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Thermo Chemical Processes: Potential Improvement of the Wind Blades Life Cycle

Davide Pico*, Gunnar Seide, Thomas Gries

Institut für Textiltechnik of RWTH Aachen University Otto-Blumenthal-Straße 1, 52074 Aachen
davide.pico@ita.rwth-aachen.de

Wind power industry has shown a continuous technological improvement that has led to a structural scale up of the blades. The rotor has evolved in the last decades from a maximal diameter of 30 m at the beginning of the 1990s to 171.2 m in 2013. The bigger rotor allows to reach a far better effectiveness (1 MW compared to 7 MW) nowadays.
The stressed evolution of wind blades is principally due to the use of glass fibre reinforced plastics (GFRP) that combine high strength to low price and specific weight. Even if the blade's length has increased during the last decades, the quantity of GFRP required to install one kW of capacity is still the same.
The old wind blades are made principally of GFRP whose only components are glass fibres (60 % - 70 %) and epoxy resin (30 % - 40 %). The new ones require a better fibrous reinforcement and therefore combine GFRP with a small fraction of carbon fibre reinforced plastic (CFRP). Independently from the type of reinforcement, the operating life time is from 15 to 25 years. According to the EU legislation the GFRP scrap cannot be landfilled anymore but must be recovered.
Aim of this work is to analyse the different recovery processes. In particular this work will be focused on thermo-chemical processes that could be easily integrated in a refinery plant. In order to reduce the environmental impact of the wind blades their full life cycle from cradle to grave has been considered trying to implement the complete reuse of the fibre reinforcement with the potential recovery of the organic fraction after the recycling process.

1. Introduction

1.1 Fibre reinforced plastics (FRP)

FRP are composite materials and consist of at least two components (reinforcement and matrix) that are not melted or blended into each other. By selecting a suitable combination of matrix and reinforcement it is possible to obtain composites that accurately fit the specific properties of a defined purpose. FRP are widely used for numerous applications such as automobile parts or rotor blades for wind power stations. Nowadays glass fibres are by far the most important reinforcement material followed by carbon fibres whose application is still limited by their price.
The enormous advantage of GFRP and CFRP is their high strength and stiffness combined with low density. In contrast to conventional materials, such as metal, glass or plastics, FRP exhibit an anisotropic behaviour which results in distinct properties depending on the fibre orientation. Concerning the life cycle assessment of GFRP and CFRP, the excellent mechanical properties of fibre reinforced composites offer an ecological benefit during the utilization phase. One of the most important sectors that use these technical materials with great environmental sound results is wind energy production. The use of larger rotor blades improves their efficiency. As a matter of fact production of fibre reinforced composites progressively augmented within the last years.

1.2 Wind Energy Market

Since the 1990s the wind power production has grown from 20 to 30 % per year and it is currently one of the most important renewable energy supplies (Figure 1 right).

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The wind power industry has shown a continuous technological improvement that has led to a structural scale up of the blades. The rotor reached a diameter of 30 meters with a installed capacity of 1 MW in the 1990s. The bigger rotor nowadays offers a better efficiency with an installed capacity of 7 MW.
GFRP enabled to bridge the technological gap in order to convert wind energy into fruitful electrical power. GFRP in particular combines high strength with relatively low price and lightness. Even if the blade's length has increased during the last decades, the quantity of FRP required to install 1 kW of capacity remains unmodified as shown in Figure 1 (left).

