

Design and Manufacturing Strategies to Eliminate Visible Adhesive-Induced Surface Distortions in Bonded Automotive Class "A" Assemblies

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Abstract

Bond-line read-through (BLRT) is a distortion in the "Class A" surface of a bonded assembly caused by differential shrinkage between the substrates and the adhesive. When these distortions are severe enough to be visible customers consider them to be unacceptable. In automotive applications in which a structural inner panel is bonded to a Class "A" outer panel, the coefficient of thermal expansion of the adhesive is higher than that of the substrate. This difference in thermal expansion between the two materials causes the outer panel to be distorted at room temperature if the assemblies were bonded at elevated temperature. The distortions become visible when other factors exacerbate the severity of these naturally occurring distortions.

The material and process factors that determine the severity of BLRT-induced distortions, and the experimental and analytical work from which those relationships were determined, have been reported previously. Understanding of the cause of and the factors that contribute to BLRT allows one to then develop design and manufacturing strategies for minimizing the severity of adhesive-induced surface distortions in bonded assemblies. The design and manufacturing strategies that are the final outcome of the Automotive Composite Consortium's BLRT project are presented.

Introduction

The exterior appearance of an automobile is one of the most important factors a customer considers when choosing a vehicle. While exterior design is typically a customer's primary appearance consideration, customers also have very exacting standards regarding the appearance of the so-called Class "A" surfaces. 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 distortions in a Class "A" surface. Distortion caused by adhesives is often referred to as bond-line read-through (BLRT).

BLRT has no impact on the structural performance of automotive body panels, yet it diminishes the customer's perception of the quality of a vehicle. Because the most straightforward solution to eliminating visible BLRT is to increase the thickness of the outer panel – essentially adding weight for appearance – the Automotive Composites Consortium (ACC) undertook a multi-year project to develop a better understanding of the causes of this distortion. The goals of the project were to a) develop an understanding of the material and process factors that cause BLRT-induced distortions to be visible on the surface of a component, b) develop a validated finite element model that can predict the occurrence and severity of BLRT, and c) establish material and process guidelines for automotive companies and suppliers to follow to insure that original equipment manufacturers (OEMs) will be able to specify minimum thickness (i.e. weight) panels while ensuring that those components will meet customer expectations for surface appearance.

BLRT has been seen in automotive applications periodically ever since bonded assemblies were introduced in the industry. Other researchers have completed studies on particular aspects of the cause of this distortion [1-4]. No experimentally based, systematic study, however, had been completed on this topic. One of the reasons for this may have been that all assessments of BLRT severity had to be done subjectively by a jury because an

objective, numerical measurement for quantifying the visual severity these distortions did not exist. Consequently, the first task that had to be completed was to develop a measurement that would quantify the severity of these distortions in a way that correlated with visual assessment of the severity of these distortions. The measurement developed as part of this project is described in detail elsewhere [5].

Once a method to obtain objective, quantitative data was available, a series of experiments could be completed to establish the relationship between material and process factors and BLRT severity. The data from those experiments was also used to determine the material properties and finite element methodology necessary to correctly predict BLRT severity analytically. The material and process factors that were found to have the most significant influence on the severity of these distortions in the physical and analytical experiments have been summarized in the literature [6-13]. This paper summarizes design and manufacturing guidelines developed to control those factors and eliminate visible distortions from production assemblies.

Background

Bond-line read-through was shown to be caused by differential shrinkage between the adhesive and the substrate [9, 13]. For adhesives in which the chemical shrinkage is minimal (e.g. epoxies and many urethanes), the primary source of shrinkage is thermal shrinkage as the adhesive cools from the temperature at bonding to room temperature. If the adhesive in an assembly is allowed to cure at room temperature, there will be no distortion in the outer panel at room temperature.

Given that most adhesives used to bond automotive closure panel assemblies require at least 30 minutes to reach handling strength at room temperature, it is generally impractical to bond composite assemblies at room temperature in high volume applications. As a result, most automotive closure panels are bonded at elevated temperature. The distortions that result from thermally induced shrinkage, however, will not necessarily be severe enough to be visible. In order to be visible, other factors must exacerbate the severity of the distortion. The factors that have the greatest effect on the severity of BLRT-induced distortions are: a) local variations in the thickness of the adhesive bead, b) the adhesive material properties, and the c) sectional stiffness of the substrate. It is then these variables that must be controlled in the design and manufacture of assemblies if one is to manufacture assemblies that are free of visible distortions.

Most automotive Class "A" composite assemblies are made from sheet molding compound (SMC). SMC is a class of composites consisting of polyester resin, glass fiber, calcium carbonate filler, and other additives. The experimental and analytical work in this project was completed using SMC and metal substrates. The authors are confident in the applicability of the findings summarized here to assemblies made with those substrates. There may be idiosyncrasies exhibited by other plastic or composite substrates that are not fully addressed by the results of this project.

BLRT Measurement

Distortions are visible because they alter the intended curvature of the surface. The degree to which a surface distortion, such as BLRT, will be visible has been shown to be determined by magnitude of the unintended curvature induced in the surface by these distortions. A detailed explanation of why curvature is the appropriate surface characteristic for quantifying the severity of surface distortions can be found in the literature [5].

The severity of BLRT induced surface distortions cannot be captured using photography. The severity of distortions can, however, be illustrated using curvature maps. Mathematically, curvature is the second derivative of the displacement in the surface and has units of 1/m. In a curvature map, the local curvature at each pixel in an image of the surface is displayed graphically. The raw curvature data is post processed to

eliminate distortions in the surface that are unrelated to BLRT and to highlight the wavelengths that affect one's perception of the severity of these defects [5]. The images presented here have also been converted to black and white. Conversion of the curvature maps to black and white removes some of the subtleties in the data; nevertheless, the general conclusions can still be illustrated. An example of a curvature map after post processing and conversion to black and white is shown in Figure 1.

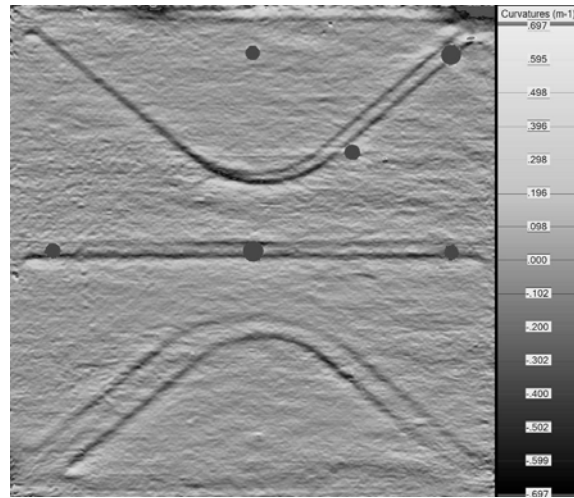


Figure 1: A Curvature Map for an Assembly with Significant BLRT after Post Processing

In the curvature maps presented here, pixels with 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). The scale used to display curvature maps after filtering is fixed in this work ($\pm 0.7\text{m}^{-1}$) to allow one to easily compare BLRT severity on different assemblies. The curvature maps produced by the instrument used in this work are typically displayed using color to display pixels with a curvature value that exceed the limits of the scale. That information is compromised when the curvature maps are converted to black and white.

