CONCEPT STUDY ON OPTIMIZED AUXILIARY MATERIAL DESIGNS AND APPLICATION TECHNIQUES FOR VACUUM BAGGING OF FULL-SCALE CFRP ROCKET BOOSTERS

Jan Faber[1], Clemens Schmidt-Eisenlohr[1], Tobias Dickhut[2] and Peter Ortmann[2]

[1]Institute of Structures and Design, Center for Lightweight Production Technology,
German Aerospace Center, Am Technologiezentrum 4, 86159 Augsburg, Germany
Email: jan.faber@dlr.de, clemens.schmidt-eisenlohr@dlr.de, Web Page: http://www.dlr.de

[2]MT Aerospace GmbH, Franz-Josef-Strauss-Strasse 5, 86153 Augsburg, Germany,
Email: tobias.dickhut@mt-aerospace.de, peter.ortmann@mt-aerospace.de,
Web Page: http://www.mt-aerospace.de

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Abstract

Rising production rates in CFRP aerospace manufacturing cause a growing need for effectivity, reproducibility and enhanced quality standards. State of the art vacuum bagging for vacuum infusion technologies still involves a high amount of manual process steps. More efficient production technologies could increase the economic attractiveness of vacuum infusion processes for large aerospace structures.

In the context of a research project, the *German Aerospace Center (DLR)*, Augsburg and *MT Aerospace GmbH*, Augsburg develop design methods and application concepts for vacuum bagging on a full-scale CFRP rocket booster case. With a diameter of 3.4 m manual application of auxiliary materials is challenging in terms of deposition accuracy, reproducibility and reachability.

Facing these challenges, a design method has been developed to generate near net-shape auxiliary materials with reduced wrinkling. As joining technology for auxiliary material packages, continuous ultrasonic welding has been selected and validated based on the suitability for vacuum infusion and out-of-autoclave curing. Manual application tests were conducted on a full-scale booster case demonstrator. The results show, that a developable shape design of the packages for the doubly curved dome sections allows best results with regards to wrinkle minimization and the complexity of the handling procedure.

1. Introduction

In aerospace CFRP production, rising part complexity and part dimensions afford optimized production technologies. Especially out-of-autoclave vacuum infusion technologies become more attractive for large aerodynamic structures as rear pressure bulkheads, new generation wings and rotor blades [1, 2, 3]. Higher production rates cause a growing need for effectivity, reproducibility and enhanced quality standards. State of the art vacuum bagging for vacuum infusion technologies still involves a high amount of manual process steps [4, 5]. As a consequence, quality standards and process efficiency depend on manual production tolerances and personal skills of the workmen. Especially handling and positioning of auxiliary materials for vacuum bagging becomes more difficult with rising part complexity. Facing these challenges, improved manufacturing standards and application concepts can increase the economic attractiveness of vacuum infusion processes for large CFRP structures.

In a government-funded research project, *MT Aerospace GmbH*, Augsburg and the *Center for Lightweight Production Technology (ZLP)*, Augsburg of the *German Aerospace Center (DLR)* develop automated production technologies for CFRP rocket booster cases (Figure 1).

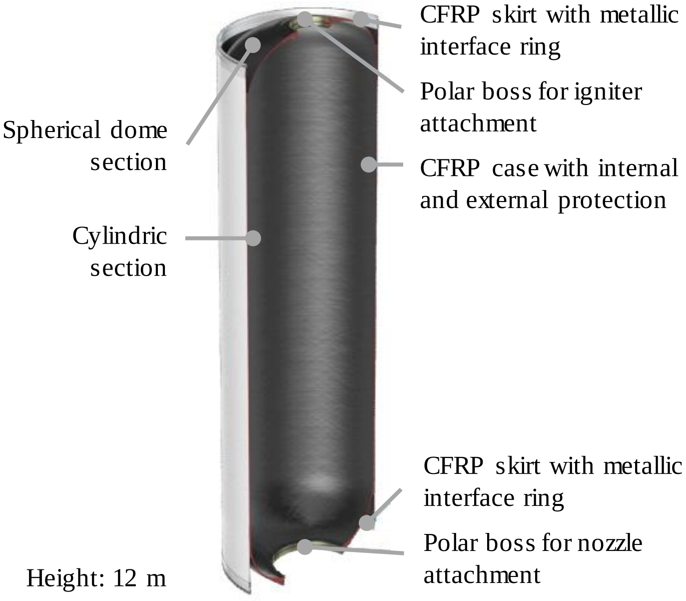

Figure 1. Model of CFRP rocket booster case [6]

