Thermoplastic composites for future wind turbine blades - Pros and Cons

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1 Introduction

Polymer composites are gaining several industrial applications in today's scenario. Among them wind industry is one, which consumes lots of material in developing turbine rotor blades. Current trend points to a growing importance of the onshore and offshore wind mill farms in the world's energy segment. The industry growth over the last decade has been spectacular. It is the time to maintain market growths exponentially by upgrading the current technologies in terms of new and innovative blade designs, new materials, and automated processing system aiming cost-effectiveness to customers [1-2].

Wind industry is continuously trying to replace the current material system (i.e. thermosets) with a new material system like thermoplastics mainly to get added advantages in terms of sustainability like recyclability and potential benefits like joining methods such as resistance welding and repair methods. Since the blade lengths are increased to 61.5m long, the weight and cost saving has become a significant role on industry growth. The best option is thermoplastic composites, which can be stronger enough for the same weight than thermosets permitting light weight structures. This can be achieved only by replacing the existing material system by introducing new materials such as thermoplastic polymers or green materials such as bio-based polymers [3-4].

The use of thermoplastics in wind turbine rotor blades is in its early stages. The basic material properties are investigated by several researchers and continuously trying to improve the interface properties between the glass fibres and various thermoplastic polymers in order to achieve comparable properties with thermoset composites. This needs a thorough investigation and proper understanding of basic material properties, manufacturing processes, and structural performance of final composite products such as static and fatigue performances under various stimulated loading conditions [5].

The present article reviews the advantages and disadvantages of thermoplastic composites for the development of future wind turbine blades. This study mainly focuses on pros and cons of different thermoplastic material systems like commingled, prepreg, and reactive based polymer systems.

2 Materials and Manufacturing Processes

The commonly used thermoplastic systems in many engineering applications are in the form of either commingled (hybrid yarns), prepreg (pre-impregnated tapes), or reactive based polymers. The current article considers the three kinds of thermoplastics and reviews the potential benefits for its suitability to wind turbine blades.

2.1 Materials

Based on material selection criteria's for the wind turbine blade application [6], very few materials were considered to check the process-ability, material properties, scanning electron micrographs to analyze the fibre/matrix interface bonding, to evaluate quality of laminates, and fracture surfaces etc. The following are the material systems considered in this study, to review the pros and cons of various thermoplastic composites.

2.1.1 Commingled Material System

A hybrid yarn is a commingled textured yarn consisting of structural fibres and thermoplastic fibres. It is also called as postpreg material (opposite to prepreg) since the fibres are impregnated with the matrix in a post process. The hybrid yarns and fabrics are also representing some kind of 'dry impregnation' and help to get uniform distribution of

polymer in composites. Very few polymers (PP, PET, PBT, and PA6) were considered as candidates, and these polymers are being processed and tested with glass fibres (GF) with many different types of sizing.

2.1.2 Prepreg Material System

Pre-impregnated materials (prepregs) are reinforcement fibres or fabrics, which have been impregnated with a thermoplastic matrix. Prepregs provide consistent properties as well as consistent fibre/resin mix and complete wet-out. This material system has several advantages like they are more consistent and can be used to create higher quality parts, as well as making component manufacture simpler and faster. Similar to commingled material system, very few polymers as mentioned above were considered as candidates.

2.1.3 Reactive Polymer System

A state-of-the art study of thermoplastic reactive polymer materials has identified resins which have similar advantages like thermoset polymers such as low viscosity providing better process-ability. The reactive polymers which qualify for wind turbine blade manufacturing are Anionic Polyamide 6 (APA6) and Cyclic Butylene Terephthalate (CBT). These polymers are competitive and can replace the current thermosets i.e. polyester and epoxy resins used today to make large structures like wind turbine blades of 61.5m length by vacuum infusion [7].