Design Guidelines

The adhesive used to bond a Class "A" automotive assembly is typically determined by the structural requirements of the assembly and the temperature at which the assemblies will be painted. Once the adhesive is selected, the temperature at which the parts will be bonded is determined by the cycle time necessary to produce the volume of parts needed for the program at the price the OEM is willing to pay. Once the adhesive and the temperature at which it will be cured are fixed, the most important remaining variable that affects BLRT severity is the consistency of the adhesive thickness. While controlling the consistency of the adhesive thickness is predominantly the responsibility of the manufacturing facility, the design of a component will affect whether it will be easy or difficult to manufacture parts in which adhesive-induced distortions are not visible. If the part design results in a condition that makes visible BLRT-induced distortions likely, increasing the thickness of the outer panel can reduce the severity of the distortion to the point that it will not be visible. Increasing the thickness of the outer panel, however, should be considered only when all other options have been exhausted. Design strategies for minimizing the likelihood that visible BLRT distortions will occur are discussed in detail below.

Variations in the Bond Gap Thickness

The consistency of the adhesive's thickness is the factor with the greatest impact on the magnitude of BLRT-induced distortions. These distortions are the result of the adhesive having a higher coefficient of thermal expansion (CTE) compared to that in the substrate as the adhesive cools from bonding temperature to room temperature. Consequently, a thicker adhesive bead will shrink more than a thinner adhesive bead,

resulting in a more severe distortion. Furthermore, if the thickness of the adhesive changes locally, there will be a localized differential in shrinkage across the width of the adhesive bead that will result in a severe, and quite visible, distortion. This is illustrated in Figure 2.

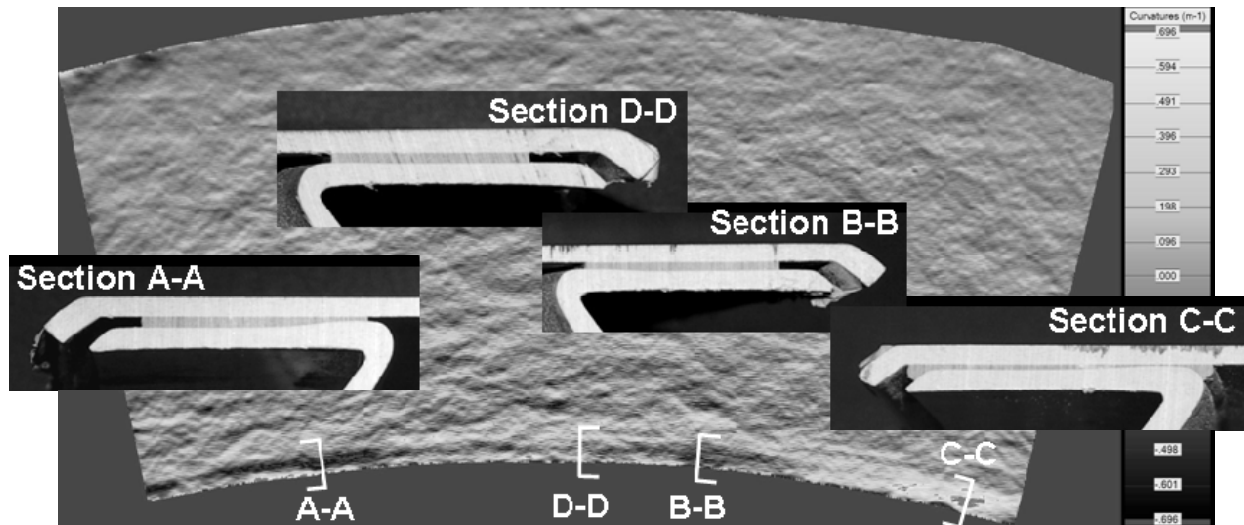


Figure 2: Effect of Localized Changes in Adhesive Thickness on BLRT Severity

Figure 2 shows that the thickness of the inner panel across the width of the bond flange in this assembly varied along the length of the bond flange. Why that occurred could not be explained by the component manufacturer; however, this illustrates one design condition that should be avoided. The variation in inner panel thickness can be seen clearly in Section A-A. Because the thickness of the inner panel varied, that caused the thickness of the adhesive to vary as well. The corresponding curvature data shows that the distortion in the outer panel was very high at that location. The distortion is a direct result of the change in adhesive thickness across the width of the bead. There was also variation in the thickness of the inner panel across the width of the bond flange at section B-B, but the variation was less pronounced than that at section A-A, and correspondingly the distortion in the outer panel, while still high, was reduced as well. Finally, at Section D-D the inner panel thickness was consistent across the width of the bond flange. The thickness of the adhesive was then also consistent at that location and as a result the adhesive induced distortion in the outer panel at that location was not severe enough to be visible. The final section in Figure 2, section C-C, illustrates a condition that has been termed adhesive squeeze-out. In squeeze-out, the adhesive intrudes into the radius of the bond flange, causing the adhesive to become thicker over a very short distance. While it difficult to see in a black and white version of the curvature data for this part, the curvature was highly positive at that location while it was highly negative at sections A-A and B-B. This sign of the curvature, however, has very little effect on one's impression of the severity of the distortion, so distortions caused by adhesive becoming thicker are just as much of a concern as distortions caused by adhesive becoming thinner. While squeeze-out is primarily considered to be a manufacturing issue, the design of a component often determines how difficult it will be for the manufacturing plant to eliminate this condition.

Variation in the inner panel thickness in the bond flange is not considered to be good design practice and, as mentioned above, it is unclear why that variation occurred in this part. This example, however, clearly illustrates that the thickness of the all bond flanges in the design of a molded component should be verified before the substrate panel tool build begins to ensure that the design of the assembly specifies a consistent bond gap across the width of the bead.

Ideally, the bond gap would be of uniform thickness in both directions everywhere in a part. Under no circumstance should there be a discontinuity in the thickness of bond gap by design. There are, however, circumstances when the bond gap will need to vary in thickness. If the bond gap thickness must change, the transition between thicker and thinner regions should occur gradually over as long a distance as feasible.

One design condition that will cause the bond gap to vary in thickness is the presence of a character line in the part. Automotive designers include character lines in the Class "A" surfaces of vehicles to increase visual interest. Since character lines are a design feature, their geometry is determined by the appearance the designer is trying to create. Prominent character lines in the design of a hood, a typical closure panel, can be seen in Figure 3.



Figure 3: Example of a Hood with Prominent Character Lines

When there is a prominent character line in the design of a part, the design must allow for variation in the thickness and geometry of the inner and outer panels. To ensure that there is sufficient clearance between the inner and outer panel at the limits of the manufacturing tolerances, the bond gap is generally thickened at character lines. As discussed above, however, this can cause visible distortions. The propensity of this type of variation in bond gap thickness to result in visible distortions was demonstrated via finite element modeling of a section of representative geometry. A section was modeled using the modeling methodology summarized elsewhere [14]. The cross sectional geometry that was modeled is shown schematically in Figure 4a. The distortion predicted across the bead at the locations in the profile noted in Figure 4a is shown in Figures 4b and 4c. The dashed vertical lines in Figures 4b&c denotes the edges of the bead.