The manufacturing process was set by *MT Aerospace* and bases on an automated dry fiber winding and dry fiber placement technology. In a subsequent process step, a vacuum bag consisting of auxiliary materials as peel ply, perforated release film and flow media is applied. Finally, the part is impregnated and cured in a vacuum assisted resin infusion process. The dimensions of the booster case are 12 m in length and 3.4 m in diameter. This dimension exceeds state of the art use cases of dry fiber winding and resin infusion. In a previous study at *MT Aerospace*, prototypes were manufactured and tested. The inner auxiliary materials were cut and placed by hand. On the single curved cylindrical middle section of the booster case, it is comparatively easy to place the auxiliary material without wrinkling. Because of the doubly curved surface, it is more difficult to apply the auxiliary materials on the outer dome sections without wrinkling. Wrinkles should be kept as small as possible in height and length, since large wrinkles can induce race tracking and resin nests during infusion. Resin nests could cause insufficient surface quality due to hindered demoulding and surface conditions as roughness. Thus, the resin flow can be impeded or stopped leading to dry spots and waste. In addition to the optimization of the auxiliary materials design, the developed production technologies have to be time- and cost-efficient facing an estimated small batch production of 17.5 booster cases per year [6, 7].

This paper describes an approach about improved manufacturing techniques and application concepts of auxiliary materials for vacuum bagging on the doubly curved dome sections. In a first part, a design method for near net-shape tailored auxiliary materials is discussed. This method aims for the optimum design considering wrinkle reduction and handling. The second part of the paper deals with joining techniques for auxiliary material packages. Different joining technologies have been used and validated in infusion tests. The third part describes the validation of the design method and joining technologies by manual application tests on the dome section of a booster demonstrator. Finally, the results are discussed with regards to automated application systems.

2. Shape design of auxiliary materials

One goal is a reasonable dimensioning of the auxiliary material cut pieces for the given application scenario. Two conditions basically influence the areal size of the cuttings. Firstly, the minimization of wrinkles increases the reproducibility of the resin flow and automation processes. Fewer wrinkles appear for smaller cut piece design. Secondly, the application process contrarily tends to larger cut pieces to reduce work steps. For any application the auxiliary material cut pieces have to be dimensioned with regard to the two conditions. In the following chapter, we introduce the method and results to define the size for our surface geometry.

2.1 Method and research setting

Figure 2a schematically displays the total geometry of the demonstrator (length ≈ 6.0 m, diameter ≈ 3.5 m). The geometry is a body of revolution, with a cylindrical middle part closed by two half spheres. The outer surface of our application needs to be thoroughly covered with auxiliary materials. Therefore, the issue to dimension the cut pieces is separated in the two geometrically characteristic sections: The cylindrical part (1) and the spherical parts (2) displayed in Figure 2a. The surface of the cylindrical section has single curvature (zero Gaussian curvature) and plies are developable without wrinkles. Therefore, the cut pieces are rectangles and the dimension is driven only by application conditions.