2.2 Manufacturing Trials

The vacuum consolidation technique is a clean and robust method for processing composite structures with very high material quality in terms of higher fibre volume fraction (50 – 55 vol.-%), low porosity (< 2 vol.-%), no un-wetted fibres, and controlled fibre orientation. In principle, this technique consists of four steps such as: lay-up of the semi-raw materials into the mould, vacuum bag and evacuate the material, heat the material and the mould to the process temperature under vacuum, and cool it all back to room temperature in order to solidify the matrix material. The impregnation of fibrous materials requires a very low polymer viscosity, since thermoplastic polymers are several orders of magnitude higher viscosity compared to thermoset polymers. In order to reduce the impregnation time and avoid the risk of thermal degradation of the polymer, proper selection of processing temperature is highly recommended. This indicates the polymers used in commingled yarns and prepreg tapes are totally dependent on temperature without any chemical reaction kinetics, unlike thermoset polymers. To study the material systems proposed in this article, a vacuum consolidation technique is used aiming to make a unidirectional laminate with standard glass fibre reinforcements (see Fig 1).

The process trials were done using autoclave to check the quality of the laminates made under perfect vacuum. Figure 2 is the consolidation cycle for GF/PBT prepreg laminate showing up the processing temperature used in producing the laminates are well above the melting temperature of PBT polymer (220 °C). That means the PBT polymer melts, impregnate with glass fibres, and solidify. Similarly other material systems were processed using the same consolidation technique, where autoclave unit controls the temperature and vacuum without applying pressure.

Fig. 1. Vacuum consolidation technique using autoclave

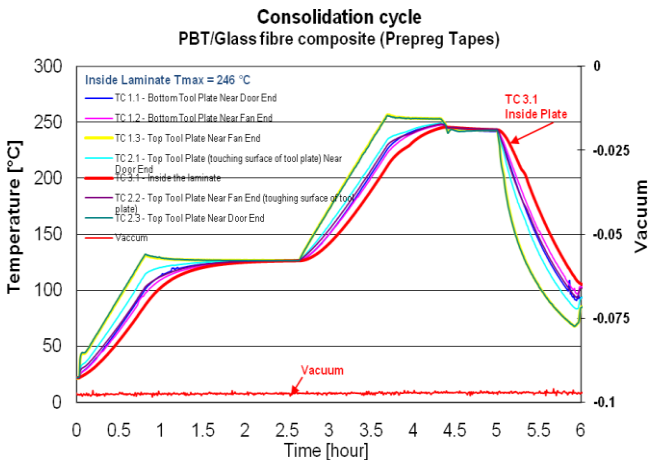

Fig. 2. Process cycle - GF/PBT prepreg laminates

The reactive based resin CBT/160 were processed using the same consolidation technique, the melt temperature of the CBT resin is between 120 - 200°C, therefore the laminates processed around 230°C for better cure kinetics and higher degree of crystallization. The APA6 resin was used to make GF/APA6 laminates. Since polyamides are highly sensitive and can absorb moisture it is very difficult to fully impregnate the glass fibres. The laminates obtained were poor quality to perform mechanical tests.

Table 1. Compression properties – Glass fibre (GF) reinforced thermoplastic composite systems

Sl. No.	Material System	Fibre Volume Fraction (%)	Compression Modulus (GPa)	Compression Strength (MPa)	Strain to Failure (%)
Prepreg Tapes (Unidirectional)					
1	GF/PP	50.9	36.2 ± 0.3	335 ± 64	1.0 ± 0.2
2	GF/PET	49.5	32.9 ± 1.6	372 ± 17	1.2 ± 0.1
3	GF/PA6	59.5	48.1 ± 1.6	619 ± 36	1.3 ± 0.1
4	GF/PBT	46.0	31.3 ± 2.1	517 ± 20	1.6 ± 0.1
Commingled Yarns (Unidirectional)					
1	GF/PP	50.5	41.4 ± 0.4	359 ± 13	0.9 ± 0.1
2	GF/PET	49.5	40.9 ± 1.9	601 ± 91	1.5 ± 0.2
3	GF/PA6	47.8	39.1 ± 1.5	577 ± 17	1.5 ± 0.1
4	GF/PBT	50.0	37.5 ± 3.2	601 ± 29	1.7 ± 0.1
Reactive Polymers					
1	GF/CBT160	50.0	36.2 ± 0.8	487 ± 61	1.4 ± 0.2
2	GF/APA6 [8]	46	39	634	1.7