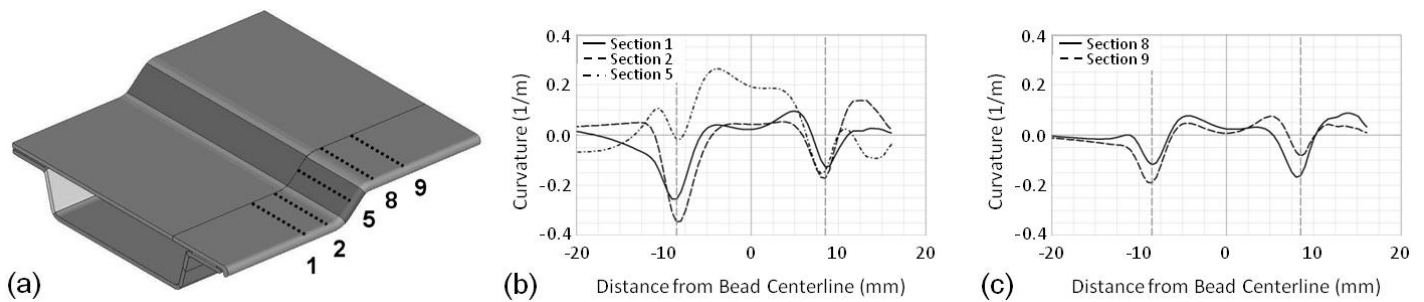


Figure 4: Illustration of the Effect of Adhesive Thickness Variations Caused by a Prominent Character Line in a Design.

a) Geometry Modeled, Including the Locations at Which the Outer Panel Curvature was Calculated, b) Predicted Curvature Induced by the Local Geometry at Points 1,2, and 5, c) Predicted Curvature Induced by the Local Geometry at Points 8 and 9

The data in Figure 4 show that the curvature induced in the surface varies significantly as one follows the bond-line across the character line. The curvature predicted for the same geometry without a character line is shown in Figure 5 for comparison.

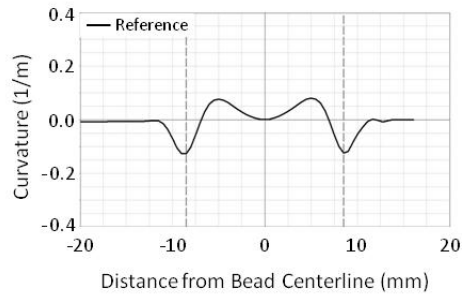


Figure 5: Predicted Curvature in a Part Without a Character Line, a) Geometry Modeled Showing the Location at Which the Curvature was Calculated, b) Predicted Curvature

Comparing the curvature predicted with and without the character line shows that the presence of character lines increase the minimum distortion possible. The reader should note that the magnitude of the distortion predicted by FE modeling should be considered a best case scenario. FE models assume an ideal geometry. Thus, the resultant prediction does not account for manufacturing variation likely to occur in actual parts. This means that the distortion in an actual part is quite likely to be more severe than that predicted. A distortion of the magnitude predicted at the inside edge of the bead at sections 1 and 2 in Figure 4 is likely to be visible, even without the effect of manufacturing variation. The reader should note that the effect of the character line extends beyond the character line. Thus, variations in bond-line thickness due to the presence of a distinct character line could be the source of a visible distortion that appears several millimeters away from the character line.

Since variation in adhesive thickness along the bond-line is required to accommodate the manufacturing variation of the panels when a distinct character line is present, the question then becomes what variation in adhesive thickness by design will allow the manufacturing plant to build parts free from visible distortions. To answer that question, a simple parametric study was completed in which the distance over which the change in thickness occurred was gradually increased. The study was completed for an SMC closure panel assembly with 2.5mm thick inner and outer panels. The width of the bead was 25mm. The nominal bond gap on one side was 1.0mm and 0.5mm on the other. The distance over which the change in bond gap occurred was 5mm, 10mm, 15mm, 20mm, and 25mm. The geometry and curvature predicted based on that geometry are shown in Figure 6 a, b, and c for the 5mm, 10mm, and 15mm cases, respectively. The geometry and curvature for the 20mm and 25mm cases are not shown since the trend is apparent with just the three cases shown. The dashed vertical lines in Figures 6 again denote the edges of the bead.

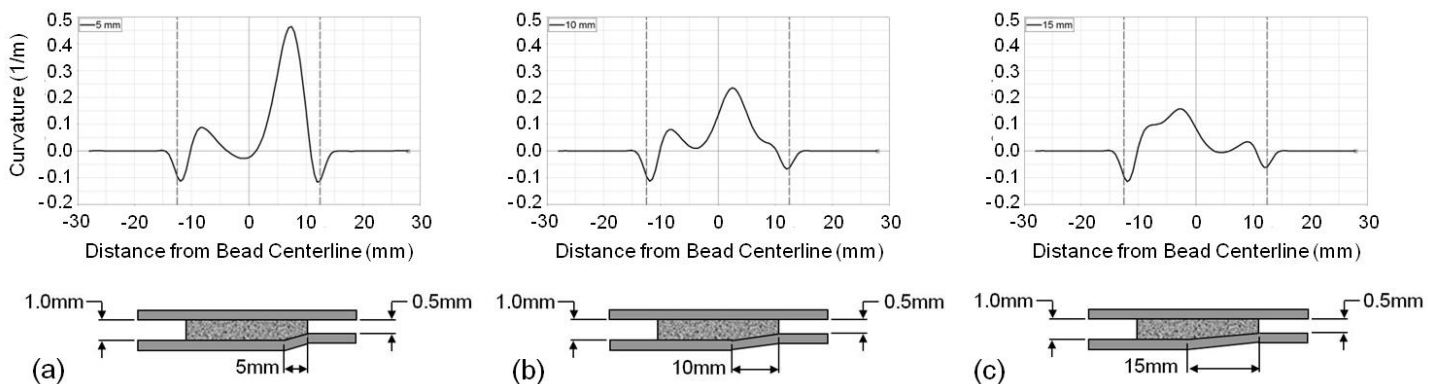


Figure 6: Change in Distortion Severity as a Function of the Abruptness of the Change in Bond Gap Thickness

The data in Figure 6 clearly illustrates that the magnitude of the curvature induced in the outer panel drops as the distance over which a change in adhesive thickness increases. While the analysis was completed for a change in thickness across the bead, the same effect will result if the change in thickness occurs along the length of the bead. Once a manufacturer has determined the maximum local curvature that can occur in the surface

before their customers will find a distortion objectionable, they can use FE analysis to determine whether a particular geometry is likely to produce acceptable parts.

One implication of this analysis is that bond "standoffs" or "dams" (i.e. small features molded into the inner panel to maintain a minimum bond gap when the assembly is bonded) should not be designed into the inner panels of Class "A" closure panel assemblies. These molded features cause very abrupt changes in adhesive thickness and thus cause visible distortions.

Bond Gap/Bead Thickness

While differences in adhesive thickness cause distortions to become visible, the presence of an adhesive bead of constant thickness will result in distortion as well. To minimize the chance that distortions will be severe enough to be visible, thinner bond lines are preferred. This is because the thickness of the adhesive determines the amount of thermally induced shrinkage and thus the thicker the adhesive, the greater the distortion. The nominal bond gap in a design should be the smallest bond gap that creates a joint with the intended structural properties while allowing for manufacturing variation.

