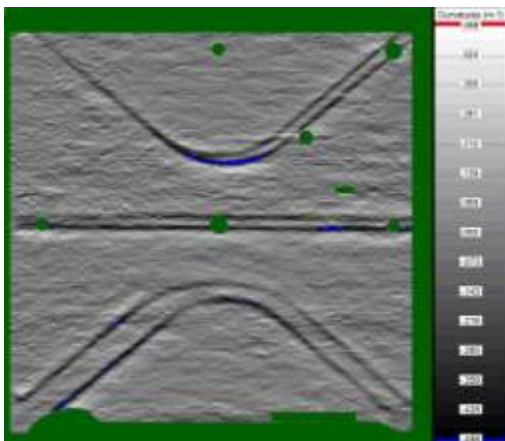


Figure 1. Curvature Map of a Panel with BLRT after Filtering and Masking.

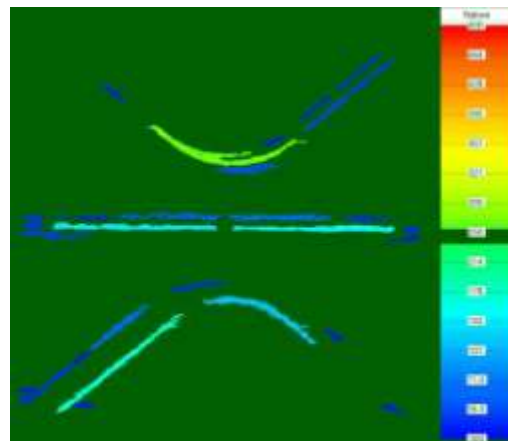


Figure 2. BLRT Score Map for the Panel in Figure 1.

The BLRT severity "score" for each individual defect on a panel is calculated by squaring the mean curvature for the defect and multiplying that by the size of the defect. The severity score for the entire panel is then the sum of the scores of all the defects on the panel.

Data was collected on the assemblies after bonding (i.e. "raw"), after priming at Meridian, and after painting. Whenever possible, the final statistical analysis was completed using the data from the panels after painting since in production panels are ultimately determined to be acceptable or unacceptable at that point in the process. In some cases, however, the data after painting may be unusable because of a high incidence of unrelated defects. In those cases, the data from the raw or primed panels may be analyzed. Additionally, the data collected at each point in the process can be analyzed to obtain preliminary results while waiting for subsequent painting operations to be completed. Furthermore, data for assemblies at each point in the process will be needed to demonstrate the predictive capability of the finite element model.

BLRT Root Cause Analysis Assemblies

The assembly used to investigate the root causes of BLRT simulated a representative automotive closure panel. Closure panel assemblies typically consist of a Class "A" outer panel that is bonded or hemmed to a structural inner panel. The inner panel carries the component loads and provides attachment points for hinges and trim. On a fully assembled vehicle it is largely hidden from the customer by the Class "A" outer panel on one side and interior trim panels or hood liners on the other.

The assemblies built in this project consisted of a 610mm x 610mm flat plaque bonded to a specially designed inner panel. A 610mm x 610mm flat "outer panel" was selected since the ACC owns both a compression and an injection molding tool of this size and configuration. In addition, it is relatively easy to obtain flat sheets of steel, aluminum, or thermoplastic to bond to the inner panel if that is required. The ACC molding tools can mold plaques in a variety of thicknesses. The outer panels used in both experiments discussed here were 2.5mm thick.

The 610mm x 610mm SMC "inner panel" used in these experiments was designed to have features common to both automotive hoods and roofs. A schematic of the inner panel is provided in Figure 3. The bond flanges that represent "lightening hole" flanges on hood inner panels are 12mm, 24mm, 36mm or 48mm wide. The remaining bonding flanges are 24mm wide. This tool was designed to mold panels from 1.0mm to 5.0mm thick. The inner panels used in the first experiment were molded 2.25mm or 2.75mm thick. The inner panels used in the second experiment were molded 2.5mm or 3.0mm thick. Twelve holes were drilled in the inner panel prior to bonding. These holes were used to hang the assemblies for painting, to allow fluid to drain from the assembly after power washing, and to vent the assembly cavities during paint bakes.

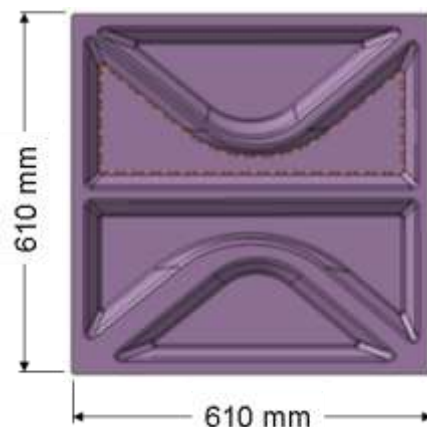


Figure 3. Schematic of the ACC BLRT Root Cause Analysis Inner Panel.

ACC BLRT Bond Cell

In production, SMC assemblies are typically bonded using a two-part adhesive. The adhesive must reach handling strength before the assemblies can progress through subsequent steps in the manufacturing process. Since two-part adhesives commonly take at least two hours to reach handling strength at room temperature, part suppliers typically fixture cure the assemblies to reduce the time required to manufacture a part.