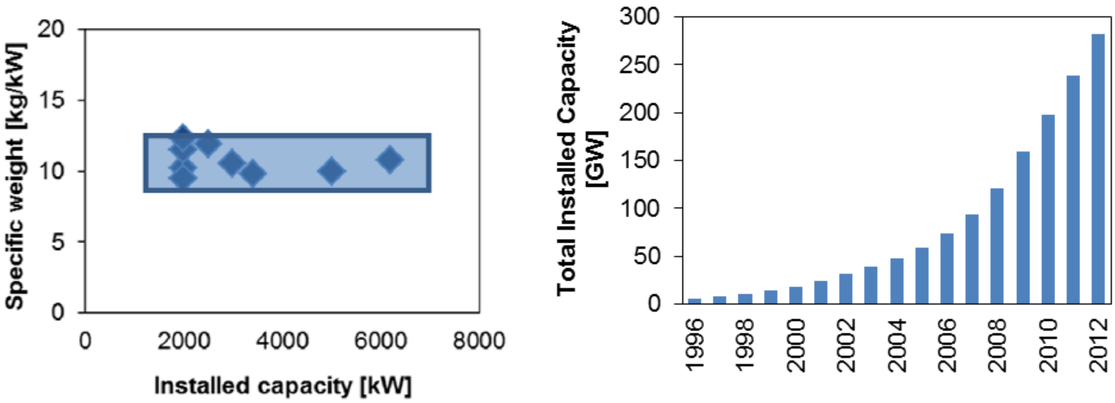

Figure 1: Specific GFRP weight per installed capacity (left) (Pico et al., 2012) and worldwide installed capacity of wind energy 1996 – 2012 (right). (Sawyer and Reve, 2013)

Even if the utilization of FRP shows unquestionable environmental advantages there is still great potential of improvements after their working life. Because of more sever legislations in the EU, landfilling has to be replaced by incineration and recycling. Referring to these motivations an economically, ecologically and rightfully feasible solution is highly requested.

1.3 Incineration

The most obvious solution for proper waste management of FRP materials is incineration. Commonly composites contain about 30 % to 40 % plastic whose caloric value is about 30 GJ/t (Pickering, 2006). During the incineration process a certain amount of the energy is reclaimable in electricity and heat.
According to the European Directive 2000/76/EC a minimum temperature of 850 °C for at least 2 s is required for waste incineration.
Incineration of glass fibre composites shows two main disadvantages. First, during the incineration the glass fibres are completely destroyed and, therefore, any reuse of them is impossible. It is evident that the incineration of plastic from GFRP is a solution for disposal. On the other hand, glass fibres inevitably melt during incineration. The formation of low melting slags can cause severe damages for fluidized bed reactors. This problem is less pronounced for stoker-fire and rotary kiln furnaces but the slag can stick to the chamber walls of the incinerator raising the maintenance costs. Japan's Recycling and Treatment Council for example stated that the costs for the clean-up of the furnace must be repaid from the automotive industries in case car components consist of glass fibre reinforced plastics (Pico, 2009). Conversely, carbon fibres are not melting and can be incinerated. The incineration of CFRP wouldn't be a technical issue. However, it is evident that a complete combustion of valuable carbon fibre will recover a very small amount of energy (32.8 GJ/t) compared to the energy required to produce them.
It is, thus, clear that a more practicable solution for the disposal of FRP is highly recommended.

1.4 Thermal treatments and fibre recovery

The recycling process depends on the type of matrix used for the FRP. Thermoplastics can easily be removed by heat without the necessity to break their structure. Thermosets are stable at high temperature, resistant to a great variety of solvents and the only way to separate them from the reinforcement is by breaking the bond that links one polymer chain to another. A general solution for the great variety of materials technically used still remains an issue. It seems, thus, quite useful to focus on the most critical matrix that is actually used for GFRP and CFRP, the epoxy resins thermosets.