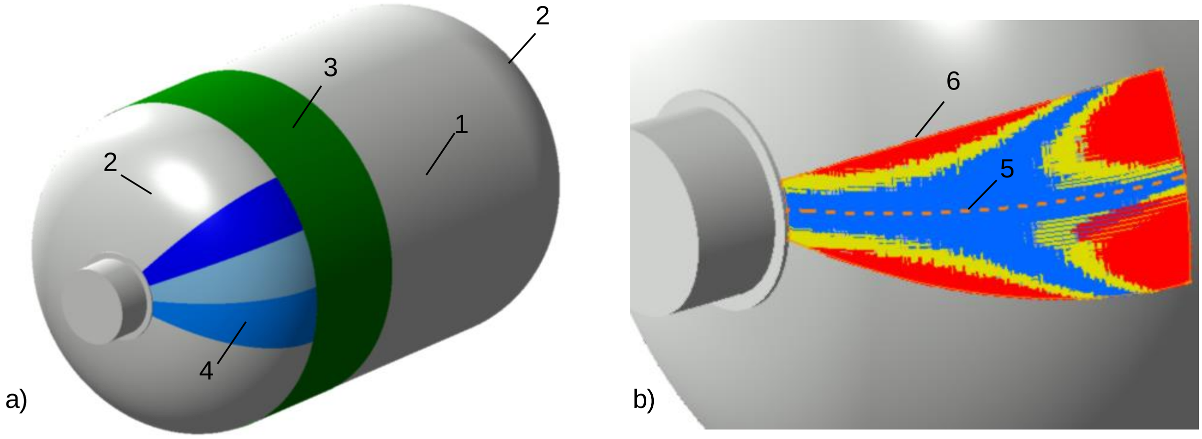

Figure 2. Schematic view (CAD) of the application scenario: a) Total view displaying the cylindrical section (1), the spherical scetion (2), an exemplary cylindrical ply (3) and an exemplary spherical ply (4). b) Draping simulation result of a spherical ply displaying the draping starting spline (5) and the colorization of the local draping distortion (6).

However, we focus on the spherical part as it is geometrically not developable (positive Gaussian curvature) and wrinkles will appear when the cut pieces are applied to the surface. These days no precise dimensioning methods of auxiliary materials exist for doubly curved surfaces. Hence, we performed a double staged method where the cut pieces are designed and simulated in CAD and subsequently experimentally examined. An exemplary spherical cut piece (4) is displayed in Figure 2a (length ≈ 1.7 m). To construct constant cut pieces, it is defined by a split of a rotated plane with the spherical geometry. In our experiment we constructed the three plies with a rotated plane of 10°, 20° and 30° for the auxiliary materials (peel ply, perforated release film, flow media).

In a first step we designed the spherical plies in the draping simulation (Program CATIA V5 R23) and defined the draping parameters. Two main influencing parameters are the material draping properties and the geometric start conditions. The draping simulation parameters are widely investigated for carbon fiber preforms and materials but not for auxiliary materials. Hence, draping parameters for auxiliary materials base on the knowledge of dry fiber preforms. We have chosen planar isotropic material parameters because the given auxiliary materials display planar homogenous materials. For example, peel ply is a homogenously woven linen textile. The geometric start conditions are displayed as the dashed curve (5) in Figure 2b. The start draping curve is the symmetric curve between the outer contour curves. Therefore the simulation is set to drape the spherical ply from the symmetry curve to the outer contour. Figure 2b displays the draping simulation result for the 20° spherical ply. The locally different shear distortion is colored from blue (no distortion) to yellow (light distortion) to red (high distortion).

2.2 Results

The full-scale application experiments provide several results and findings. The application of the cut pieces is possible for plies of 10° and 20° (Figure 3a and 3b). Though, the application of the 30° ply is not possible with a sufficient layup quality (Figure 3c).

After application, the accuracy of the outer contour is measured. The deviations of the contour in comparison to the laser projection increases for the larger cut pieces. A maximum deviation of 37 mm is measured at the right edge of the 20° perforated release film ply. For the same ply, the deviation at the lengthwise edges is less than 10 mm. For the 30° cut piece no contour measurement was performed as it was not sufficient applicable (Figure 3c).

The amount of wrinkles and the wrinkle pattern is evaluated visually, based on personal experiences. With regard to the wrinkle pattern, several results are obtained. The experiments show differences of the wrinkle pattern while we applied the three materials, peel ply, perforated release film and flow media on the tooling geometry. For the same ply sizes, obviously, less wrinkles appeared within the flow media and the peel ply. Most wrinkles are formed within the perforated release film plies.

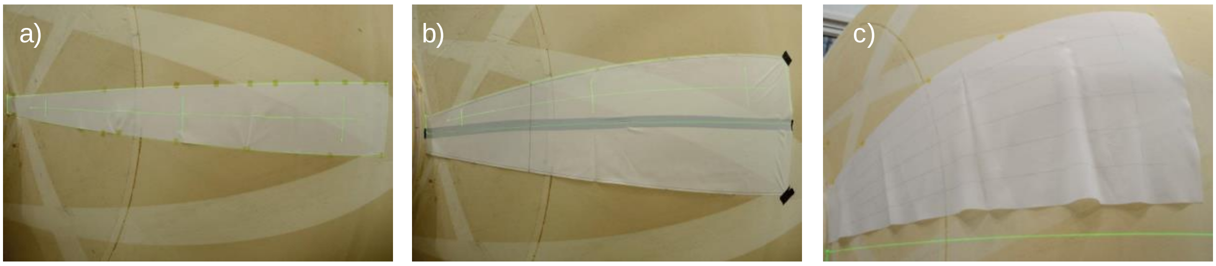

Figure 3. Experimental application result for peel ply: a) for cut piece size 10°, b) for cut piece size 20° and c) for cut piece size 30°.