To simulate this manufacturing process, an electrically heated bonding fixture was built to fixture cure the assemblies. The fixture was built with removable sections to allow the team to evaluate the effect of heating the entire panel (using a "full nest") as well as the effect of heating only the bond-lines (using a "skeletal nest"). To heat only the bond-lines, the heaters to the sections between the bond-lines can simply be turned off or the fixture sections can be removed. In all experiments discussed here, the fixture was used in the "skeletal" configuration with all of the sections between the bond-lines removed from the nest.

Adhesive was applied to the inner panel to ensure that the bead was properly located on the bond flanges of the inner panel. Consequently, the flat "outer panel" was located in the top of the fixture and held in place by vacuum using four suction cups. The inner panel was placed into the fixture after the adhesive has been applied to it and was also held in place by vacuum with four suction cups. Vacuum was used to hold both panels against the fixture to improve heat transfer between the fixture and the part and to improve the consistency of the bond gap around the panel.

A small up-acting bond press was built to actuate the fixture. The press closes on stops to control the gap between the fixture halves. Shims can be added to or removed from the corner posts to allow for varying panel thicknesses and for varying nominal bond gaps.

To cure assemblies, panels were held in place in the fixture with vacuum, the press was closed on the stops and the adhesive was fixture cured for the prescribed time and temperature. Vacuum was released, the press opened, and the assembly was removed from the fixture.

Panel Finishing

Exposing bonded assemblies to the thermal stresses of the painting process is believed to affect BLRT severity. In addition, BLRT is more visible to the unaided eye after painting. Consequently, all assemblies in the present studies were painted after bonding. Because the heat history to which a panel has been exposed is believed to affect BLRT severity, all assemblies, regardless of their composition, were painted using the same process.

The painting process was intended to be representative of the process an SMC closure panel would experience when painted on-line in an OEM paint shop using liquid primer. A typical on-line painting process consists of a conductive primer application at the SMC supplier, an e-coat application and bake, a second primer application and bake, and a basecoat/clearcoat application and bake. Since some of the assemblies in this work were bonded using a urethane adhesive (which will degrade at typical e-coat bake temperatures), the e-coat bake was omitted from the painting process used to paint these assemblies.

After ONDULO curvature data was obtained on the assemblies after bonding, the parts were primed at Meridian-Shelbyville using their production system. The assemblies were attached in a vertical orientation to paint racks built for these parts. Meridian-Shelbyville's conductive priming process included an initial power wash step typical to SMC painting processes. The parts were dried at 93°C for 15 min after power washing. A Red Spot UAE2560C conductive

primer/surfacer was then robotically applied at a nominal film build of 25µm. The primer was allowed to flash-off for 15 minutes. The temperature during flash-off started at 27°C but finished at 38°C. The prime was then baked at 115°C for 20 min. The assemblies were shipped to Ford Research & Advanced Engineering after priming.

After the curvature was measured on the primed assemblies, they were shipped to ACT Test Panels for top coating. The assemblies were first cleaned and dried. The panels were then primed using Dupont 708DM730 at a nominal film build of 23µm. The panels were baked at 152°C for 30 min to cure the prime layer. The panels were then painted with 13µm (nominal) Dupont 648DN027 black basecoat and 46µm (nominal) Dupont RK8014 clearcoat. The basecoat/clearcoat layers were allowed to flash off for 20 minutes prior to baking at 143°C for 30 min. The assemblies were returned to Ford Research & Advanced Engineering. Curvature data was collected a third time.

Format of the SMC Formulation and Inner Panel Thickness Experiment

SMC material properties were expected to influence BLRT severity. Unfortunately, many material properties are interrelated, making it impossible to change one material property without affecting other properties. This means that one cannot positively attribute a change in BLRT severity to a change in one particular property when comparing BLRT severity on panels molded from different SMC formulations. Nevertheless, the team wanted to investigate the sensitivity of BLRT distortions to changes in material formulation, so an experiment was designed to investigate that relationship. Since SMC formulations are typically referenced by density and the relationship between formulation density and other material properties is not necessarily linear, three different densities of SMC were chosen for the outer panels and for the inner panels. The density of the materials used to mold the inner and outer panels are summarized in Table I. The inner and outer panels were molded with the same formulation for the low density factor level and for the high density factor level. The mid-density formulation used to mold the outer panel was different from that used to mold the inner panel.

The thickness of the inner panel was also expected to influence BLRT severity, so inner panel thickness was included as another variable in this experiment. The inner panels were molded at two thicknesses in this experiment. Those factor levels are summarized in Table I as well. The experiment was structured as a full factorial experiment with three replicates, so a total of fifty-four assemblies were manufactured. The material properties that were considered as potential predictors in the statistical analysis are summarized in Table II for each formulation.

Table I. Factors Included in the Density & Inner Panel Thickness Experiment

Factor	Low Level	Mid Level	High Level
SMC Outer Panel Density	1.28 g/cc	1.48 g/cc	1.89 g/cc
SMC Inner Panel Density	1.28 g/cc	1.55 g/cc	1.89 g/cc
Inner Panel Thickness	2.25 mm	NA*	2.75 mm

*There were only two levels for inner panel thickness included in this experiment.