Epoxy resin is made of cross-linked polymer chains. This structure provides high temperature stability and excellent chemical resistance and it allows a wide range of applications. The same properties that are valuable during the product life make the recycling process quite complicated.
Technically viable technologies are based on thermal processes like pyrolysis (Pickering et al., 2000) and chemical processes like solvolysis.
Pyrolysis is a thermochemical decomposition of organic materials in the absence of oxygen. Pyrolisis can be run also with epoxy resins at temperatures between 200 °C and 550 °C (Cunliffe et al., 2003). The output of pyrolysis is composed by a wide range of hydrocarbons that can be used for further processing. The most evaluable products are oil and gas. The oil can be used as a liquid fuel or returned to the refinery for processing. Gas can be used directly as energy vector for the pyrolysis process itself.
The presence of char and solid residues on the contrary is affecting the recycling process of fibrous reinforcement.
Solvolysis is an alternative process to pyrolysis. It has been investigated on in the last years especially for CFRP recycling. Essentially, by using reactive solvents and catalysts it is possible to break down the chemical bonds of thermosets. Solvolysis is currently considered one of the best favourable recycling techniques. Different solution systems have already been successfully tested. Subcritical/supercritical fluids (Piñero-Hernanz, et al., 2008), hydrogen solvents (Yang et al.,2012). The most promising solvolysis process is based on poly(ethylene glycol)/NaOH system at 150 °C under atmospheric pressure (Yang et al., 2012). Even if many solvolysis processes have been successfully tested by now no proper industrial process based on solvolysis has been used on composite waste.
In comparison to the combustion process pyrolysis and solvolysis permit the preservation of the fibre materials and enable the subsequent reuse of both components. After the separation from the fibres, the processed plastic matrix can either be combusted for energy recovery or used as hydrocarbons feedstock. According to EU directives these methods will not account for disposal but for recovery or even recycling. Concerning the energy consumption required for fiber production, which ranges between 30 and 50 GJ/t for glass fiber (Pickering, 2006) and about 373 GJ/t for carbon fibre (Suzuki, 2005), a recycling process is also ecologically feasible.

2. Experimental Details

In this study the fibre/matrix separation has been realized by pyrolysis. This process is well-known and it has been commonly used for waste during the last decades.
The pyrolysis process has been investigated in order to determine the better process conditions that allow a complete reaction of the matrix and the recovery of a valuable fibrous material.

2.1 Analysis of the Matrix Decomposition (TGA)

First experiments have been conducted by using a TGA with the purpose of determine the lower temperature that would be necessary to complete the decomposition of the matrix.
The samples of GFRP from wind blades have been initially analyzed by TGA in N2 atmosphere. The temperature profile was defined by a first temperature ramp of 10 °C/minute then a hold time of one hour at the setting temperature and a final ramp up to 800 °C. Four setting temperatures have been tested (400 °C, 450 °C, 500 °C and 600 °C) as shown in Figure 2.
The TGA samples defined the temperature parameter that can be used during the pyrolysis. Independently from the setting temperature, the matrix was fully decomposed during the hold phase.

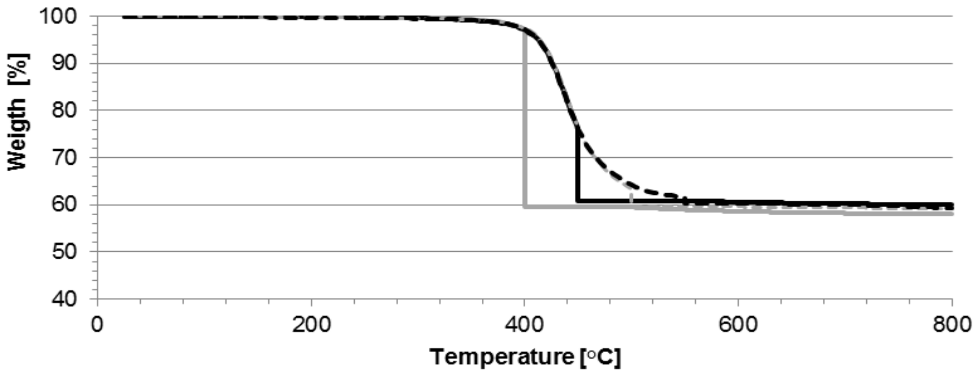

Figure 2: TGA results and GFRP behavior under thermal decomposition

After determining by thermogravimetry the temperature parameters required by the decomposition process of the matrix, parts of the wind blades have been used to analyze the process in a bigger scale.