2.3 Mechanical Properties

Among the static and fatigue properties of composite turbine blades, in-plane compression properties were most critical static properties for the blade design. The thermoplastic materials considered in this article were tested for compression loading as per the standards ISO 14126. The properties of unidirectional (UD) glass fibre reinforced thermoplastic composite systems considered in the present study were summarized in the Table 1.

Among the prepreg materials tested for compression, GF/PA6 laminates show higher compression strength (619 MPa) compared to other material systems, where as similar performance shown compared to GF/APA6 laminates (634 MPa). The disadvantage with the prepreg system is processing temperature. In order to melt the pre-impregnated polyamides for better impregnation the process temperature should be around 260°C, which is much higher than the processing temperature of APA6 resin (which is 180 °C). The other systems are highly attractive in terms of cost and processing temperatures but the compression properties are low which is not suitable for wind turbine blade design. Several researchers extensively work towards the development of these low cost thermoplastic polymer (pre-impregnated tapes) using nano-clay or nano particles to improve the mechanical properties as similar to GF/Polyester composites.

Compared to prepregs, commingled laminates show better compression properties. The GF/PBT and GF/PET has almost same strength (601 MPa) with a fibre volume fraction around 50%. Both the materials are attractive for the wind turbine blades whereas the laminates GF/PBT require higher processing temperature (250°C) compared to GF/PET system (220 °C). The GF/PET commingled system is also underway for the development of modified version which suits turbine blade requirements in terms of process-ability, properties, and environmental resistance.

The failure modes observed for the prepreg and commingled systems are slightly different under compression loading. The failure surfaces of test specimen show acceptable failure modes as prescribed by the ISO 14126. For example GF/PA6 laminates made by prepregs and commingled systems were showing up mostly kink band formation as shown in Figure 3b), whereas prepreg specimens shown a longitudinal splitting as given in Figure 3c).

van Rijswijk et al. [8] tested GF/APA6 composites for compression properties, the laminates show highest compression strength compared to other prepreg and commingled systems. GF/APA6 material system is currently under development stage and needs a very well sophisticated tooling system to infuse the caprolactam (anionic polyamide 6), which is similar to polyester resin for vacuum infusion. The GF/CBT composites is having similar potential like GF/Polyester in terms of process-ability by the vacuum infusion technique but the properties are related with the polymerization of CBT resin. The GF/CBT laminate compression properties shown in Table 1 were low compared to GF/APA6 and

commingled systems, and also observed the quality of laminates after processing. Few researchers studied the effect of polymerization on laminate properties, the higher the degree of crystallization the better mechanical properties i.e. formation of a long-chain resulting high-molecular-weight PBT. Éire Composites, Galway patented MechTool (Mold efficient cooling and heating) tooling system for processing CBT resins (thermoplastic polymers) under controlled process parameters by vacuum infusion technique. The tooling system can decrease the production time and cost which was demonstrated by the group worked in a European project named GREEN BLADE.

Another important mechanical property for blade design is fatigue properties. Wind turbine blades require materials which can reduce material degradation by demonstrating longer fatigue life. Several researchers reported in the literature, the study on fatigue properties of thermoplastic composite systems like commingled/hybrid yarns, prepregs, and reactive based polymer such as GF/APA6 composites.