Table II. Material Properties of Interest for the SMC Formulations in Table I

Material Property	Formulation			
	A	B	C	D
Density (g/cc)	1.28	1.48	1.55	1.89
CLTE ($10^{-5}/^{\circ}\text{C}$)	1.58	1.53	2.20	1.68
Tensile Modulus (GPa)	12.2	15.0	9.2	8.2

The low density Class "A" SMC material (1.28 g/cc density) used in this experiment required that an in-mold coating be applied to the "A" surface of the panel to achieve a Class "A" surface. To determine whether application of the in-mold coating affected the results, an additional six assemblies were made with 1.89g/cc density outer panels that had been in-mold coated. Three of those assemblies were built with 2.25mm thick 1.89g/cc density inner panels. The other three assemblies were built with 2.75mm thick 1.89g/cc density inner panels.

Results of the SMC Density and Inner Panel Thickness Experiment

ONDULO data was collected on all of the assemblies in the "raw" state. Unfortunately, the reflectivity of the outer panel surface was dependent upon the SMC formulation used to mold the panel. Differences in surface reflectivity can affect the ONDULO measurements, so a comparison of the raw data would not necessarily be reliable. This was especially true for the assemblies made with outer panels that had been in-mold coated. The surface reflectivity of in-mold coating is more similar to that of conductive prime than it is to that of a Class "A" SMC. Consequently, comparing BLRT data from assemblies made using an in-mold coated outer panel to assemblies made with regular density SMC could be misleading. For this reason, that data was not analyzed.

Another issue discovered after the assemblies were manufactured was that the surface quality of the outer panels varied with the formulation. This became a problem when trying to collect and analyze the BLRT severity data. The difference in waviness as a function of material formulation was evident in the ONDULO data after both priming and painting, but it was only visible on the surface after painting. Unfortunately, waviness due to the material formulation was not filtered out by the standard data analysis process. Examples of curvature maps collected on painted assemblies after standard filtering for one assembly manufactured with each of the SMC formulations are shown in Figures 4-6.

A comparison of Figures 4-6 illustrates that panels molded with both the 1.55 g/cc density formulation and the 1.28 g/cc density formulation had a higher level of "background curvature" variation than the panels molded with the 1.89 g/cc density formulation. This difference in surface roughness was visible after painting. Since the difference in surface roughness was not removed from the data by the filtering processes and the surface roughness resulted in high measured curvature values across the surface, particularly in the 1.55 g/cc formulation, this roughness was identified by the BLRT algorithm as a defect. The surface appearance of these panels after painting was unacceptable; however, the intention of this experiment was to determine the impact of SMC formulation on BLRT induced distortions rather than on overall surface appearance. Since the background curvature due to material formulation was not filtered out of the data, its contribution to the BLRT severity score is confounded with the contribution of BLRT-induced distortions. This confounding of two unrelated factors made the data after painting unusable for determining the relationship between the material and panel properties and BLRT severity.

Since the data after bonding and after painting in this experiment were not usable, the data obtained after priming was analyzed. There was still a difference in surface roughness between different material formulations after priming; however, the magnitude of the background curvature was lower after priming than it was after painting. Therefore, it could be more easily decoupled from the curvature due to BLRT distortions. Consequently, the data collected after priming was analyzed. The reader should note, however, that data from primed assemblies should not be compared directly to data from painted assemblies gathered in other experiments due to the potential impact of differences in surface reflectivity on the ONDULO measurements.

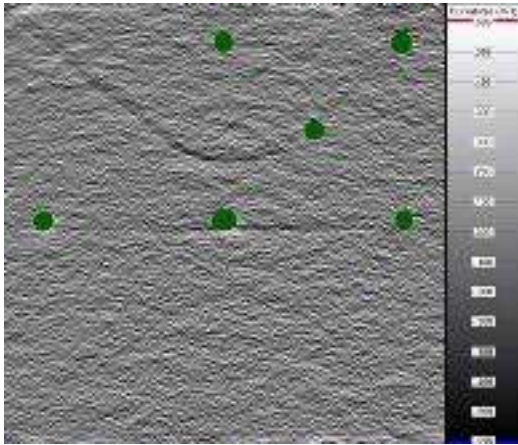


Figure 4. Curvature Map for an Assembly made with a 1.89 g/cc Density Outer Panel.

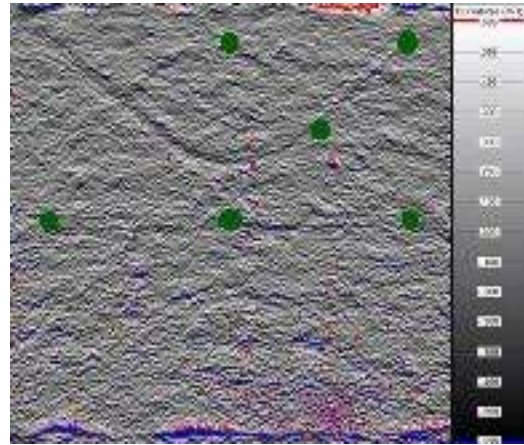


Figure 5. Curvature Map for an Assembly made with a 1.55 g/cc Density Outer Panel.

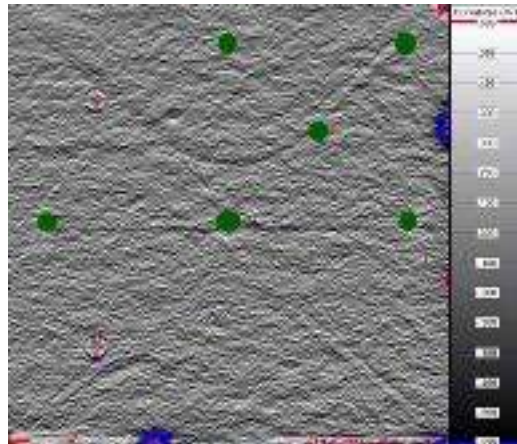


Figure 6. Curvature Map for an Assembly made with a 1.28 g/cc Density Outer Panel.

