Wind power's portrayal as a 100% clean source of renewable energy bodes well for those seeking a power source with little environmental impact. Nevertheless, to stay true to this green promise, we mustn't lose sight of the carbon footprint laid down prior to the generation of electricity. Composite materials, acknowledged as an enabler of the green promise, can contribute greatly to this footprint. In recognition of this reality, manufacturers' have turned from open mould processing to closed mould vacuum infusion processing.

By Patrick Mack, Chief Technologist, Polynova Composites, USA

Keeping it Green

Advances in Textiles for Vacuum Infusion Processing

Closed mould vacuum infusion processing of composites is recognised as offering reduced volatile emissions, higher fibre content and improved laminate quality relative to the baseline open mould wet lay-up process. Additional benefits include a low capital investment and an easily manageable learning curve. Accordingly, examples of its use in wind turbine construction abound, from rotor blades to nacelles. Recent advances in infusion-specific textiles present an evolutionary step towards further reductions in manufacturing costs while reducing the carbon footprint for wind turbine manufacturers. The advantages these products pose extend beyond consideration of cost and carbon footprint, however, as they offer superior post-fabrication adhesive joining of composite structures.

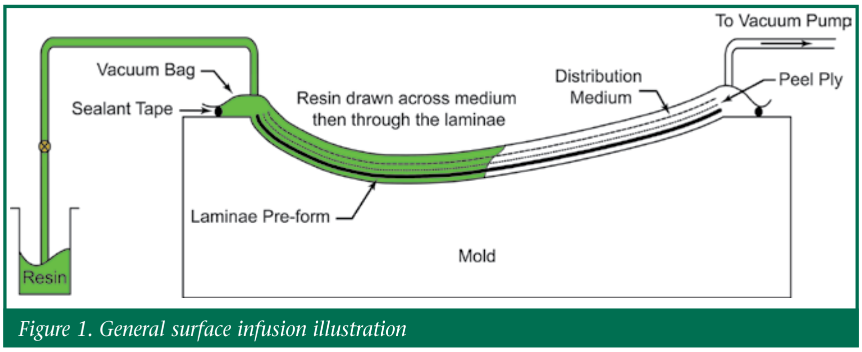

Figure 1. General surface infusion illustration

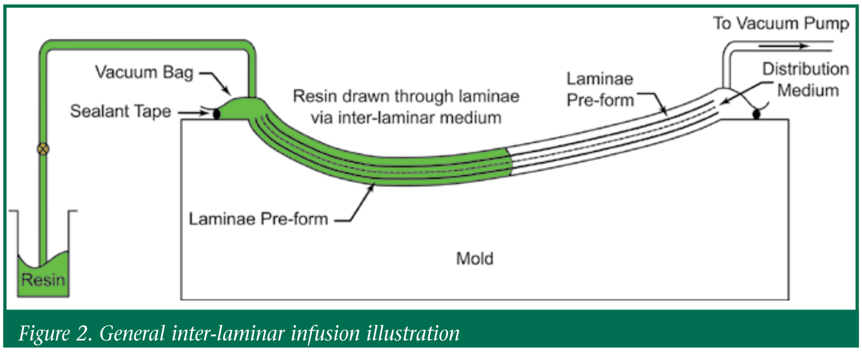

Figure 2. General inter-laminar infusion illustration

Process Explanation

Vacuum infusion processing was born from the desire to mate the value proposition of aerospace closed moulding to the needs of the commercial manufacturer engaged in open mould processing. In closed mould processing, liquid resin is injected using a pressure gradient. In vacuum infusion processing, negative pressure provides the gradient needed to motivate resin flow.