The effect of bead thickness is illustrated in Figure 7. In this figure, the predicted distortion induced in the outer panel of an SMC assembly is compared for 0.75mm, 1.0mm, and 1.25mm bond gaps when the assembly is bonded with epoxy adhesive. The SMC substrate assumed in this analysis is 2.5mm thick, standard density, Class "A" SMC.

Figure 7 shows that the thicker the adhesive, the greater the curvature induced in the outer panel. This clearly demonstrates the importance of minimizing the nominal thickness of the adhesive in the assembly. While the data shown here are for assemblies made with SMC substrate, the relationship between adhesive thickness and distortion severity is valid regardless of substrate.

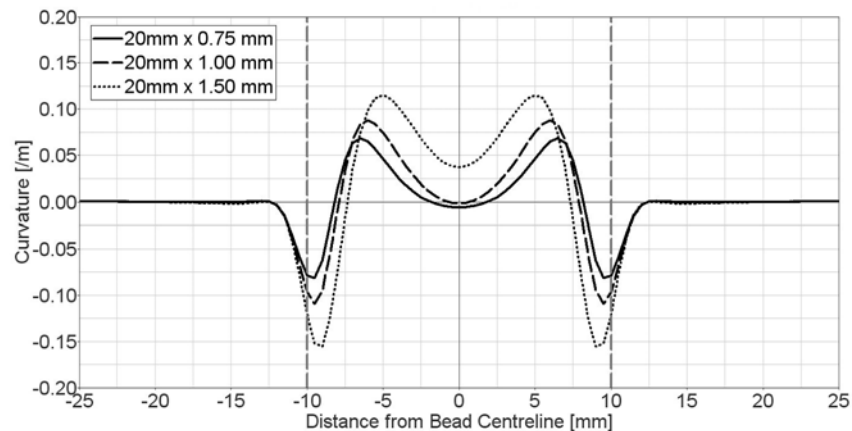


Figure 7: Curvature Induced in a SMC/Epoxy Assembly as a Function of Increasing Bond Gap

Because the relative change in thickness determines the allowable thickness variation, the reader may wonder if there might be cases where a thicker nominal bead is desirable. Unfortunately, increasing the nominal thickness of the bead to allow for more variation is not a practical solution for the bead thicknesses typically used in automotive assemblies. The nominal bond gap would have to increase so much to have a practical effect on the likely severity of the distortion that it is likely that the structural performance of the assembly would be compromised. That is not an acceptable tradeoff. Consequently, manufacturing facilities should instead adopt manufacturing strategies to reduce the variation in their processes.

Bead Width

Analysis of the effect of bead width has shown that the width of the bead can affect the severity of the distortion. This is because these distortions are caused by stress concentrations at the edges of the bead. As the

edges of the bead get closer together, the two distortions constructively interfere making the combined distortion more visible. The nominal adhesive bead width, however, is generally determined by the assembly's structural requirements. Fortunately, for all three adhesives used in this project the typical minimum bead width used in closure panel assemblies were found to be wide enough that significant interaction did not occur between the stress concentrations at the edge of the bead.

The width at which the stress concentrations at the edge of the bead begin to interact appears to be affected by an adhesive's properties. Consequently, the authors recommend that part suppliers or OEMs calculate the predicted distortion in their design for a bead at the minimum allowable width to verify that a particular combination of geometry and materials is not likely to cause objectionable distortions. If the minimum bead width is predicted to result in severe distortions, designers can increase the nominal bond flange and bead widths in the design.

Inner Panel Bond Flange Width

The width of the inner panel bond flanges is the variable with the greatest influence on the likelihood that adhesive squeeze-out will occur in production parts. If the bond flanges are too narrow, the variation in component thickness and alignment and in adhesive dispense volume and location make it very likely that adhesive will get into the radius of the bond flange in some production parts. To provide enough tolerance for the manufacturing facility, the authors recommend that inner panel bond flanges in composite closure panels be designed to be at least 8mm wider than the nominal bead width. In no case should the flanges be less than 6mm wider than the nominal bead width.

Another factor that influences the choice of inner panel bond flange width is the occurrence of extra adhesive dispensed at the beginning and end of the adhesive dispense path. The flow characteristics of the adhesive and the design of the dispense equipment generally cause a "blob" of extra adhesive to occur where dispensing begins. In addition, the viscosity of the adhesive is frequently such that at the end of the adhesive dispense path the adhesive doesn't end where the dispense ends, but rather some adhesive is drug along the by the motion of the dispense nozzle. The adhesive finally ends where it thins sufficiently to finally separate from the adhesive still in the dispense nozzle. This phenomenon is generally referred to as a "tail". A blob and tail are illustrated in Figure 8.



Figure 8: Example of a "Tail" and "Blob" at the End and Beginning, Respectively, of a Dispense Pattern

Well designed dispense equipment can reduce the size of blobs and tails in a dispense pattern, but it is very difficult to eliminate blobs and tails completely. A blob obviously adds extra adhesive at the start of the dispense path as compared to the volume dispensed elsewhere. Since any change in adhesive bead thickness, whether the adhesive gets thicker or thinner, can cause a distortion to become visible, the tail should be drug over the start of the path, adding even more adhesive at the start/stop location. Consequently, it is helpful to the manufacturing facility if designers provide a location in the inner panel design with a particularly wide bond flange at which the dispense pattern can be started and stopped. By providing a specific location in the inner panel design at which to start and stop the bead, it makes it far less likely that the extra adhesive that inevitably occurs at the beginning/end of the bead path will intrude into the bond flange radius and cause a visible distortion. The authors recommend that the bond flange location for starting and stopping the adhesive dispense be at least 40mm wide by 50mm long. Ideally the location provided for starting and stopping the dispense

pattern would also be located in an area of the part where distortions will be difficult for customers to see if they do become severe enough to be visible.

Adhesive Selection

As mentioned in the introduction to these design guidelines, the adhesive used to bond an assembly is generally selected based on the structural requirements of an assembly and the temperature at which the assembly will be painted. This generally limits the choice of adhesive. Nevertheless, there may be cases in which there are multiple adhesives which meet those requirements. If that is the case, one can then consider choosing an adhesive based on its propensity to cause visible distortions.

The authors recommend the use of two component adhesives to bond closure panel assemblies. One component adhesives must always be cured at elevated temperature. Since BLRT is primarily a thermally driven effect, the use of two component adhesives allows the manufacturing facility much more latitude in selecting the adhesive cure temperature. Since one component adhesives are generally cured in the paint oven, the conditions required to cure the paint will determine the process conditions under which the adhesive cures. If objectionable read-through is found in assemblies in which the adhesive is cured in the paint oven, there are frequently few options for reducing the severity of the distortions.

If the propensity of an adhesive to cause visible distortions can be considered in the choice of adhesive to be used, the adhesive modulus and coefficient of thermal expansion (CTE) are the relevant adhesive properties to be considered. When all else is equal, designers should choose an adhesive with the lowest modulus that will produce an assembly with the required structural characteristics. Similarly, an adhesive with a CTE closer to the CTE of the substrate will cause smaller distortions. Because the modulus of the adhesive has a stronger influence on the severity of the distortion than the CTE, an adhesive with a low modulus, but higher CTE will cause less distortion than one with a high modulus and lower CTE.