2.3 Discussion

The application of the three auxiliary materials in different geometric sizes leads to continuing findings and optimization potential. In general, the experimental investigations demonstrate that the simulation method for computed designs of the cut pieces is suitable for auxiliary materials. However, the simulation has to be improved to reduce misalignments at the outer contours. Further investigation needs to be performed to understand the effect of material parameters on the simulation. These parameters specify the draping start conditions for different materials. Our results show that as long as the simulation is not precise enough, predicted draping results can hardly be used as input for an experimental verification. In matters of sizing the 20° ply is the most favorable. The 20° ply represents a balanced solution between a reduced amount of wrinkles and application issues, where large cut pieces are preferred. Hence, 18 segments of 20° plies are necessary for a dome segment. The outer contour of the specific plies, however, needs to be optimized and adjusted to avoid gaps .

3 Joining technologies for auxiliary materials

In this chapter we describe a method to find a suitable joining technology to generate packages out of single plies of auxiliary materials. This joining technology has to enable handling and positioning of materials designed as described in chapter 2. Relevant auxiliary materials are peel ply, perforated release film and flow media, which will be applied on the dome section of the booster demonstrator. In addition to specific functionalities as handling and applicability, basic functionalities of these materials have to be guaranteed as well. Basic functionalities of auxiliary materials are vacuuming of the vacuum bag, distribution of the resin on the textile preform, damage free release after curing and creation of a defined part surface.

These functionalities must not be influenced negatively by the joining technology. Furthermore, used materials and methods have to comply with existing manufacturing standards and specifications. For example, adhesives could have a chemical impact on the characteristics of the epoxy resin, such as changes of viscosity or curing mechanisms. Therefore, material combinations of resin and adhesive would have to be tested extensively to exclude negative effects on the manufacturing process. In consideration of existing specifications, we were searching for joining technologies without usage of additional materials.

3.1 Test setup

In consideration of the functionalities of auxiliary materials, we pre-selected three promising joining methods for further investigations: sewing, areal adhesion and ultrasonic welding. As a reference method, the sewing technology was used to compare the manufacturing procedures and the material handling of different joining techniques. Nevertheless, the sewing yarn is an additional material, which has to comply with the epoxy resin. As second method, the ultrasonic welding technology matches the requirements for joining technologies since there is no need for additional adhesives. Though, we conducted further investigations to analyze the impact of welding seams on the resin flow and on the impregnation of the preform. As third method, areal joining based on adhesion was tested focusing on handling and flexibility of the joined packages.

In cooperation with the Institute of Textile Technology (ITA) of RWTH Aachen University, packages of auxiliary materials were manufactured using sewing, ultrasonic welding and areal adhesion. Based on the shape design of the dome sections (chapter 2), joining areas for sewing and ultrasonic welding were positioned on the long sides of each package (Figure 4). Using a continuous ultrasonic welding process, ITA selected rolling sonotrodes with a width of 10 mm and a shaded or dotted profile to ensure resin flow through the joining area. As listed in Table 1, we investigated two varieties of ultrasonic welding. In a direct welding process (Table 1, Technology 2 a, 2 b), the auxiliary materials were melted directly and fixed to each other. In an indirect welding process (Table 1, Technology 3 a, 3 b) an additional thermoplastic polyurethane (PU) tape applied between the layers was melted by ultrasound and thereby used as an adhesive.

At DLR-ZLP in Augsburg we analyzed the quality of the joining areas. In a first inspection, the degree of damage has been verified qualitatively. The higher the damage of the auxiliary materials, the higher is the impact on the resin infusion. For further investigation, we conducted infusion tests to analyze the effects of the joining on the resin flow and on the cured part characteristics. Specimen consisting of eight layers of carbon fiber fabric with a dimension of 150 x 35 mm were infiltrated and cured in a VAP infusion process. Therefore, we cut samples out of the joined auxiliary material packages from ITA. Afterwards, the packages were positioned on top of the fabrics considering an angle of 90 degree between joining area and resin flow front. As reference, a specimen with a package without joining area has been prepared. For infusion, we used the standard epoxy resin of the CFRP booster case. During infusion the velocity and the shape of the flow front when crossing the joining area were documented. Imprints and markings on the part surface were detected after debagging.