There are two basic vacuum infusion processing techniques: *surface infusion and inter-laminar infusion*. In both practices, a flexible bag or membrane is sealed to a rigid mould to form the 'closed' mould. As the closed mould is evacuated by vacuum, the bag collapses against the pre-form, consolidating it against the mould. While this consolidation promotes high fibre content in the final laminate, it does so at the expense of in-plane resin flow. Hence, both practices employ a distribution medium designed to facilitate in-plane resin flow, allowing out-of-plane (through thickness) resin infusion to occur. The terms surface infusion and inter-laminar infusion denote the location of the distribution medium relative to the laminae pre-form.

In conventional *surface infusion* (Figure 1), a removable layer, commonly referred to as a peel-ply, is placed on top of the pre-form before applying the flexible bag, and the distribution medium and/or perforated injection tubing is placed on top of the peel-ply. Once the bag is in place, vacuum is applied and resin is drawn through feed-lines into the mould across the distribution medium and through the pre-form. Upon resin cure, the bag is removed, as are the peel-ply and distribution medium, which need subsequent disposal. The peel-ply facilitates removal of the distribution medium while leaving a textured surface on the part for improved secondary bonding. To date, the greatest drawback of surface infusion has been the high waste and cost associated with the application, removal and disposal of peel-plies and distribution media.

In inter-laminar infusion (Figure 2), the distribution medium is integrated with other laminae in the ply stacking sequence, typically in the centre or neutral axis, and maintains an open porosity while the laminae pre-form is being compressed under vacuum. Because the distribution medium remains within the laminate, the need for peel-ply can be reduced to areas where a textured surface is desired. Since the composite becomes the infusion pathway, placement of vacuum and resin feed-lines is simplified and the post-process waste stream is reduced. Inter-laminar infusion is particularly proficient at infusing thick composites because its placement in the centre of the ply stack halves the out-of-plane distance the resin needs to travel. To date, the non-structural nature of available distribution media has been cause for concern, even when used in the neutral axis.

Advances in textile design have led to the development of a new class of distribution media known as Infusion Flow Reinforcements (IFR). Aptly named, this class of textiles facilitates infusion flow while contributing to the laminate as a constituent material. This shift in thinking broadens process control for inter-laminar infusion and affords the opportunity to eliminate the waste stream associated with conventional surface infusion. In inter-laminar infusion, ply stack placement of an IFR would not necessarily be limited to the neutral axis. Placement of IFR would be driven by optimum flow considerations (i.e. off-neutral axis or in multi layers in a thick composite). In surface infusion, IFR could be used as the last ply in the laminae, replacing the disposable medium, and potentially eliminating the need for peel-ply altogether.

Application Study

Recently, Polynova Composites participated in a test programme to evaluate a commercially available IFR, HIFLUX-90, as the last ply in surface infusion.

Constructed of high tenacity polyester fibre, the open nature of this textile, shown in Figure 3, assures a high degree of out-of-plane permeability, while its periodically raised or ribbed members (knops) lend a third-dimensional prominence to separate adjacent layers and ensure bilateral in-plane resin flow. Engineered with preferential in-plane flow in the weft (90°) direction, the product is well suited for high aspect ratio applications, such as wind blades, where the width presents the shortest infusion path. Further, its good handling and draping properties eases lay-up of complex parts.

The test programme investigated the lap shear and cross peel adhesive performance of ITW Plexus MA530, MA560 and MA590 methyl methacrylate adhesives. The adhesives were used to bond composite substrates: (i) identical peel-ply textured surface coupons; and (ii) identical HIFLUX-90 surface coupons.

Both composite substrate panels were fabricated at Polynova Composites, of Milford, Massachusetts, USA, by surface infusion using Ashland Aropol 63301-10 INF polyester resin initiated with 2wt/% Norox CHP. Both resin and room temperature were 23°C, and both composite panels were infused under 91.43kPa vacuum. Table 1 identifies the substrate laminate schedules.

Panel 07501-1	**Panel 07501-3**
Tool surface	Tool surface
E-BXM 1708 (mat against tool) [0°]	E-BXM 1708 (mat against tool) [0°]
E-2LT 3600 [02°]	E-2LTI 3600 [02°]
HIFLUX-90™ knop down [0°]	Econo Ply E peel-ply [0°]
Nylon vacuum bag	Resin Flow 75 [0°]
	Nylon vacuum bag

Table 1. Substrate laminate schedules

Table 2 compares the measured lamina and laminate weights and highlights for both panels.