Outer Panel Bending Stiffness

The bending stiffness of the outer panel, particularly in composite closure panel assemblies, has the second most significant impact on the severity of BLRT-induced distortions after the temperature at which an assembly is bonded. The bending stiffness of a flat, isotropic plate is shown in equation 1.

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

Equation 1 shows that one way to significantly increase the bending stiffness of a flat plate is to increase its thickness. This is often the only practical means for increasing the bending stiffness of outer panels in an assembly as the panel's Young's modulus and Poisson's ratio is determined by the choice of outer panel material. Increasing the thickness of the outer panel, however, is not the preferred way to reduce the severity of adhesive-induced distortions since increasing the thickness of the panel increases its weight. In cases where the design of the assembly eliminates all of the other options that have been discussed for minimizing the severity of BLRT-induced distortions, the outer panel can be thickened to reduce the severity of the distortion. In molded panels (e.g. SMC), the panel should be thickened only where one expects the additional thickness will be needed to eliminate visible distortions.

Manufacturing Guidelines

From a manufacturing standpoint, the two factors that must be controlled most tightly are 1) the temperature at which the assembly is bonded and 2) the consistency of the thickness of the adhesive bead across its width. The guidelines discussed below summarize the lessons learned in the ACC BLRT project regarding

ways to control these two factors. It is important to control the variability inherent in all steps of the manufacturing process to ensure that the resulting assemblies are free from visible adhesive-induced distortions. Many of the guidelines discussed below may appear obvious to readers unfamiliar with current processes; nevertheless, many of the recommendations discussed below deviate from what was typically done in the manufacture of automotive closure panels at the time this paper was written.

Bond Fixture Temperature

The highest temperature reached by the outer panel of the assembly determines the minimum severity of distortions in an assembly once the adhesive and substrate have been selected. Some adhesives can reach full strength when cured at room temperature while others cannot. When the adhesive can reach full strength when cured at room temperature, distortions visible at room temperature could be eliminated by allowing the adhesive to cure at room temperature. In many cases, however, the amount of time required for the adhesive to reach handling strength at room temperature exceeds the amount of time available to make a part. In those cases, the adhesive's cure must be accelerated with heat. Thus the temperature at which an assembly is bonded should be the minimum temperature at which the adhesive can reach full strength and at which the resulting cycle time can support production volumes at an acceptable cost.

There are people who believe that metal assemblies are not susceptible to adhesive-induced distortion. The infrequency of BLRT in metal assemblies has more to do with the manufacturing process, however, than any particular characteristic of the substrate. Metal assemblies are bonded and hemmed. If the adhesive used to bond the parts is a two component adhesive, it will cure at room temperature and thus no adhesive-induced distortion will be present at that temperature. Thus the lack of BLRT is caused by the choice of manufacturing process rather than the choice of substrate. If metal assemblies are bonded with a one component adhesive that cures in the paint ovens, adhesive-induced distortion will occur.

Another difference between the manufacturing processes for composite and metal assemblies stems from the fact that the thermal conductivity of most polymer composite materials is low compared to that of metals. This means that in composite closure panel assemblies, the maximum outer panel temperature will not necessarily be the same as the maximum inner panel temperature. This project demonstrated that reducing the temperature on only the outer panel side of the bonding fixture reduced the distortion in the assembly even when the temperature on the inner panel side of the fixture was held constant. This provides one strategy for reducing BLRT in production as composite assembly manufacturers can preferentially heat assemblies in a bond cell from the inner panel side of the assembly. Reducing the fixture temperature on the outer panel side relative to the inner panel side does increase the cycle time required for the adhesive to reach handling strength; however, the additional cycle time required if the temperature of only one side of the fixture is reduced is less than that required if the temperature on both sides of the fixture is reduced. This strategy is not likely to be applicable in metal assemblies since metals have a higher thermal conductivity and the panels are much thinner. These two factors greatly reduce the temperature differential that can be achieved between inner and outer panels in metal assemblies.

One of the peculiarities of the visibility of distortions is that an observer is less likely to notice a distortion when it is near an edge or character line. This means that a customer is much more likely to notice, and complain about, a distortion in an area of a part that has relatively constant curvature. Thus it is particularly important to minimize the severity of distortions associated with adhesive that is not located around the perimeter of the part. Since achieving handling strength in the adhesive around the perimeter will allow a component to be handled without damaging it, any adhesive away from the perimeter would not necessarily have to reach the same degree of cure as the adhesive around the perimeter and therefore could be cured at a lower temperature. All the adhesive in a component should be cured enough to resist flowing under load so that the bead stays rectangular. That requirement, however, does not necessarily require the adhesive to have reached handling strength. Thus the temperature at which adhesive away from the perimeter will be cured can be lower than that used for the adhesive around the perimeter to reduce the severity of the distortion in the high visibility locations.

Applying heat from only the inner panel side of the assembly in these locations may be a particularly useful strategy for composite assemblies.

Once the temperature at which assemblies will be bonded has been chosen, the manufacturing process should bond assemblies at that temperature throughout the life of the production program. In cases where assemblies are bonded at an elevated temperature, this requires that the bond fixture monitor and control the outer panel temperature as much as feasible, preferably by incorporating closed loop temperature control in the bonder. Use of closed-loop control systems are recommended since bonders are open to the atmosphere and manufacturing plants are generally not environmentally controlled. Consequently, the temperature of the assembly will fluctuate with the ambient conditions, both over the course of a shift and over the course of a year if there is no way to directly monitor and control the fixture (and therefore the substrate) temperature.

The ability to monitor and control the temperature of the substrate in the bond fixture is determined by the type of bond fixture chosen to bond the assemblies. Most metal assemblies are hemmed and the adhesive is allowed to cure in either the work-in-progress racks or in the paint oven. In composite closure panel assemblies, however, the cure of the adhesive generally must be accelerated in a bond fixture using heat. There are a number of different types of bonding fixtures used by automotive composite closure panel manufacturers. The most commonly used heating sources for composite bonding fixtures are blown hot air, electric cartridge heaters, circulating steam, and circulating oil. The temperature at which an assembly is bonded, though, is far more important than the method used to apply heat to the parts (i.e. the type of fixture).

Control of the Adhesive Bead Geometry

Once the temperature at which the assembly will be bonded has been chosen and that temperature will be controlled as well as possible, elimination of adhesive squeeze-out becomes essential to eliminating visible distortions from production components. Unfortunately, bonding fixtures are typically designed so that all variation is driven into the bond-line. This manufacturing strategy makes generation of squeeze-out more likely. To prevent squeeze-out the variation in all steps of the manufacturing process must be minimized.

Inner and Outer Panel Substrate Thickness

The importance of maintaining consistent substrate thickness from part-to-part will be obvious to many readers. Nevertheless since reducing variation the SMC substrate thickness is a key factor in controlling the severity of BLRT-induced distortions in those assemblies, this discussion would be incomplete if the impact of part-to-part thickness variations was not discussed.