3.2 Results

The test results for the joining technologies of auxiliary materials are shown in Table 1. The reference samples without joining show disadvantages in the handling and positioning procedure. This refers to the state of the art manual and therefore time consuming depositing and fixation. The ultrasonic welding technology shows appealing results during infusion, especially when using a shaded sonotrode. After curing, only little modification of the part surface compared to the characteristic peel ply surface can be observed. Disadvantages of this method refer to the visible damage of the materials in the joining area. Material damage can be compensated by adding a PU tape. This PU tape has a lower melting point than auxiliary materials and therefore needs less welding energy. Nevertheless, the resin flow is influenced measurably by the tape and slide imprints remain on the part surface. Independent of the tape, the flow rate is constant compared to the reference when using a shaded sonotrode. The sewing technology shows little influence on the package characteristics. Limitations refer to imprints of the yarn which occur on the part surface. The areal adhesion technology leads to comparatively stiff packages. On one side, this reduces the flexibility and the drapability of the package. On the other side, the handling and deposition accuracy are improved. Samples with areal adhesion show no imprints on the part surface.

Table 1: Comparison of joining technologies

	Joining Technology	Additional Material	Damage of Auxiliary Materials	Drapability	Handling of package	Resin flow in joining area	Flow rate	Imprint on part surface
1	Reference (no joining)	++	++	++	--	++	++	++
2 a	Ultrasonic welding (shaded sonotrode)	++	-	-	+	+	++	+
2 b	Ultrasonic welding (punctated sonotrode)	++	-	-	+	-	-	+
3 a	Ultrasonic welding + Tape (shaded sonotrode)	--	+	+	+	-	++	-
3 b	Ultrasonic welding + Tape (punctated sonotrode)	--	+	+	+	-	-	-
4	Sewing	--	+	+	+	+	+	--
5	Areal adhesion	--	+	--	++	+	+	++

“++” very good; “+” good; “-“ bad; “--“ worse

3.3 Discussion

For industrial VAP processes most important properties are the impact on handling, resin infusion and part quality. As a result, sewing and adhesion can be rejected due to disadvantages in these categories (Table 1). However, the influence of imprints on the part performance has to be investigated to find out, whether it is relevant for stress resistance or not. Packages joined by areal adhesion can improve the handling compared to other joining technologies. Due to a decrease of the drapability this technology shows potential for developable surface geometries such as the cylindrical section of the booster case. Further investigations are intended in the current research project. For the manufacturing of auxiliary material packages, we found continuous ultrasonic welding with a shaded sonotrode the most suitable technology. Further improvement is needed for the joining process to gain less damage of the material and higher accuracy of the contours. However, we have seen that damage of the material caused by the welding procedure has only little impact on the resin flow. Material damage should rather be reduced to avoid imprints or modification on the part surface.

4 Manual application tests on booster demonstrator

The aim of the current research project is the development of mechanical or automated application systems for auxiliary materials on the spherical dome sections of the booster case. Therefore, basic knowledge of the behavior during handling and positioning is needed. In this context, we conducted manual application tests with joined packages on a full-scale demonstrator set-up. To verify the depositing accuracy on the 3D surface, first, we measured manufacturing tolerances of the packages in a 2D state.

4.1 Check of 2D accuracy

In a first test series, we investigated if the material contours change during the joining process. The packages were positioned on a plotted 2D pattern where we measured the deviation between contour and pattern in length and width. To detect variations depending on the material, each layer (peel ply, perforated release film and flow media) was measured (Table 2).

