

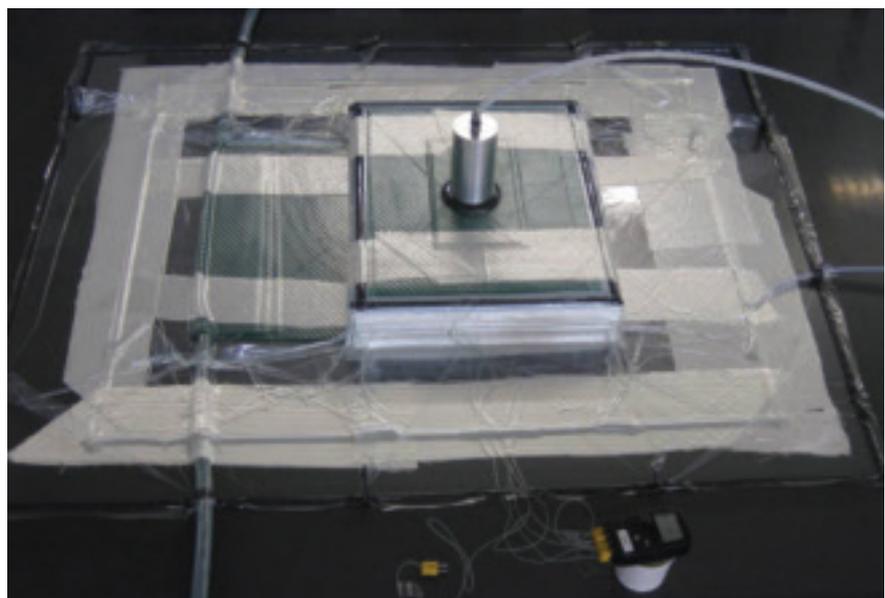
Big challenges: the role of resin in wind turbine rotor blade development

The demand for bigger wind turbines, powered by longer blades, has placed many challenges on the blade manufacturers and their suppliers. Paul Langemeier, Director, Global Market Development, and Christoph Scheuer, Market Development Manager, of Hexion Specialty Chemicals reviews the history of blade manufacture and the challenges facing resin manufacturers today.

When the first multi-megawatt (MW) wind turbine prototype was built in the early 1980s, the wind energy industry saw its future. And it was big.

The prototype proved that 2-3 MW turbines could reliably deliver a magnitude more energy over a lifetime than their 300 kilowatt (kW) predecessors. The industry could increase yields, decrease cost per kW and become a more competitive energy source by making turbines progressively larger. This insight, combined with the exploding demand for 'green' energy alternatives to decrease reliance on fossil fuels, meant 'big' would be the next big thing.

The success of the prototype also ushered in a new generation of materials. As blades



VARTM process at Hexion's lab.

increased in length from less than 20 m to greater than 26 m, epoxy resin systems began to replace polyester resins and have since become the standard matrix resin for longer blades. In addition, although glass fibre was strong enough to handle the stresses exerted on the longer blades required for a 3 MW turbine, it added too much weight to them. Though most multi-MW blades are still being built out of glass, carbon fibre-based epoxy resin composite materials could provide the required mechanical strength while minimising additional weight. Years of research and development into these raw materials followed. This work continues today and promises to accelerate as the demand for wind energy explodes, and the need grows for ever larger turbines powered by ever longer blades.

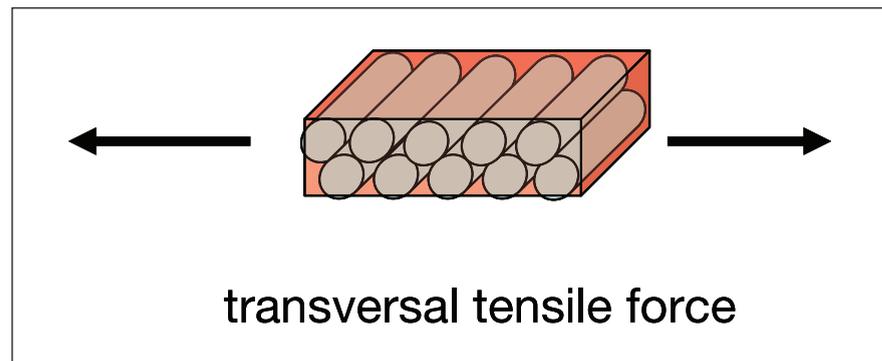
The challenges which this has placed on blade manufacturers and their resin suppliers are many. We'll try to identify the key issues both historically and on the horizon.