In metal assemblies, the thickness of the metal substrates is quite consistent from part-to-part and run-to-run. That is not, unfortunately, necessarily the case for molded substrates. Each time a new batch of SMC components is molded, the thickness of the panels can change, both globally and locally, because of changes in the specific gravity of the SMC compound, charge weight, charge placement, location of the tool in the press, and the press in which parts are molded. Note that some process factors, such as charge placement and the location of the tool in the press, can result in parts that are thicker than nominal on one side and thinner than nominal on the other. Variations in thickness around a part are, in fact, common in molded parts.

When production begins on a new composite assembly, the bond fixture will be "tuned" to account for variations from nominal thickness around the part. In a composite assembly bonding fixture, only the total thickness of the assembly (substrates plus adhesive) is controlled. In tuning, the process is adjusted to account for deviations from nominal in the inner and outer panel thickness by adding or removing shims from specific locations the bond fixture or by adjusting the amount of adhesive dispensed in a particular location. Note that since the thickness of molded parts can vary locally, the bond gap around an individual part may be thicker than nominal in some locations and thinner than nominal in others. The tuning process is an attempt to adjust for that variation.

Once the process has been tuned, however, it becomes critical that the molder produce parts that replicate the geometry of the parts that were used in the tuning process every time a new batch is molded. If the thickness of the inner and outer panels varies from that of the panels used during tuning, that change in substrate thickness will translate to a change in the thickness of the bond gap. Since tuning is time consuming and expensive, the same amount of adhesive is applied to every assembly after the bond fixture is tuned. If the bond gap in a particular part is thicker than nominal because the total substrate thickness is less than that used during tuning, the adhesive bead in the bonded assembly will be narrower than the nominal width. If the bead is excessively thick and narrow, that can lead to structural deficiencies in the assembly. If the bond gap in a particular part is thinner than nominal because the total substrate thickness is greater than that used during tuning, the adhesive bead in the bonded assembly will be wider than the nominal width. In cases where the adhesive is wider and thinner than intended, it becomes likely that adhesive squeeze-out, and therefore visible BLRT, will occur. It is, therefore, critical that composite molders implement processes to minimize thickness variations in inner and outer panels for Class "A" assemblies.

Adhesive Dispense Process Recommendations

If the thickness of the panels is consistent, adhesive squeeze-out can still occur if the volume of adhesive dispensed or the location at which it is dispensed is not consistent. Achieving consistent adhesive dispense volume and location can be more difficult than some readers may realize. For instance, automotive manufacturing plants are rarely environmentally controlled, so the ambient temperature can vary dramatically between seasons and at times even between the beginning and end of a shift. If the dispense equipment is not designed to maintain the adhesive at a consistent temperature, the volume of adhesive dispensed will vary with temperature. Furthermore, the design of a component is often such that all of the manufacturing variation must be contained within the bond gap and result in no more than ± 3 mm of variance in the location of the edge of the bead. While ± 3 mm is a generous tolerance in some applications, that tolerance is affected by all of the variation in molding, adhesive dispense, and component bonding. Consequently, in reality manufacturing plants often struggle to maintain the tolerances required in each process step so that the entire variance stack-up allows the edge of bead location to fall within the ± 3 mm tolerance.

Temperature control of the adhesive resin and curative is critical if the system is to dispense a consistent volume. The volume of adhesive dispensed by a system that does not control the adhesive components' (i.e. resin and curative) temperature can vary so much between the beginning of the shift and the end of the shift in some seasons that consistently making distortion-free parts becomes nearly impossible. The target temperature for dispensing each component of the adhesive is adhesive dependent and may be different for the two components. The temperature sensitivity of each component varies as well. When designing the temperature controls for a dispense system, the adhesive supplier for the particular adhesive will have to be consulted. In general, though, the temperature of the resin and curative should be independently monitored and controlled. Temperature control of $\pm 5^{\circ}\text{C}$ prior to entering the meter and $\pm 2.5^{\circ}\text{C}$ between the meter and dispense point can be used as a rule of thumb for most automotive adhesives. Note that if adhesive components are fed to the dispense system by a central delivery system in the plant, the system for adjusting the component temperature prior to entering the meter may need reduce the incoming temperature by as much as 30°C or increase it by as much as 12°C , depending on the season.

The intent should be to always dispense adhesive at the same temperature regardless of ambient conditions. Nevertheless, some temperature variation will inevitably occur. To mitigate the effect of changes in adhesive volume dispensed as a function of temperature, a closed loop control system should be incorporated into the system to automatically adjust the process for changes in dispensed volume. Provided that the adhesive density is constant over the temperature range at which it will be dispensed, it is fairly inexpensive to measure the weight of adhesive dispensed during a fixed time at the start of each shift and after each break. The system could then automatically adjust one of the dispense parameters to account for a difference between the intended and actual volume (weight) dispensed. The actual volume of adhesive at any location on a part is function of the rate at which adhesive is dispensed and the speed at which the dispense nozzle moves around the panel. Consequently, either the meter could be adjusted to correct the dispense rate or the global speed of the robot

could be increased or decreased. To modify the speed of the robot, however, upfront planning by the robot programmer is required. Typically, a dispense program is developed with the "global" speed of the robot set to 100%. If that is the case, there is no way to speed up the whole program if the actual volume of adhesive being dispensed exceeds nominal. If, on the other hand, the dispense program is established with the global speed of the robot set to 50%, then speed of the entire program can be adjusted to account for changes in adhesive dispense volume. This strategy may seem obvious to the reader, but it represents a significant change to typical robot programming procedures in the automotive composite closure panel supply base.

A final recommendation for monitoring and controlling the temperature of the adhesive is to have the system verify the temperature of the adhesive being dispensed when the volume being dispensed is checked. No adjustments would necessarily be made to the system based on that data, but maintenance could be automatically notified if the temperature as dispensed does not fall within the prescribed temperature range.

As mentioned above, the speed at which the dispense nozzle (i.e. robot) travels during dispense is what determines the actual volume of adhesive present at any given location on a part since the rate at which adhesive is dispensed from the mix nozzle is constant. The bead geometry (i.e. width and thickness) is generally intended to be constant for a given assembly, so ideally the robot speed would be constant throughout the program. That, however, is unrealistic as a robot must slow down to change direction or go around corners. In fact, in cases where the robot must turn a corner that is tighter than 90° (e.g. at the rear corners of a hood), the robot has to stop to reverse direction. Unless the volume of adhesive dispensed varies as a function of the speed of the robot (which was not a viable process control at the time this paper was written), the amount of adhesive dispensed will increase as the robot slows down, potentially leading to squeeze-out in some locations. To minimize the variation in speed, and the resulting variation in adhesive volume around the path, the speed at which the robot dispenses adhesive on a part should be the minimum speed necessary to achieve the desired cycle time.

The reader should note that another benefit of minimizing the speed at which the robot moves is that it allows the placement of the adhesive to be controlled more precisely. The robot path is programmed manually. The operator moves the robot slowly from one location to the next. If the robot moves much more quickly during the dispense process than it did during programming, the adhesive may not fall in the intended location because of inertial effects. This variation in actual placement versus intended placement is very difficult to eliminate through programming if the robot moves quickly during the dispensing process and that variation can easily result in squeeze-out.