Since several material properties changed when the SMC formulation changed, the data was analyzed first using a General Linear Model (GLM) analysis with the SMC formulation as the predictor. A GLM analysis converts the predictor settings to coded values, so the results of this analysis only indicate whether changing the factor level influences the output (i.e. the BLRT severity score), not the relationship between particular factor settings and the output. The GLM analysis found that the inner panel formulation and the outer panel formulation had statistically significant influences on BLRT severity while the inner panel thickness did not. The only interaction term found to be statistically significant was inner panel formulation x outer panel

formulation. The main effects plot for panel formulation versus BLRT severity is provided in Figure 7. The interaction plot for inner panel formulation \times outer panel formulation is shown in Figure 8.

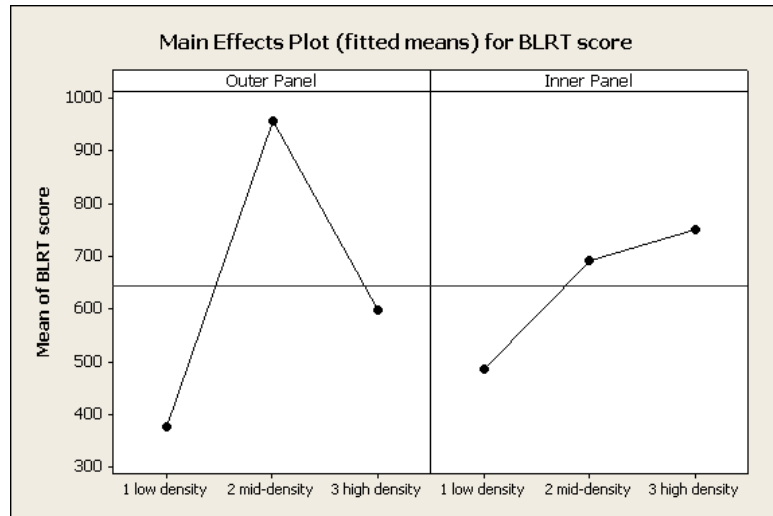


Figure 7. Main Effects Plots for Statistically Significant Factors in the SMC Density Experiment.

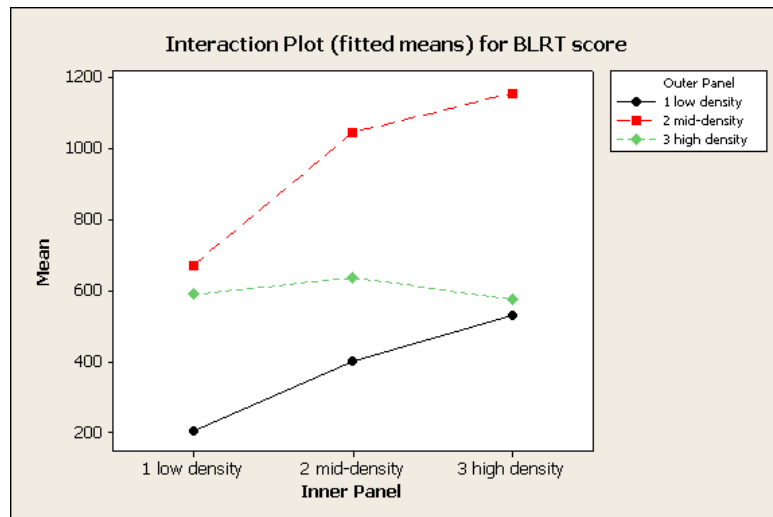


Figure 8. Interaction Plot for Statistically Significant Factors in the SMC Density Experiment.

Figure 7 shows that BLRT severity in the assemblies made with 1.55 g/cc density formulation was higher than that of the other assemblies. Note that this result is likely to have been somewhat confounded by the higher background curvature caused by poor surface quality of that formulation since it was not possible to completely eliminate the influence of the surface quality on the BLRT severity scores. Nevertheless, the fit of the data to the model illustrated in Figures 7 and 8 was acceptable, with an R-Sq(adjusted) value of only 70.1%¹.

¹ The R-Sq(adj) value is an indication of the correlation of the model and the data. The minimum acceptable R-Sq(adj) for a "good fit" is 64%, or 80% correlation ($0.8^2 = .64$).

While the results of the GLM analysis were encouraging, the team really wanted to understand which material property or properties were responsible for the variation in BLRT severity seen in these assemblies. To better understand that relationship, a series of regression analyses were completed. The regression equations in which all of the predictors were found to be statistically significant at the 95% confidence level are summarized in Table III.