Lystrup [9] studied the fatigue performance of commingled materials like GF/PP (twintex) and GF/PET (comfil) systems, where the fibres are at 0° orientation with a fibre volume fraction (V_f = 40%). The fatigue strength (tension-tension) is higher for GF/PP (380 – 270MPa) compared to GF/PET (280 - 180MPa), whereas the shear fatigue strength is higher for the GF/PET (30 – 26MPa) compared to GF/PP (20 – 17MPa). The decrease in strength values were corresponds to 10,000 cycles – 1000,000 cycles. The reason for showing higher fatigue strength for GF/PP is glass fibres are straighter and more aligned, whereas the shear fatigue strength is higher for GF/PET because of higher bond strength between GF and PET fibres. Similarly van Rijswijk et al. [10] demonstrated the vacuum infused APA-6 composite, which has a higher fatigue resistance than the melt processed PA6 composite. This is most likely caused by a much stronger fibre-matrix interface.

This study shows the static and fatigue properties of thermoplastic composites are significantly important for turbine blades. The mechanical properties are mainly related with the fibre-matrix interface bonding (by proper sizing's), processing (optimum conditions) and better tooling systems.

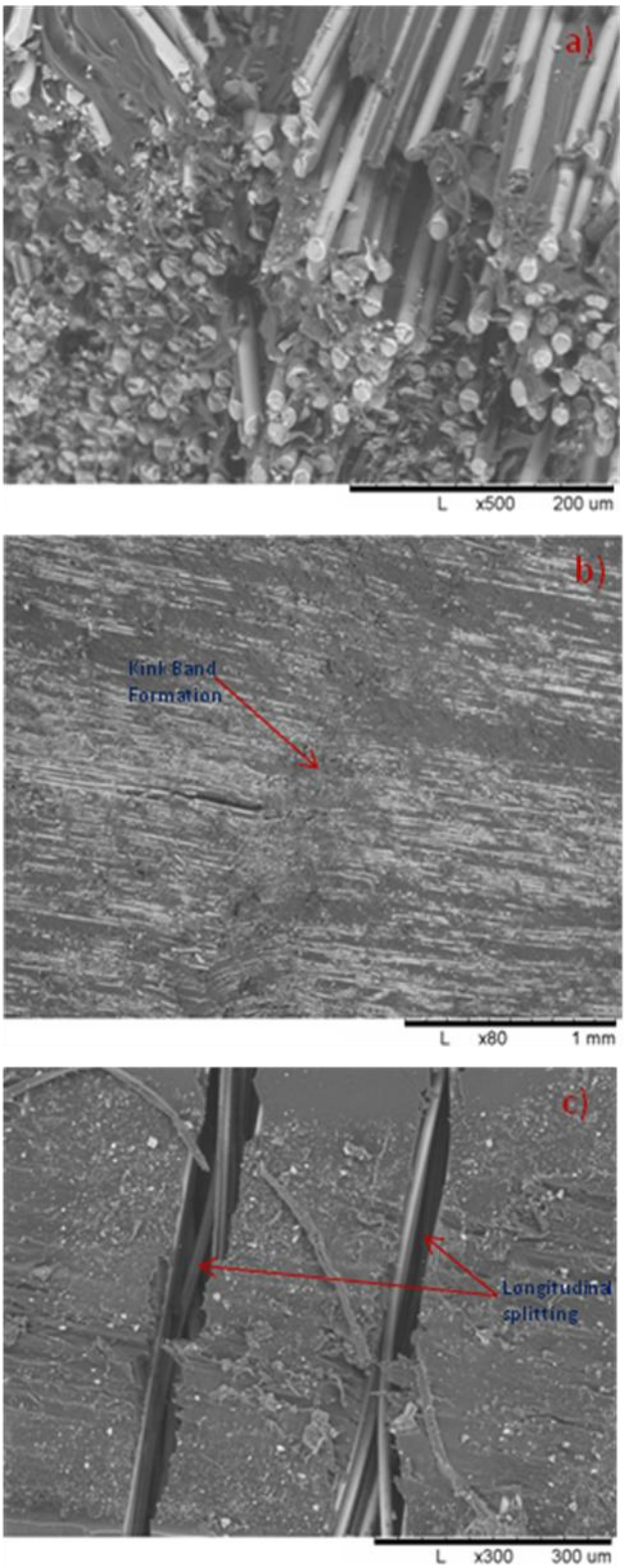

Fig. 3. Compression test specimen fracture surfaces (using SEM) both a) and b) GF/PA6 commingled specimens, c) GF/PA6 prepreg specimens