While minimizing the speed at which the robot travels when dispensing adhesive is important, minimizing sources of vibration that might affect the positioning of the robot is also important. Manufacturing facilities contain many vibration sources. It is generally not necessary for the adhesive dispense robot to be isolated from all sources of vibration. It is, however, necessary for the support structure to be designed to minimize the transfer of vibrations, whether they be externally or internally generated, through to the robot. For instance, the authors recommend that fans be mounted on the floor rather than on the robot support structure as the rotation of the fan can induce vibration in the support structure which will then degrade the accuracy of the adhesive placement.

One of the factors that is often overlooked in the ability of a process to eliminate squeeze-out is the design of the adhesive dispense equipment itself. For instance, dispense systems are often designed using a rod displacement system because of the properties of the adhesive resin and curvature. In this type of system, a shot meter is used. The size of the meter has a significant impact on the pressure drop in the system at the beginning of the adhesive dispense. Unfortunately, larger pressure drops result in larger blobs and tails (illustrated in Figure 8) in the dispense pattern. While it may seem that sizing the dispense system for a particular application should be a straight forward task, and it is, in most manufacturing plants, one dispense system is used to manufacture a wide range of parts. It is therefore possible that a meter sized to dispense adhesive on a Class 8 heavy truck hood could also be used to dispense adhesive on a significantly smaller part. This is not

recommended. Nevertheless, suppliers and OEMs are often reluctant to purchase new capital equipment when existing equipment is available and not being used at full capacity.

Other factors that affect the pressure drop between the shot meter and dispense point include a) the distance between the meter and the dispense point, b) differences between the system working pressure and the pressure to which the meter recharges the system, c) the use of outlet valves, d) the use of hard versus flexible tubing between the meter and dispense point, and e) the presence of flow restrictions between the meter and dispense point. The exact design of the dispense system will determine the pressure drop in the system. In the past, the pressure drop through the system was not a major design consideration. The effect of a large pressure drop, however, may be to cause visible distortions at any start/stop point in a dispense pattern. Consequently, it is important to design dispense systems to minimize the pressure drop. The recommended maximum pressure drop for new systems is 200psi.

Another process control that should be incorporated into the design of the dispense equipment is the automatic verification of the tool center (mix tube tip location). When an operator changes the disposable static mix tube, the location of the tip of the mix tube and the rotation of the tube could differ from the location and rotation on which the adhesive dispense path program was based. Any change in tip location or tube rotation could cause the location of the adhesive on the part to deviate from the intended location. This can result in adhesive squeeze-out. Software exists that can automatically update the robot path based on actual position/rotation data as compared to the position/rotation when the path was programmed. Incorporation of this control into the adhesive dispense system can reduce the variation in the adhesive bead location and make squeeze-out less likely.

The final variable in the dispense process that must be controlled to prevent squeeze-out is the placement of the adhesive. Since the total variation in the location of the edge of the bead is limited to ± 3 mm, accurate placement of the adhesive is essential. There are several process aids and process controls that should be incorporated into the manufacturing process to reduce the variation in actual the location of the bead on the part.

First, in automotive closure panel assemblies, regardless of whether they are made from metal or composite, adhesive is typically dispensed on the outer panel of an assembly. To maintain a Class "A" appearance on the outer panel the only feature on the outer panel that the robot programmer can use as a reference when programming the path is the edge of the panel. Since the centerline of the bead is often 10-15mm away from the edge of the panel – and it is not always intended to be the same distance away from the edge of the panel at every location – it is generally difficult for the programmer to tell if the robot is in the correct location at every point on along the bead path. Therefore, it would extremely helpful to the programmer if a faint line, either molded into the outer panel or scribed onto it by a CNC machine, was created on the outer panel being used to create the robot path to show where the bond line is supposed to be located. This would provide a known location to which the programmer can line up the robot when programming the path.

The location at which the programmer starts and stops the adhesive dispense path can be critical since complete elimination of blobs and tails at the beginning and end of the dispense path is difficult. Consequently, the programmer should start and stop dispensing in a location where distortion in the surface is less likely to be visible if it occurs. Ideally, the bead path would start/stop at a location where the bond flange on the inner panel is particularly wide. If there is not a wide bond flange provided in the panel design, then the programmer should start and stop the dispense near a character line or other geometric feature as the presence of significant local changes in part curvature can often mask nearby distortions. In addition, the number of start and stop locations in the bead path should be minimized. It is recommended to start and stop the dispense path around the perimeter of a part in one location only whenever possible.

A second recommended deviation from typical robot programming is for the programmer to keep the tip of the mix tube perpendicular to the ground, when possible, rather than having it be perpendicular to the part. Regardless of the orientation of the tube, the adhesive falls from the end of the mix tube onto the part. If the

mix tube is oriented at, for instance, a 45° angle compared to the ground, then as the perpendicular distance between the mix tube and part increases, the location of the adhesive on the part shifts. If however, the mix tube is perpendicular to the ground, the location of the adhesive on the part shifts much less as the distance between the part and the mix tube increase. This is illustrated schematically in Figure 9.

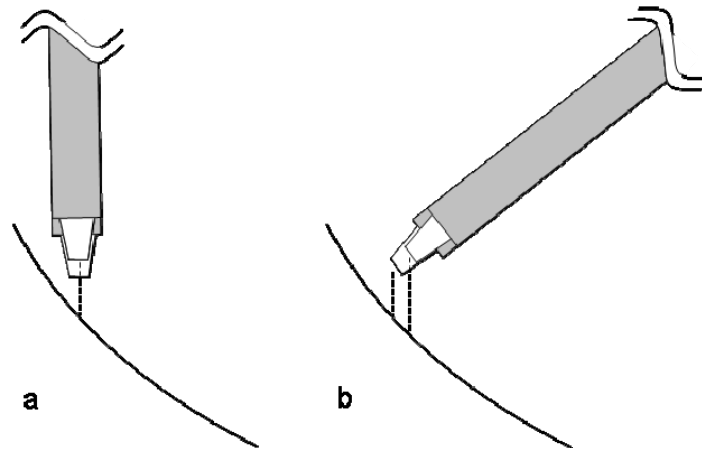


Figure 9: Illustration of the Effect of Mix Tube Orientation as a Function of Distance from the Part to Mix Tube Distance on Adhesive Placement

By programming the robot so that the mix tube is aligned with gravity, the variation in location of the adhesive on the part should be minimized. The authors acknowledge, however, that it will often be impossible to dispense adhesive with the mix tube in that orientation. There is no reason, however, that the mix tube needs to be perpendicular to the part as was typical when this paper was written.

The design of the adhesive dispense nest also has a significant impact on the amount of variation in the location of the adhesive on the part. The dispense nest determines the position of the part while adhesive is being dispensed, so both the variation in the part location within the nest and the variation in the robot position relative to the nest must be minimized. In both metal and composite closure panel assemblies, adhesive is typically dispensed on the outer panel of an assembly even though it is the location of the adhesive on the flange on the inner panel that is important. Because of that, the location of the part in the bond dispense nest should be as close to its position in the bond fixture as possible. Consequently, the locating strategy used in the bond dispense nest should mimic that used in the bond fixture. Similarly, the bond dispense nest should provide enough support to the part that its position will not fluctuate due to vibration, air movement, etc. If the strategy for supporting and locating the part in the bond dispense nest mimics that of the bonding fixture, then the dispense nest may end up looking very much like the corresponding half of the bonding fixture. This represents a significant change from current conventional automotive composite closure panel manufacturing strategy.