Panel	**07501-1**	**07501-3**
E-BXM1708 (g/m^2)	913	913
E-2LTI3600 (g/m^2)	2,795	2,823
HIFLUX-90™ (g/m^2)	363	-
Total measured laminae weight (g/m^2)	4,072	3,736
Measured laminate weight (g/m^2)	6,983	6,135
Fibre content (wt%)	***58%***	***61%***

Table 2. Panel laminae/laminate comparison

Table 3 presents the measured post-fabrication waste stream associated with the use of the peel-ply, disposable distribution medium and associated resin.

Panel	**07501-3**
Econo Ply E peel-ply (g/m^2)	83
Resin Flow 75 (g/m^2)	111
Total measured dry weight (g/m^2)	194
Measured infused weight	927
Resin waste (g/m^2)	733

Table 3. Post-fabrication waste stream

Tensile lap shear testing was performed in accordance with ASTM D 5868 and cross peel testing was performed in accordance with SAE J1553. For each adhesive, test specimens were created by dry rag wiping the substrates then bonding coupons at room temperature. The bond line was 0.0762cm in each case.

Study Results

Table 4 contains all lap shear data for this study and Table 5 contains all cross peel data for this study.

Adhesive	Substrate	Bonding surfaces	Lap shear strength (MPa)	Failure mode	Standard deviation
MA530	07501-1	HF-90™ to HF-90™	6.93	Fibre-Tear	0.50
MA530	07501-3	PPTS to PPTS	6.49	Light-Fibre-Tear	0.42
MA560	07501-1	HF-90™ to HF-90™	6.87	Fibre-Tear	0.43
MA560	07501-3	PPTS to PPTS	6.83	Light-Fibre-Tear	0.33
MA590	07501-1	HF-90™ to HF-90™	6.39	Fibre-Tear	0.41
MA590	07501-3	PPTS to PPTS	7.16	Light-Fibre-Tear	0.55

HF-90 = HIFLUX-90; PPTS = Peel-ply Textured Surface

Table 4. Lap shear data

Adhesive	Substrate	Bonding surfaces	Strength (Mpa)	Failure mode	Standard deviation
MA530	07501-1	HF-90™ to HF-90™	2.38	Fibre-Tear	0.33
MA530	07501-3	PPTS to PPTS	2.15	Light-Fibre-Tear	0.52
MA560	07501-1	HF-90™ to HF-90™	1.86	Fibre-Tear	0.43
MA560	07501-3	PPTS to PPTS	1.93	Light-Fibre-Tear	0.33
MA590	07501-1	HF-90™ to HF-90™	2.32	Fibre-Tear	0.20
MA590	07501-3	PPTS to PPTS	1.70	Light-Fibre-Tear	0.32