3. Pros and Cons of Different Thermoplastics

Based on the thorough research study with the thermoplastics, following are the advantageous and disadvantageous of different material systems at laminate level as well as at structural level of product and process developments of composites.

Commingled composites have several advantages like uniform distribution of matrix and reinforcement material, good wet out, free of solvents, no storage time limitations, short process time, weld ability, and good impact behavior. The degree of commingling and type of matrix material is very important in retaining the properties of laminates. Materials specifically designed to lower process temperatures are considered for study. Most of them are completely amorphous, even after processing, and becomes liquid at temperatures below 200 °C. The bonding and wetting out properties are excellent, but its end use temperature is limited to -30 °C to + 55 °C.

Prepregs offer engineers the freedom to design structures of optimum performance, the main advantages are: the ability to align the fibre orientation with the direction of principle stresses and, therefore, achieve high structural efficiency, exceptional environmental degradation and corrosion resistance properties, very low coefficient of thermal expansion, with the added possibility of designing the material to give desired thermal expansion in a particular direction, improved vibration damping properties, etc. Fibre alignment is most important in prepregs, if it is deviating few degrees compression properties get decreased.

The reactive polymers are able to replace the current thermoset resin in making large structures due to its low viscosities under higher temperatures. The polymers (CBT and APA6 resins) are highly sensitive to moisture, and need perfect drying at the time of processing. Apart from the drying, these polymers are not having standard reinforcements with perfect compatible sizing on the surface of glass fibres in order to make the composite with very good interface properties. Several researchers demonstrated the laminate trials at academic level, whereas industries are seriously trying to develop these systems for wind turbine blade processing. Moreover these materials are still under development stage [6-7].

4 Major Challenges to Wind Industry

Wind industry continuously trying to solve many research issues with respect to introducing of new material system like thermoplastics. As a part of current issues, the following are the major challenges needed to resolve to go for thermoplastic material systems for future wind turbine blades:

1. Processing a material that requires 200˚C, is difficult in molds of 40 to 60m with very high thermal expansions and larger energy consumption leading to increase in the overall cost of the blade.
2. Processing equipment and tooling system should have provision of drying the material before processing and measure the moisture content, allowable limit should be less than 50ppm.
3. Enhanced molding system with very much faster and higher cooling rates like 8 to 100C/min is desirable to achieve good performance composite structures in order to minimize the process induced defects like voids, dry fibre due to improper impregnation, resin rich zones etc.
4. Extensive research on fiber surface treatments and sizing is also underway to augment the fiber/matrix chemical bond, further increasing static and fatigue properties.
5. Even distribution of resin with a fully online monitoring of resin flow and resin impregnation along thickness direction (around 50 – 100mm thick structures).
6. Compaction and curing of sections that can reach 100mm thick at blade roots, reducing time in mould and process automation to reduce manufacturing time/cost and, critically, to improve consistency are all challenging.
7. Thermoplastics joining, but none of the methods are really tried in the wind industry shop floor where large blade shells are needed to weld instead of bonding by using specially designed chemical adhesives.
8. Best possible solution to protect thermoplastic blades from lightning.

5 Conclusions

The article describes the pros and cons of different thermoplastic material systems and challenges ahead to wind industry in developing a large scale turbine rotor blade. The main focus areas needed to resolve first are mainly highlighted as challenges to - mould designers, material specialists, blade designers, and polymer/chemical experts. This article also helps industrial designers and manufacturers to focus on thermoplastic or green materials instead of existing thermoset blade materials.

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