Table III. Summary of the Regression Analyses Completed for the SMC Formulation Experiment

Model ID	Regression Equation (i.e. Model)	R-Sq(adjusted) value
a	$y = \beta_0 + \beta_1 * \rho_{OP}$	8.9%
b	$y = \beta_0 + \beta_1 * \rho_{OP} \times \rho_{IP}$	22.8%
c	$y = \beta_0 + \beta_1 * CLTE_{OP}$	39.3%
d	$y = \beta_0 + \beta_1 * CLTE_{OP} + \beta_2 * CLTE_{IP}$	47.5%
e	$y = \beta_0 + \beta_1 * CLTE_{OP} + \beta_2 * CLTE_{OP} \times CLTE_{IP}$	49.0%
f	$y = \beta_0 + \beta_1 * CLTE_{OP} \times CLTE_{IP}$	26.9%
g	$y = \beta_0 + \beta_1 * E_{OP}$	19.7%
h	$y = \beta_0 + \beta_1 * CLTE_{OP} + \beta_2 * CLTE_{OP} \times CLTE_{IP} + \beta_3 * E_{OP} + \beta_4 * E_{IP}$	66.8%
i	$y = \beta_0 + \beta_1 * CLTE_{OP} + \beta_2 * CLTE_{OP} \times CLTE_{IP} + \beta_3 * E_{IP} + \beta_4 * E_{OP} \times E_{IP}$	67.5%
j	$y = \beta_0 + \beta_1 * D_{OP}$	19.7%
k	$y = \beta_0 + \beta_1 * CLTE_{OP} + \beta_2 * CLTE_{OP} \times CLTE_{IP} + \beta_3 * D_{OP} + \beta_4 * D_{OP} \times D_{IP}$	66.4%

Where:

- β_i are the regression coefficients
- ρ_{OP} is the outer panel density
- ρ_{IP} is the inner panel density
- $\rho_{OP} \times \rho_{IP}$ is the interaction between outer panel density and inner panel density
- $CLTE_{OP}$ is the coefficient of linear thermal expansion for the outer panel SMC formulation
- $CLTE_{IP}$ is the coefficient of linear thermal expansion for the inner panel SMC formulation
- E_{OP} is the Young's Modulus for the outer panel SMC formulation
- E_{IP} is the Young's Modulus for the inner panel SMC formulation
- $CLTE_{OP} \times CLTE_{IP}$ is the interaction between $CLTE_{OP}$ and $CLTE_{IP}$
- $E_{OP} \times E_{IP}$ is the interaction between E_{OP} and E_{IP}
- D_{OP} is the bending stiffness of the outer panel
- D_{IP} is the bending stiffness of the inner panel
- $D_{OP} \times D_{IP}$ is the interaction between D_{OP} and D_{IP}

Bending stiffness of the panels was approximated assuming isotropic properties and was based solely on the theoretical bending stiffness of the flat plate via Equation 1:

$$D = \frac{Et^3}{12(1-\nu^2)} \quad (1)$$

Even though the inner panel used in this work is not a flat panel, modeling of BLRT severity in the assembly [8] has found BLRT-induced deformations to be very localized phenomena.

Consequently, Equation 1 is a reasonable approximation for the local inner panel bending stiffness even though the inner panel is not a flat plate.

Table III shows that the three prediction equations that best explain the variation in the BLRT severity scores are regression models h, i, and k. These prediction equations were the only models to explain at least 80% of the variation in the data (i.e. had an R-Sq(adj) value above 64%). The difference between these prediction equations is that models h and i assume the Young's modulus influences BLRT severity while model k assumes the panel bending stiffness is the significant characteristic. In addition, models h and i require that the properties of the inner panel influence BLRT severity whereas model k relies only upon the outer panel properties and the interactions between the outer and inner panel properties. To determine which of these prediction equations is more likely to define the correct relationship, one should consider previous experimental results.

While models h and i have slightly higher R-Sq(adj) values than model k, inferring that the inner panel modulus influenced BLRT severity would be inconsistent with the earlier finding from this experiment; namely, that the inner panel thickness did not have a statistically significant affect on BLRT severity. These two findings are inconsistent because both the inner panel modulus and inner panel thickness affect the panel bending stiffness, as shown in Equation 1. Conversely, the inference from model k is that the outer panel bending stiffness affects BLRT severity. This conclusion is supported by previous experimental results [6]. Consequently, the prediction equation that appears to best explain the variation in BLRT severity in this experiment is model k, in which the outer panel coefficient of linear thermal expansion (CLTE), the outer panel bending stiffness, the interaction between the outer panel and inner panel CLTE, and the interaction between the outer panel and the inner panel bending stiffnesses all play a role in the BLRT severity. In addition, the fact that this equation explains 80% of the experimental variation and the fact that the included terms correlate well with the results of the initial modeling work by Fuchs and Deslauriers [8] is extremely encouraging as it indicates that true FE prediction of BLRT severity may be achievable.

One potential concern regarding the validity of those results was that application of in-mold coating (IMC) to the outer panels molded with the 1.28 g/cc density formulation could have influenced the results for those assemblies. To determine whether IMC was likely to have confounded the results, assemblies were made with in-mold coated, 1.89 g/cc density outer panels as discussed earlier. The BLRT severity on these assemblies was then compared to the BLRT severity on the equivalent assemblies made with uncoated panels. An example of an assembly made with an uncoated, 1.89 g/cc density outer panel and one with an in-mold coated, 1.89 g/cc density outer panel are provided in Figures 9 and 10. Those two curvature maps illustrate the typical difference between the assemblies built with coated and uncoated outer panels. These figures indicate that there is not much difference between the two sets of assemblies. This apparent equivalence of assemblies made with and without IMC was substantiated by statistical analysis of the data. Two sample t-tests were completed to determine whether there was a statistically significant difference between the assemblies made with and without IMC. These analyses, in which the level of significance (p -value)² for the assemblies made with 2.25mm thick inner panels was 0.33 and the p -value for assemblies made with 2.25mm thick inner panels was 0.77, showed that addition of in-mold coating had no statistically significant impact on BLRT severity regardless of the thickness of the inner panel. Consequently, the results discussed earlier for the assemblies made with in-mold coated, 1.28 g/cc density outer panels are likely to be valid regardless of whether these panels are made with or without IMC.