HF-90 = HIFLUX-90; PPTS = Peel-ply Textured Surface

Table 5. Cross peel data

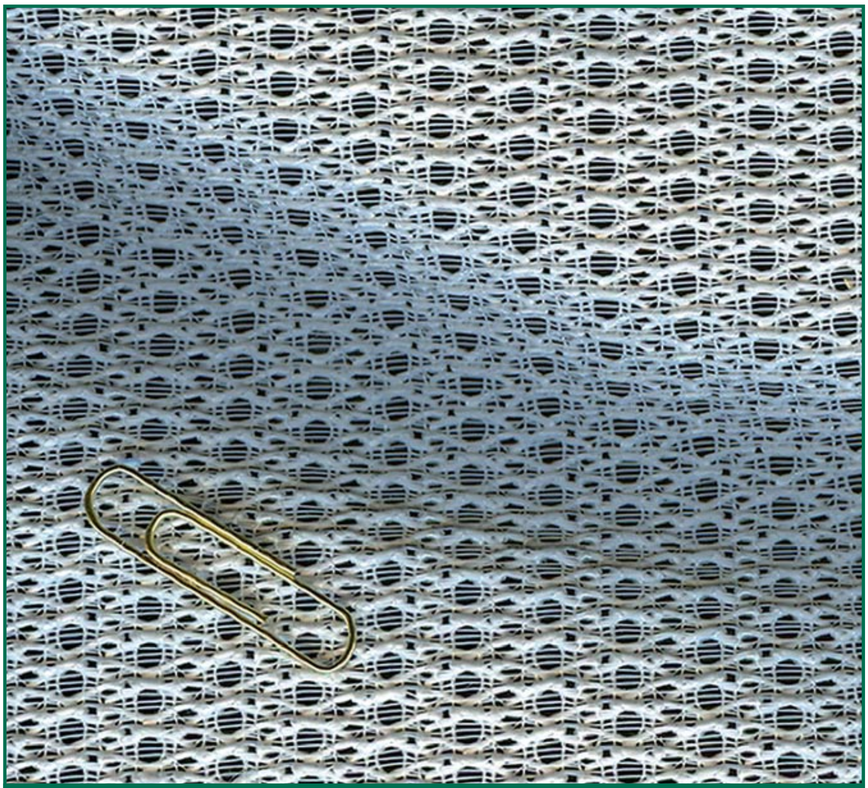

Figure 3. Example IFR

Plexus MA530, MA560 and MA590 adhesives produced quality bonds to both the peel-ply textured surface and the HIFLUX-90 IFR surface, with a favourable fibre-tear failure mode noted for the HIFLUX-90 surface.

For the peel-ply textured surface (07501-3), the mode of failure was light-fibre-tear (Figure 4) which occurs when resin and fibres are pulled free from the surface of one coupon while the adhesive bond-line remains intact on the other coupon. Such failures indicate good adhesion between the adhesive and the substrate, and point to substrate integrity as the limiting factor of obtained strength values.

For the HIFLUX-90 surface, the mode of failure was fibre-tear (Figure 5). Fibre-tear occurs when resin and fibres are pulled free from within the laminate of one coupon, while the adhesive bond-line and laminate remain intact on the other coupon. Such failures indicate