2.2 Thermal Treatment Matrix Decomposition

The experiments in this study have been performed in a pyrolysis oven, wherein the temperature range in it was between 350 °C and 500 °C. In order to complete the decomposition of the last residues of coke, at the end of the pyrolysis the glass fibres have been exposed to oxidation.

In figure 3 are shown the surfaces of three different samples after 90 min of pyrolysis and 30 min of oxidation. The fibres that have been processed at a temperature of over 350 °C showed an entirely clean surface. On the contrary, the surface of the sample after pyrolysis at 350 °C was not completely cleaned.

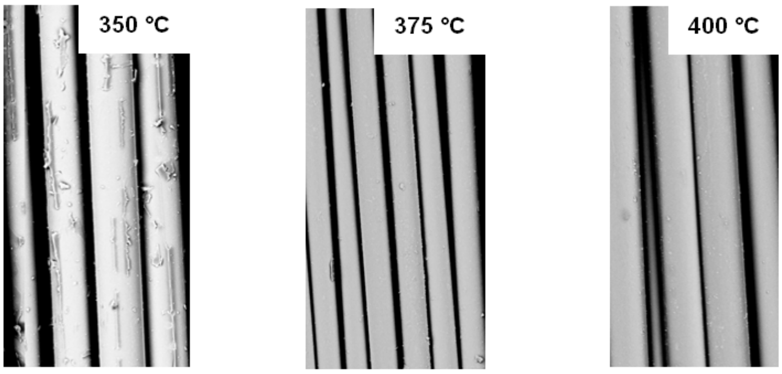

Figure 3: SEM Pictures of glass fibers after 90 min of pyrolysis process and 30 minutes of oxidation at 350 °C (left), 375 °C (middle), 400 °C (right)

On one hand temperature and time mainly influenced the pyrolysis process. On the other hand, morphological characteristics of the waste in the feed strongly varied the kinetics of the reactions. In order to reduce the costs, a process has to be feasible without any mechanical pre-process (shredding) before the thermal process. Therefore large portions of GFRP have been directly tested. No mechanical pre-treatment implied a reduced surface of reaction.

Aim of the experiments was also to determine if a low specific surface of the samples can influence the pyrolysis of the wind blades. A shredding process would increase the specific surface. GFRP have been reduced to cuboids (an example is shown in figure 4) were 40 mm high (Z axis), 72 mm long (X axis), along the reinforcement's orientation) and 72 mm wide (Y axis, transverse to the reinforcement's orientation).

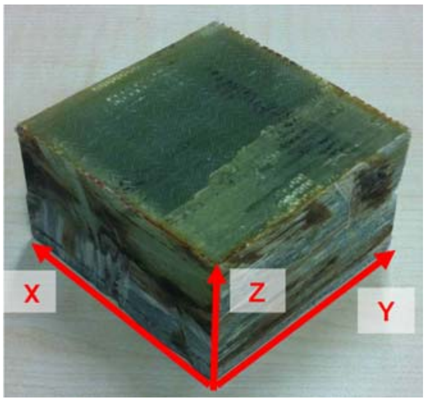

Figure 4: Sample of GFRP from wind blade used for the experiments

The fibres have been pyrolized at 375 °C, the lowest temperature that reached a complete decomposition of the matrix.

Each sample showed an internal core that was not completely clean.

The complete sample has been analysed in order to quantify the residual matrix and its distribution in the GFRP bulk.

In Figure 5 the layers of a cuboid processed at 375 °C for 60 min and without an oxidation phase are shown. The residual matrix was under 1.6 % (originally 40 %) and homogeneously distributed. A core was present in the lower part but the percentage of matrix was reduced to less than 1.6 %. No particular effect on the fiber orientation was observed.