² A p -value less than 0.05 indicates that two populations are statistically different at the 95% confidence level. P -values greater than 0.05 indicate that there is not a statistically significant difference between the two sets of data.

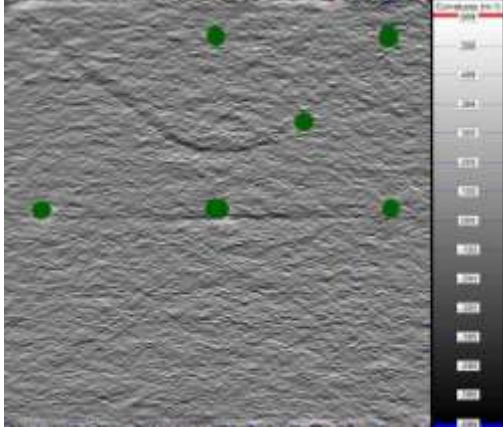


Figure 9: A Painted Assembly Built using an Uncoated 1.89 g/cc Outer Panel.

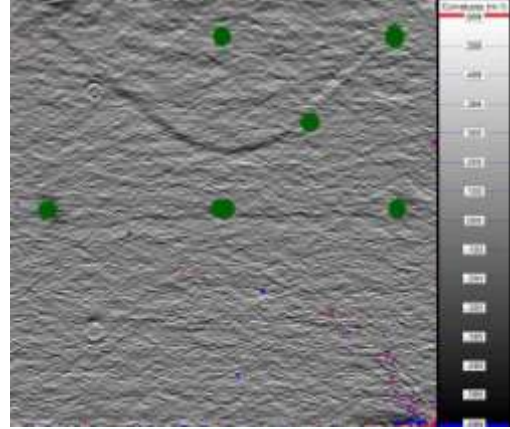


Figure 10: A Painted Assembly Built using an In-Mold Coated 1.89 g/cc Outer Panel.

Format of the Standoff Experiment

Parts manufacturers have reported that adding standoffs (i.e. small raised areas molded into the bond-line) to an inner panel can result in high levels of BLRT on the outer panel above the standoffs. To investigate this, the ACC had 0.5mm tall, oval standoffs cut into the ACC BLRT inner panel tool. Two sizes of standoffs were cut into the bond flanges: the smaller was 8.5mm x 5mm, the larger was 10mm x 8mm. A schematic of the inner panel illustrating the size and location of the standoffs is provided in Figure 11.

Manufacturers have also anecdotally reported that other factors can influence BLRT when standoffs are present in the bond-line. Consequently, those factors were included in the experiment as well. Those factors were inner panel thickness, the type of adhesive, and bond gap. The factors and factor levels included in this experiment are summarized in Table IV. The experiment was structured as a full factorial experiment with three replicates, so a total of forty-eight assemblies were manufactured.

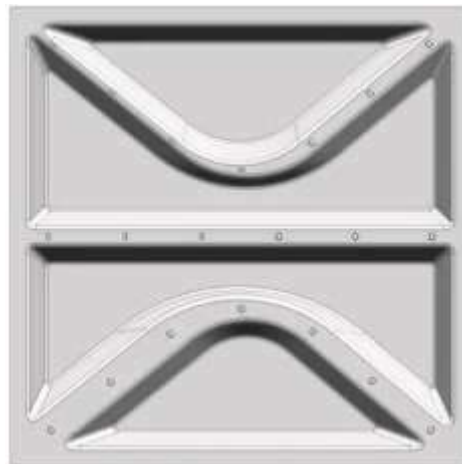


Figure 11. Inner Panel Schematic Illustrating the Location and Size of the Added Standoffs.

Table IV. Factors and Factor Levels for the Standoff Experiment

Factor	Low Level	High Level
Standoffs	No	Yes
Inner Panel Thickness	2.5 mm	3.0 mm
Adhesive	Urethane	Epoxy
Bond Gap	0.75 mm	1.25mm

The reader should note that the amount of the flange covered by adhesive has been found to have a significant impact on BLRT severity. Consequently, the amount of adhesive dispensed was increased when assemblies were made with the larger bond gap to maintain a consistent flange coverage level. Since the inner panel mold had been modified to mold the standoffs into the inner panels, the standoffs had to be removed from the inner panels prior to bonding for the "no standoff" factor level. The standoffs were manually removed from the inner panels using an orbital sander for those assemblies.

Preliminary Results from the Standoff Experiment

All of the assemblies in this experiment were made using 1.89 g/cc density, Class "A" SMC, so the ONDULO data collected on the assemblies after bonding (i.e. "raw") was consistent and of good quality. As of this writing, the assemblies are in the process of being painted, so the results reported here are based on the data collected on the raw assemblies.