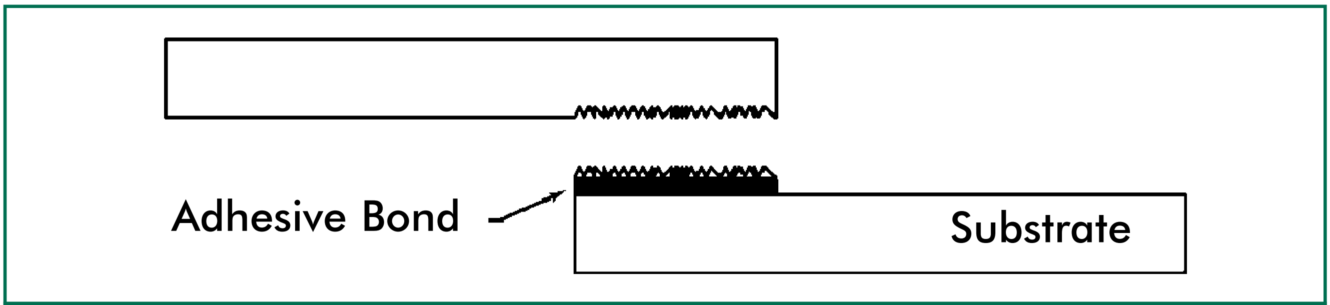

Figure 4. Light-fibre-tear failure

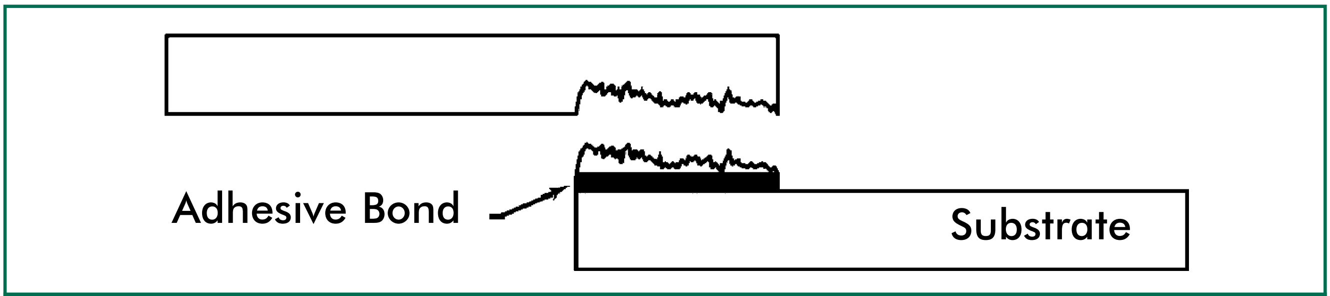

Figure 5. Fibre-tear failure

Lamina legend:

E-BXM 1708 (Vectorply Corporation)

Fibre type:	*E-Glass*
Architecture:	*+45°/-45° double bias w/chopped strand mat*
45°:	*304g/m2*
-45°:	*304g/m2*
Chopped mat:	*275g/m2*

E-2LTI 3600 (Vectorply Corporation)

Fibre type:	*E-Glass*
Architecture:	*0°/90°/0°/90° biaxial*
0°:	*627g/m2*
90°:	*608g/m2*

HIFLUX-90 (Polynova Composites)

Fibre type:	*High Tenacity PET Fibre*
Architecture:	*Proprietary*
Areal weight:	*363g/m2*
Knop:	*Surface projection*
Knop down:	*Projection facing tool surface*

Econo Ply E (Airtech International): Peel-ply designed for use in more difficult environments or when a more textured surface is required for secondary bonding.

Resin Flow 75 (Airtech International): High flow rate disposable surface infusion media.

good adhesion between the adhesive and the substrate, and point to substrate integrity as the limiting factor of obtained strength values; examination of the specimens reveals that the failure occurred within the E-2LTI 3600 laminae. Also there appears to be a strong correlation between the adhesive gel time and the depth of fibre-tear, with longer gel times corresponding to greater depth. This observation holds true for both the lap shear and cross peel sample. This may be attributed to the resin-rich surface provided by the HIFLUX-90 and the extent to which the adhesive is allowed to etch into this surface as a function of time.

Conclusion

Social sentiment has undeniably shifted towards an emphasis on reducing industry's environmental impact. Governmental policies increasingly reflect such interests. Composite materials are widely recognised as key enablers of the green promise. Ultimately, the wind energy industry must adopt composite processing techniques that truly fulfil the green promise by minimising the carbon footprint created prior to generation of the first watt. Using Infusion Flow Reinforcements™ as the last ply in a surface infusion process enables the elimination of disposable waste streams, while enhancing post-fabrication adhesive joining of the composite structures in the intended application. These attributes pose a winning combination for the environment and manufacturers of wind turbines. While the Plexus® adhesives present a strong choice for adhering the two composite substrates in this study, it is recommended that customers prepare a testing protocol to determine the adhesives' suitability for their particular applications and processes. ■

Biography of the Author

Patrick Mack has more than 20 years of multidisciplinary experience in technology, engineering and management. He is currently the Chief Technologist of Polynova Composites, where he leads the development of innovative market-driven product solutions for the composite materials marketplace, fostering their growth from inception through laboratory validation to commercial implementation.

Affiliation

Patrick Mack
Chief Technologist
Polynova Composites
229 East Main Street, Ste. 204
Milford, MA 01757 USA
e-mail:
pmack@polynovacomposites.com
www.polynovacomposites.com