A look back

Modern wind turbines were first manufactured in the 1950s using glass fibre reinforced polyester blades. The reason was simple: at that time glass fibre with polyester resin was the best understood and most fully refined composite material technology. Glass polyester composite materials had been used for many years in consumer and industrial applications in which significant composite mechanical strength was not required.

As blade lengths increased with the move toward multi-MW turbines, and fatigue resistance performance became extremely important, blade designers and manufacturers began substituting stronger, more durable epoxy resin systems with glass and carbon fibre for the traditional polyester glass fibre materials.

In the early days of blade production, hand lay-up was the standard processing method. Fibre was literally dipped in a bath of resin, laid across a mould, and brushed out by hand. The product safety issues were obvious, and the process was time-consuming. The fibre volume fraction was limited, and the risk of failures like wrinkles



An illustration of transversal tensile strength.

and voids was high, along with inconsistency in the weight and poor reproductibility in the blade composition.

The advent of epoxy prepreg addressed the limitations of fibre volume and many of the worker exposure issues of hand lay-up, but it also requires multiple manufacturing and transportation steps, has additional cost elements such as plastic films, and employs manual labour. Prepreg is made by impregnating fibre with resin and then partially curing the resin at elevated temperature (B-stage), usually at a separate facility operated by a prepreg manufacturer and requires storage at low temperature. The prepreg is then shipped to the blade manufacturer and requires storage at low temperature. At the blade producer's plant, layers of prepreg are placed in a mould, pressed together and then fully cured at elevated temperature to form the composite material part.

A key inflection point in technology development was the introduction of vacuum assisted resin transfer moulding (VARTM) for the epoxy systems used with glass fibre. This process had already been implemented for polyester blade manufacturing and had proven to reduce steps and lower costs.

With the VARTM process for epoxy resin systems, a glass and/or carbon preform could be placed in a closed mould, with epoxy resin sucked in and the part cured in one relatively automated step rather than the required curing between individual steps of blade manufacture by hand lay-up. The much improved blade quality, shorter process cycle times and overall cost savings of VARTM have

led to its general adoption by the industry. The industry, in turn, has looked to its fibre and resin suppliers for continuous improvements in several key areas.

Resin mix viscosity

In the resin infusion process, a resin/curing mixture is sucked into a mould in which preformed glass or carbon fibre has been placed. Before the part cures, a vacuum pump draws excess resin, which should be minimal, into a capture vehicle. The time required to fill the mould is dependent upon the resin velocity through the fibre/sandwich preform.

The resin velocity is computed using Darcy's law for flow through porous media:

$$v = - \frac{K}{\eta} \nabla P$$

This equation states that the resin velocity (v) is proportional to the permeability (K) of the preform material and the pressure gradient (η) and inversely proportional to the mixture viscosity (∇P). The pressure gradient is proportional to the pressure difference along the resin flow. In essence, this means that to optimise the infusion process time, blade manufacturers are always looking to minimise resin mix viscosity, while maximising permeability factors, and applying the lowest possible pressure during infusion.

Applying Darcy's law, it's obvious that the lower the viscosity of the resin, the faster it can be sucked through the mould, and the faster the overall process. However, resin suppliers need to respect certain limits when developing new infusion systems. Making use

of low molecular weight reactive and non-reactive diluents, which typically reduce resin mix viscosity effectively, often results in weaker mechanical properties of the cured part and a higher vapour pressure of the resin mixture.

Alternatively, increasing the infusion temperature can be employed to decrease resin mix viscosity. However, infusion at higher than recommended temperatures significantly impacts the resin mix pot life, i.e.

the resin mix viscosity increases over time, and demands that special attention be paid to the vapour pressure.

Resin vapour pressure

As mentioned above, blade makers also want to minimise the absolute pressure for the VARTM process. Achieving this depends on the vapour pressure of the resin mixture at infusion temperature. Raoult's law states that the vapour pressure of a blend of liquids (e.g. a resin/curative mixture) at a given temperature is the sum of the partial pressure of the components.

$$p = \sum_i x_i \cdot p_i$$

The vapour pressure (p) of the mixture is the sum of the mole fraction (x_i) times the corresponding vapour pressure (p_i) of each component.

In their drive for the lowest possible absolute pressure, manufacturers must be careful. Reducing the absolute pressure of the infusion process to the level of the highest partial pressure of the ingredients will result in boiling of the corresponding component which, in turn, leads to mix ratio misalignments and increasing risk of voids in the laminate.

What manufacturers strive for is 'low pressure resins' which allow for the lowest possible absolute infusion pressure. There are trade-offs to consider. The low mix viscosity resins usually correlate with higher vapour pressures. To infuse these resins properly, the absolute pressure of the process has to be increased. To optimise the VARTM process, blade makers and their resin suppliers must get the mix of resin viscosity and vapour pressure just right, while making sure the strength of the finished composite isn't compromised.