The impact of adding standoffs to the inner panel was evident even before a statistical analysis of the data was completed. Figure 12 is a curvature map for an assembly built using an inner panel with standoffs. The blue or dark gray dots in this figure are areas on the outer panel with very high curvature. These areas are located directly above the standoffs on the inner panel. Figure 13 is the curvature map for an assembly built using the same parameters used to manufacture the assembly in Figure 12, except that the standoffs were removed from the inner panel prior to bonding. The BLRT score maps for these two panels are shown in Figures 14 and 15. The reader should note that the outside edges of the outer panels were sanded after molding by the molding operator in this set of panels. When SMC panels are sanded, that creates a significant amount of "background curvature" in the sanded areas. As a result, the edges of the assemblies were masked prior to analyzing the data to avoid having the sanded areas confound the BLRT data.

Figures 12-15 confirm that adding standoffs to the bond flange causes a significant amount of BLRT. To determine the effect of all of the factors included in this experiment, the raw data from these assemblies was analyzed using a standard ANOVA analysis. The model that best fit the data included all of the main factors and all interactions except adhesive \times inner panel thickness. The fit of the data to that model was very good, with an R-Sq(adjusted) value of 95.6%. The main effects plots are provided in Figure 16. The interaction plots are provided in Figure 17. The level of significance (p -value)³ for each factor or interaction is displayed in each plot.

³ In this context, p -values less than 0.05 indicate that the factor is statistically significant at the 95% confidence level.

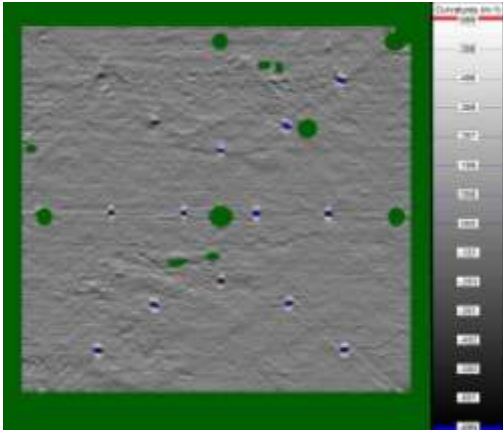


Figure 12: Example of a Curvature Map when the Assembly Inner Panel had Standoffs.

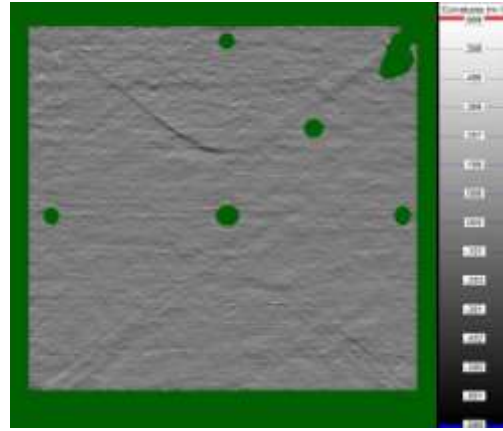


Figure 13: Example of a Curvature Map when the Assembly Inner Panel did not have Standoffs.

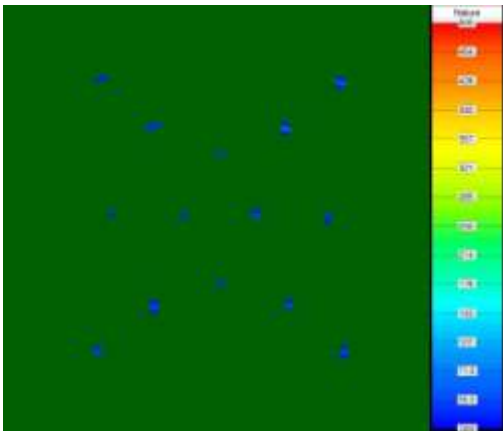


Figure 14: BLRT Score Map for the Assembly shown in Figure 12.

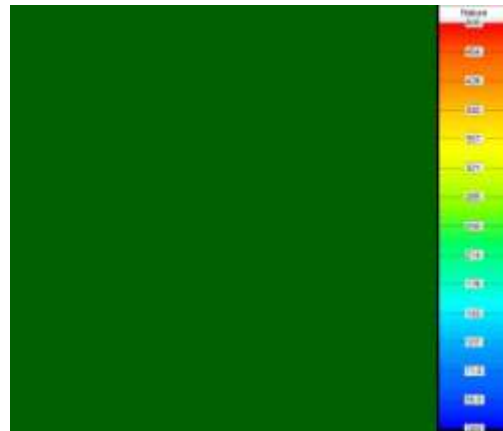


Figure 15: BLRT Score Map for the Assembly shown in Figure 13..

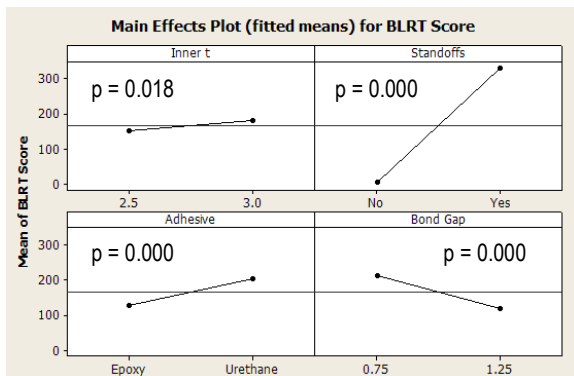


Figure 16: Main Effects Plots for the Raw Data from the Standoff Experiment.