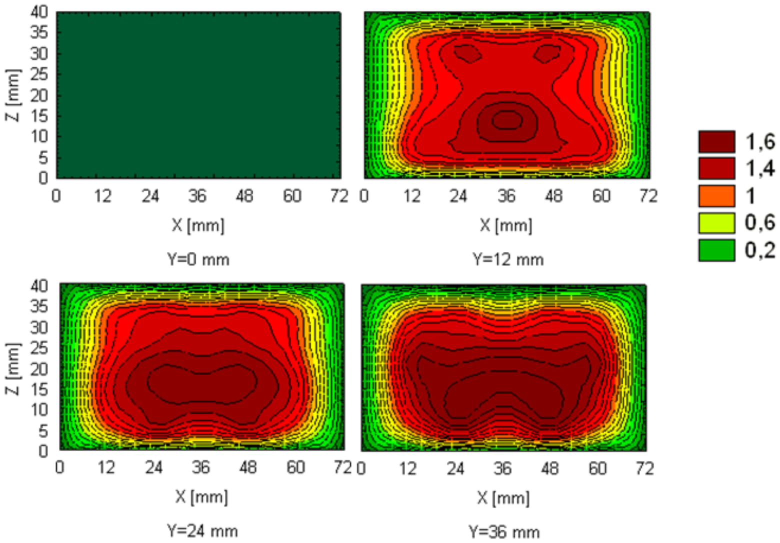

Figure 5: Percentage of the organic residuals on different layers of sample after pyrolysis at 375 °C for 60 min (Y layers)

On one hand the recovered fibres are almost completely free from organic residue. The small amount of unreacted matrix still allows a post processing of the fibrous reinforcement. The recovered fibres can be separed and the application of a new coupling agent requires a new sizing in order to be processed in new products like nonwoven, textile or reinforcement.
On the other hand, the plastic matrix has been transformed in different organic fractions that can be used as energetic vector as well as plastic feedstock (Figure 6).

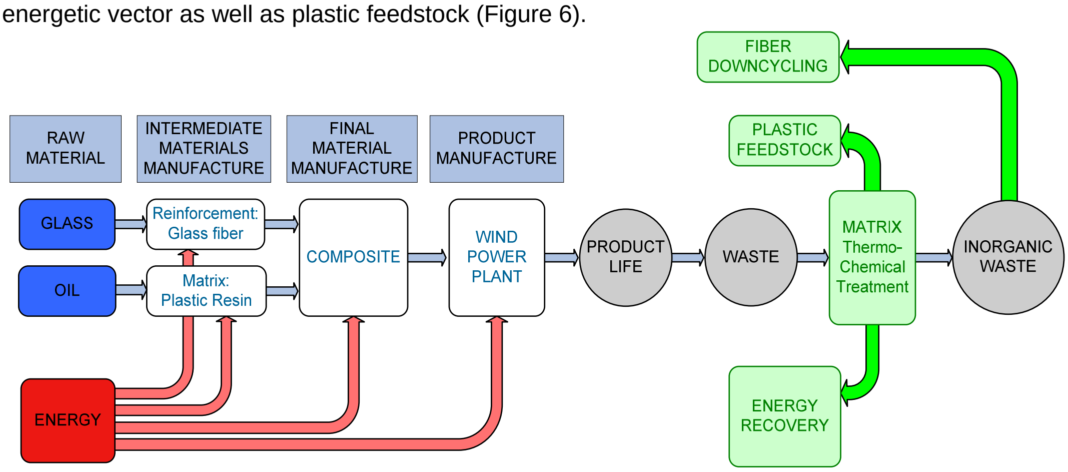

Figure 6: Wind energy plant from cradle to grave – future scenario for waste management

3. Conclusions

Glass and carbon fibre reinforced plastics are innovative materials that offer several advantages. Their waste on the contrary is still an unsolved issue. In the last years several solutions have been presented in order to separate the matrix from the reinforcement. State of the art is nowadays that pyrolisis and solvolysis could offer a complete recycling of the reinforcement combined with the recovery of organic compounds. Wind energy is the most promising sector to implement the composite materials in an integrated waste management. The wind blades scraps can be fruitfully processed by integration of the

thermochemical process into a refinery plant allowing the direct recovery of the matrix as feedstock combined with the energy recovery.
The implementation of this process to the refinery plant is environmentally sound and it is justified by the fast growth of wind energy installed capacity.

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