Fibre wetting

Another area which has gotten a lot of attention is inconsistent fibre impregnation. Manufacturers are anxious about dry spots, where critical fibre material is inadequately wetted by resin sucked into the mould.



Blade lengths increased with the move to multi-MW turbines.

This is especially true with carbon fibre filament, which is much smaller than glass fibre, harder to impregnate completely, and difficult to inspect visually.

The interfacial tension between resin and fibres plays a key role in optimal wetting. Young's law summarises the relationship:

$$\sigma_{si} = \sigma_s - \sigma_f \cdot \cos\theta$$

The interfacial tension (σ_{si}) is equal to the surface tension of the fibres (σ_f) minus the surface tension of the resin mixture times the cosine of the contact angle (θ). To obtain complete fibre wetting, the surface tension of the fibre must be equal to or greater than the surface tension of the resin mixture ($\sigma_f \geq \sigma_s$). The best adhesion is obtained when the surface tension of the resin mixture equals the surface tension of the fibres.

A range of research and development has been done on this front. Fibre manufacturers are integrating new sizings into their products that are easier to wet consistently. New infusion resins which are lower in viscosity, easier to pump, and provide better wetting have been introduced.

Although big improvements have been made in fibre wetting, many types of defects can still arise during production. Advanced non-destructive inspection (NDI) technologies – such as ultrasound – are being actively investigated to detect unacceptable defects in the early stages of manufacturing.

These efforts promise to make the infusion process much more uniform and predictable across both glass and carbon materials. This improvement in quality control will be critical as blades lengthen and the demands on critical parts become larger.

Next big breakthrough

While work on VARTM variables such as resin mix viscosity, resin vapour pressure and fibre wetting have all been critical in driving improvements that have made longer blades possible, a new epoxy resin

system technology advance could greatly eclipse them.

To determine the strength and stiffness of components operating at allowable ambient temperatures between -30 and +50°C, the GL-Wind *Guideline for the Certification of Wind Turbines Edition 2003 with Supplement 2004* requests seven glass fibre reinforced plastics (GRP) dedicated properties be tested. Among these, tension tests perpendicular to the fibre determine the transversal tensile strength. Blade designers' key interests for property improvements are the increase of the transversal tensile strength (TTS) and the fatigue performance in key parts of the blade, allowing longer, stronger blades with less material weight.

New epoxy resin systems are currently being developed that combine low mix viscosity with significant improvements in TTS performance. Tests with traditional glass fibre have shown increased TTS (+15%) under lab conditions.

The implications are significant. Resins that can impart improved TTS require less fibre which, in turn, requires less resin. That means a lighter overall blade, which translates into a lighter drive train and gearbox to power it and a lighter tower to support it. Or, conversely, increases in TTS mean ever longer blades can be used with the same size turbine.

The cost of energy (COE) can be reduced by making use of these new resin developments in future blade designs. Most blade designers believe that for every 1% increase in TTS, they can save 1% of blade weight. Manufacturers with visions of much longer, lighter blades may soon have to look no further than the resin systems they're using.

Advances on the horizon

Of course, all of the current practices and materials based on past innovations may seem quaint when compared to new material technologies such as the aforementioned new resin technology and new

processing techniques perfected in the years and decades ahead.

One processing practice which could radically improve blade quality while shortening process cycle times is automated components deposition. Today, building a blade with VARTM is still a relatively time-intensive and somewhat error-prone process. Workers must first lay out all of the dry components in the mould, positioning fibre in various thicknesses at different places. Because people are involved, there is the potential for misalignments and wrinkles. This can compromise the integrity of the final composite product.

With automated components deposition, the fibre would be placed mechanically and monitored electronically, so that any necessary corrections could be made prior to the infusion process. This would make for much more predictable and repeatable parts. Increases in quality control would also allow for more complex blade designs.

Another area of material technology which shows real promise is the introduction of unique optimised resin systems for each of the blade's primary components. In the past, the industry has had a 'one size fits all' approach to resin systems, which has required some compromises. As blades become bigger, and the performance of each part is examined more closely, blade designers and manufacturers will likely start to look at the weight, processability and mechanical properties of each in isolation – and choose resin systems appropriately.

Whatever path the technology takes, the direction toward bigger blades is all but assured. National sponsorship of wind energy continues apace. The demand for wind turbines to stabilize the grid – and for their 'green' benefits – is growing rapidly. The most efficient turbines in cost per kWh will be the largest. This focus on the 'big' will continue to drive resin innovation in ways both big and small. ■

Further information

Hexion Specialty Chemicals; www.hexion.com