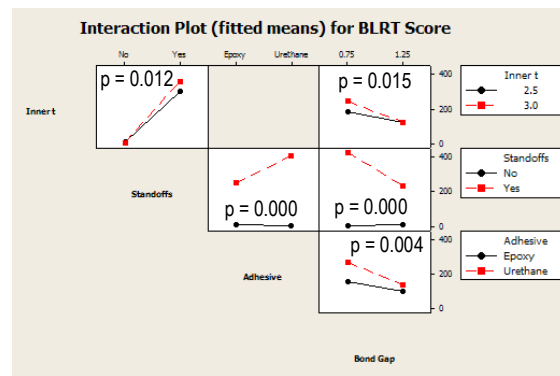


Figure 17: Interaction Plots for the Raw Data from the Standoff Experiment.

This was the first experiment in which assemblies built with urethane adhesive had higher levels of read-through than assemblies built with epoxy adhesive, as shown in Figure 16. That result was surprising and initially appeared to contradict the results of earlier experiments. The

finding that there was an interaction between standoffs and the type of adhesive, however, provided some indication that this unusual result did not necessarily contradict earlier findings. The FE modeling work described in the companion paper by Fuchs and Deslauriers [8] provided additional evidence that this result is compatible with previous results. That work found that urethane causes higher levels of read-through when standoffs were present because the difference between the CLTE of the SMC and the CLTE of the urethane is larger than the difference between the CLTE of the SMC and the CLTE of the epoxy. That larger CLTE difference resulted in a greater difference in actual shrinkage in the thick adhesive around the standoff as compared to that in the thin adhesive on top of the standoff. The reduced shrinkage on top of the standoff essentially pushed the outer panel out above the standoff. Figures 12 and 14 illustrate that that deformation was quite visible. The modeling work implies that a gradual change in bond thickness, rather than the abrupt change caused by standoffs, may not cause visible BLRT. That hypothesis, however, will have to be tested.

The reduction in BLRT severity noted when the bond gap was increased confirmed results found previously. The reduction in BLRT severity with increasing bond gap appeared to be even more pronounced when standoffs were present. This should not be surprising when one considers that increasing the bond gap from 0.75mm to 1.25mm with a 0.5mm standoff present effectively triples the amount of adhesive above the standoff. In addition, the relative amount of adhesive above the standoff as compared to that around the standoff increased from only 33% in the 0.75mm gap condition to 60% in the 1.25mm gap condition. The smaller difference in adhesive volume above the standoff as compared to that around the standoff in the thick gap condition caused less difference in shrinkage above versus around the standoff. When the difference in shrinkage was reduced, the deformation of the outer panel above the standoff was reduced as well.

The fact that the inner panel thickness was found to be statistically significant in this experiment also initially appeared to contradict the results of the SMC formulation experiment. Closer examination of the results, however, showed that not to be the case. Consider the interaction plot for inner panel thickness and standoffs in Figure 17. That plot shows that when standoffs were not present, then the inner panel thickness had no effect. When standoffs were present, assemblies made with a thicker inner panel had slightly higher levels of read-through.

The assemblies from this experiment were in the process of being painted when this paper was written. The data collected on painted assemblies will be analyzed when it is available.

Summary

Two experiments were completed to investigate the root causes of bond-line read-through (BLRT). BLRT severity data obtained using the ONDULO technology was used to quantify the severity of the distortions on the assemblies manufactured in these experiments. The first experiment varied the formulation of the SMC used to mold the outer panels and the inner panels and also varied the inner panel thickness. Variations in the surface quality of the SMC as a function of formulation could not be completely filtered out of the ONDULO data. This impacted the quality of the conclusions that could be drawn regarding the effect of material changes on BLRT severity, particularly after the assemblies had been painted. Nevertheless, analysis of the data after priming was useful in understanding the relationship between material properties and BLRT severity. Several material properties changed when the SMC formulation changed, so a series of regression analyses were completed to determine which material properties best explained the variation in the data. The regression equation that resulted in the best fit of the data included the outer panel coefficient of linear thermal expansion (CLTE), the

outer panel bending stiffness, the interaction between the outer panel and inner panel CLTE, and the interaction between the outer panel and inner panel bending stiffnesses. This regression equation explained just over 80% of the variation in the data. Inclusion of CLTE and bending stiffnesses in the prediction equation resulted in much better prediction of BLRT severity than any analysis using SMC density as a predictor. This experiment also found that the thickness of the inner panel did not affect BLRT severity.

The second experiment investigated the impact of inner panel thickness, adhesive type, adhesive bond gap, and the presence of standoffs on the bond flange on BLRT severity. That experiment showed that adding bond standoffs to the bond flange causes a significant amount of BLRT. The other factors included in that experiment were also found to have a statistically significant effect on BLRT severity, although in some cases that was only true when bond standoffs were present. In addition, statistically significant interactions were found between most of the factors in the experiment. The results from this experiment correlate with results from previous experiments.

The results from these experiments provide the best data yet regarding which material and process factors have the greatest impact on BLRT severity in bonded SMC assemblies. These experiments provide useful data for guiding and validating the development of a finite element model to predict the severity of BLRT. To date, the results from the ACC experimental work and the preliminary FE modeling work contracted to Multimatic Engineering Services Group [8] have correlated well. These initial results indicate that development of an FE model that can predict BLRT severity prior to building physical assemblies is an achievable goal.

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