Table 2. Maximum deviation of outer contour (2D)

	Max. deviation (length)	Max. deviation (width)
Package No.1	-11 mm	8 mm
Package No.2	-11 mm	≤ 1 mm
Package No.3	-12 mm	5 mm

We observed two main characteristics. First, the packages are shortened in length up to 11 ± 1 mm. Second, two of three packages show distortion on the narrow side, equivalent to deviation in width between 5 and 8 mm. Both characteristics refer to the joining process, since the single layers were proved as sufficient before joining. The shortening can be caused by applied compression strains during the continuous ultrasonic welding process. For compensation of this effect, either the layers can be extended or the joining parameters as feed rate and pressure can be varied. We decided to extend the layers since the joining parameters were set and optimized according to bond strength and according to avoid material damage. Punctual fixation before linear joining can reduce distortion on the narrow side of the package.

4.2 Check of 3D accuracy

For 3D testing on the booster case demonstrator, we chose *Package No.2* (Table 2) with highest accuracy and without distortion. In three different application tests (Figure 4), the package was positioned and fixed manually on the surface of the dome section. To check the deposition accuracy, the target contour of the package was highlighted with a projection line. On each side and each corner of the package, we measured the difference between package contour and projection line. The draping starting line helps to compare the test results with the results of the draping simulation in Chapter 2.

Figure 4: Deposition of *Package No. 2* on 3D surface: a) punctual fixation on package contour, b) punctual fixation on outer corners, c) linear fixation on upper and lower contour

In Figure 4a, the package was fixed punctually with tape stripes, first on the upper contour and second in the lower right corner. In Figure 4b, tape for punctual fixation was applied exclusively on the four outer corners of the package. In the third application test (Figure 4c), the package was positioned and fixed first on the upper contour and second on the lower contour. In this case, the tape was applied continuously.

After deposition and fixation, characteristic folds and wrinkles occur on the package surface. For packages with punctual fixation (Figure 4a, 4b), single folds can be observed on the upper or lower contour. Comparing Figure 4a and 4b, additional tape stripes help to arrange folds more even on the outer contour. Though, continuous fixation as shown in Figure 4c, results in visible stress and shear effects due to the direction of the tape application. Wrinkle length is increased compared to the punctually fixed packages. Referring to basic requirements for vacuum bagging, the reproducibility and the quality of open mold infusion processes is significantly influenced by the coverage of the preform with auxiliary materials. In detail, wrinkles should be as small as possible and furthermore,

they should be arranged on the surface as even as possible. We conclude that less fixation ensures more flexibility in the positioning and orientation of wrinkles. As a result, packages cover the surface without restrictions during vacuuming and compression.
Results of deposition accuracy for each *application test a, b and c* are listed in Table 3. Measured deviations in length vary in a range from -12 mm (*deposition test a, c*) to 2 mm in *deposition test b*. Maximum deviations in length vary in a range from 1 mm to 11 mm. Comparing the values for the upper and the lower corners, the package of *test b* is deposited symmetrically. In contrast to this, packages in *test a* and *test c* differ both in length and in width. This effect may result from an asymmetric deposition movement during application. However, it can be concluded that the deposition procedure of *test b* leads to an adequate deposition result with minimum complexity of fixation.

Table 3. Maximum deviation of outer contour (3D)

	Max. deviation upper right (length)	Max. deviation lower right (length)	Max. deviation upper right (width)	Max. deviation lower right (width)
Deposition test a)	-2 mm	-12 mm	≤ 1 mm	8 mm
Deposition test b)	2 mm	2 mm	11 mm	10 mm
Deposition test c)	0 mm	-12 mm	10 mm	≤ 1 mm

Comparing the 2D deposition accuracy of *Package No. 2* (Table 2) and the 3D *deposition test b* (Table 3), it can be concluded that a shortening of the package of about -10 mm in length results in a congruent deposition in the corners. In contrast to this, a 2D alignment in width results in deviations in 3D of about 10 mm. In a redesign step, we adapt these values to the design method to rework the shape of the packages (chapter 2).

4.3 Conclusions

A design method for auxiliary material packages has been developed and validated successfully by manual application tests on a full-scale rocket booster case demonstrator. The generated developable packages reach the calculated draping behavior on the spherical dome sections in a tolerance of about 10 mm. This value matches specified manufacturing tolerances for overlaps. Best handling and application results were achieved when fixing the package punctually and symmetrically on the outer corners. This behavior allows automated application systems to pick and place packages without complex fixation devices. Ultrasonic welding was found to be a suitable joining technology for auxiliary material packages. Since no additional adhesives have to be used, this technology seems appropriate for industrial vacuum infusion manufacturing processes without extensive qualification procedures.

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