Bond Fixture Design Considerations

The two primary functions of the bond fixture are to 1) produce a part that will meet dimensional requirements and 2) manufacture a part with a constant bond gap everywhere around the perimeter as well as in any other location in which adhesive is located. As discussed previously, the temperature at which an assembly is bonded is far more important than the method used to apply heat to the parts (i.e. the type of fixture). The design of the fixture, though, will affect whether parts can be made with a consistent bond gap if the thickness/geometry of the inner and outer panels are well controlled. To control the bond gap, the parts must be held against the fixture's surface. The ability of the fixture to hold the panels in the intended location then determines whether the geometry of the adhesive in the assembly resembles its design intent geometry.

The tolerance for the location of the inner and outer panels relative to one another is normally determined by the margin and flushness requirements for the assembly. In typical automotive designs, the margin and flushness

requirement-based tolerance is sufficient to minimize the likelihood that variation in the relative location of the inner panel and outer panel will cause squeeze-out. To be sure that this will be true, however, manufacturers may need to complete a variation simulation analysis for the assembly.

Vacuum cups are typically used to hold inner and outer panels against the bond fixture surface when bonding composite closure panel assemblies. Traditionally, vacuum cups have been located in areas of the fixture that are easily accessible. This means that they have frequently been located some distance away from the bond flange. The only locations on the inner and outer panels that are positively located, though, are the locations directly under or over the vacuum cups. Any location far from a vacuum cup can deflect away from the fixture. This is particularly true for the panel on the upper side of the bond fixture. Since it is critical that the fixture hold the entire bond flange in design position to the extent practicable, the authors recommend that a larger number of smaller vacuum cups be used to hold the part in place. Increasing the number of vacuum cups will reduce the variation between the actual panel location and the intended design position. Vacuum cups cannot generally be placed directly under the bond flanges as that would require a discontinuity in the heating source. Nevertheless, the vacuum cups should be located as close to the bond flanges as is practical. This is particularly important for very flat parts as those parts tend to be more flexible, and less able to hold their intended shape, than more highly contoured parts. If there are localized regions where the bond flange is particularly narrow (i.e. locations in which squeeze-out is particularly likely), vacuum cups should be located as close to those locations as possible to minimize the chance that panel deflection will reduce the bond gap in those areas.

One potential factor that could influence the design of bonding fixtures is the need to keep the inner panel bond flange parallel to the outer panel bonding surface. Unfortunately, there is not much that can be done in the bond fixture to ensure that these two surfaces are parallel everywhere in the assembly. The effect of poor parallelism between the inner panel bond flange and the outer panel bonding surface is illustrated in Figure 10. The adhesive beads modeled in Figure 10 were 20mm wide. Figure 10a shows the predicted surface curvature when the bead is uniformly 1mm thick. Figure 10b shows the predicted surface curvature for a bead that changes linearly from 1mm thick to 1.5mm thick across its width. Figure 10c shows the predicted surface curvature for a uniformly 1.5mm thick bead.

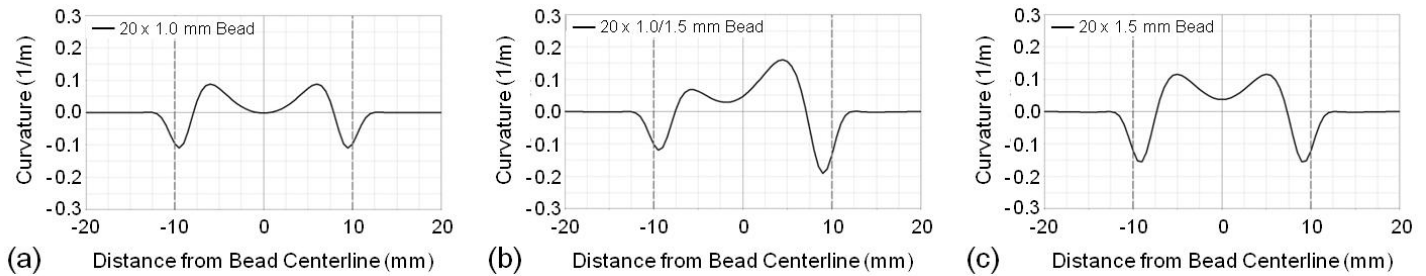


Figure 10: Predicted Curvature for an SMC Assembly Bonded with Epoxy Adhesive for a 20mm Wide Bead at a) 1.0mm Thick, b) 1.0mm Thick Transitioning to 1.5mm Thick, c) 1.5mm Thick

A comparison of the peak predicted curvatures in Figures 10 a, b, and c illustrates that while the peak distortion may be higher in an assembly in which the adhesive bead changes in thickness than in an assembly in which the thickness of the bead is consistent, that increase is relatively minor. In addition, a 20mm wide bead is at the lower end of the bead width range generally needed for an assembly to meet structural requirements in SMC assemblies. As discussed earlier, as the width of the bead increases the change in thickness will occur more gradually, and as a result, the increase in the severity of the distortion will become even less pronounced. So while it would be ideal for the inner panel bond flange to always be parallel to the outer panel bonding surface, this analysis shows that a small deviation in the parallelism of these two surfaces will not have a significant impact on the severity of the surface distortion as long as the deviation from parallelism is relatively small and that variation does not result in adhesive squeeze-out.

Summary

Design and manufacturing guidelines were created to educate manufacturers about what strategies will enable them to produce automotive closure panel assemblies with minimum thickness outer panels that will meet customer's expectations for surface appearance quality. These guidelines were based on a comprehensive understanding of the cause of adhesive-induced distortion and the material and process factors that affect the severity of the distortions that were reported previously [6-13].

The design of a component will affect whether it is easy or difficult to manufacture parts that are free from adhesive-induced distortions. Ideally, a part would be designed with a consistent bond gap everywhere. This paper recommends strategies for minimizing the effect of variations in the thickness of the bond gap when maintaining a consistent bond gap everywhere is not possible. Design guidelines were also presented for the width and thickness of the adhesive bead, the width of the inner panel bond flange, factors to consider in adhesive selection, and utilization of outer panel bending stiffness when necessary.

Manufacture of assemblies free from visible adhesive-induced distortion requires that component suppliers tightly control all aspects of the component manufacturing process. The factor with the greatest influence on BLRT severity is the temperature at which assemblies are bonded. Strategies for managing the temperature used to accelerate the cure of adhesives while minimizing the resultant distortions are presented. Control of the geometry of the adhesive bead as manufactured is also critical to minimizing the severity of adhesive-induced distortions. A number of recommendations for controlling the process factors that influence the shape of the adhesive bead in the assembly are presented and explained. These include a series of detailed recommendations regarding changes to the adhesive dispense equipment and processes that represent significant deviations from the equipment and processes typically used at the time this paper was written. Recommendations regarding the design of bonding fixtures were presented as well.

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