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Manufacturing, Testing and Recycling of a small recyclable wind turbine blade

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Manufacturing, Testing and Recycling of a small recyclable wind turbine blade

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Abstract: Thermoplastic resins are likely to replace thermoset resins in wind blade manufacturing, as their similar structural properties together with their recyclability would enable the reuse of the raw materials in other composites at the end of life. This paper presents the manufacturing, testing and recycling process of a 1 m thermoplastic composite wind turbine blade compared to a similar thermoset blade. The results showed that the static and centrifugal performance of the two blades were similar, but the thermoplastic composite blade had a lower deflection compared to the epoxy blade. The different components of the thermoplastic blade were recovered by immersion in a suitable solvent for their possible reuse in the manufacture of a new wind turbine blade. Thus, this study provides an example of the use of circular economy principles in a strategic renewable sector, wind energy, validating the use of a new thermoplastic resin in the design and recycling of wind turbine blades, without changing their current manufacturing process.

Keywords: Recyclable wind turbine blade, Thermoplastic composite, Thermoset composite

1. Introduction

Composites are widely used in diverse sectors, from aerospace to automotive to wind energy (a market of approximately 74 billion dollars in 2020). Thus, composite waste represents a major loss of resources and energy, all the more so as the limited amount that is currently recycled down cycles the fibres and completely wastes the polymer matrix.

Nowadays, wind energy presents two challenges: [1] the supply of large and sustainable wind turbine blades that can be fully recycled and [2] recycling solutions for all the blades that are about to be decommissioned. Our aim with this study is focused in the first challenge by providing a solution at its roots, by developing sustainable wind blades with materials that can be recycled and reused for manufacture new wind blades, using a new liquid thermoplastic resin.

A similar study has been carried out using a liquid thermoplastic resin, called Elium and developed by Arkema, in wind blades. This is a thermoplastic liquid (100–500 mPas) that can be processed with the same processes as epoxy resins, e.g. vacuum infusion, resin transfer moulding (RTM), and wet compression moulding. This resin has recently been validated with the manufacture of a 25-m wind turbine blade in the framework of the project "EFFIWIND" [3]. The results showed that the new blade had similar structural static performance and fatigue performance to conventional epoxy blades, but the thermoplastic composite blade had increased damping, which may result in reduced operational loads [4]. Additionally, recycling analysis showed that 90% of the resin and 50% of the glass fibre could be recovered by dissolution in a solvent [5].

The main objective is to develop a 100% circular small wind turbine blade by using a thermoplastic resin, called Akelite [6], developed and patented by ICTP-CSIC. Thus, the aim is to recover both main components, fibres and thermoplastic resin, in optimal conditions for their reuse in the fabrication of new composites. The specific objectives to fulfil the main objective consider material characterization, manufacturing, testing and recycling of the blade. Another objective of this work is to compare the structural performance of thermoplastic composite blade to an identical epoxy composite blade. Two small recyclable wind turbine blades of 1 m length were manufactured using this new thermoplastic resin Akelite. One of them was recycled recovering in optimal conditions fibres and thermoplastic resin, to obtain a revalorization in the fabrication of new composites.

2. Experimental

2.1. Materials

Two resins have been used to manufacture the wind turbine blades, a thermoplastic resin, Akelite, patented by the CSIC, and a commercial epoxy resin, SR1280 from Sicomin [7]. Akelite is a reactive acrylic resin that polymerizes by adding benzoyl peroxide as an initiator at 60 ºC for 2 h. Epoxy resin is a two-component system based in an epoxy SR1280 and a fast hardener, SD4772 at a specified ratio of 100:27 in parts by weight. It is a very low viscosity system, especially suited for infusion processes. According to the supplier's specifications, the epoxy resin is cured at room temperature for 24 horas, and at 60 °C for 16 hours.

As fibres, two carbon fibres have been used, one unidirectional fibre 12 K and an areal weight of 322 g/m^2 and a biaxial -/+ 45º carbon fiber fabric 50 K and 305 g/m^2 of areal weight, supplied by Mel Composites, and an unidirectional glass fibre with an areal weight of 625 g/m^2 supplied by Gavazzi Tessuti Tecnici.

2.2. Manufacturing of laminates at coupon level

Coupon-scale laminates prepared using a vacuum-assisted resin infusion were initially done to compare the mechanical properties of Akelite with the commercial epoxy resin. Four ply laminates were prepared using the following configuration 45C/0G/0C/0G (i.e. 45° Carbon fiber, 0° Glass fiber, 0° Carbon fiber and 0° Glass fiber). The fiber content in the laminate is about of 70 wt.%.

2.3. Manufacturing of small recyclable wind turbine blade

Five small wind turbine blades, two with Akelite and three with Sicomin (Figure 1), were manufactured by vacuum infusion process (Figures 2-4) and using the following configuration: 45C/0G/0C/0G (i.e. 45° Carbon fiber, 0° Glass fiber, 0° Carbon fiber and 0° Glass fiber). Once the vacuum infusion process of two blade halves was over, they were filled with low density epoxy foam Sicomin PB170+DM03, and glued together with a two-component epoxy adhesive Sicomin Isobond 735 (Figure 5). The length of the small wind turbine blade was 1212 mm (Figure 6).

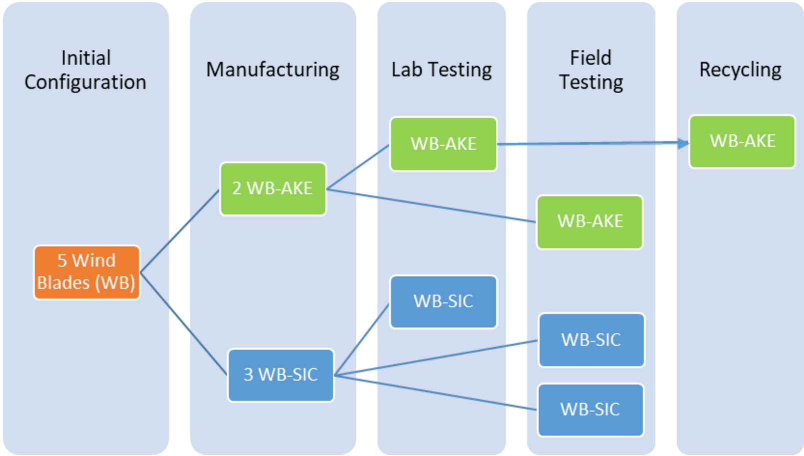

Figure 1. Work scheme

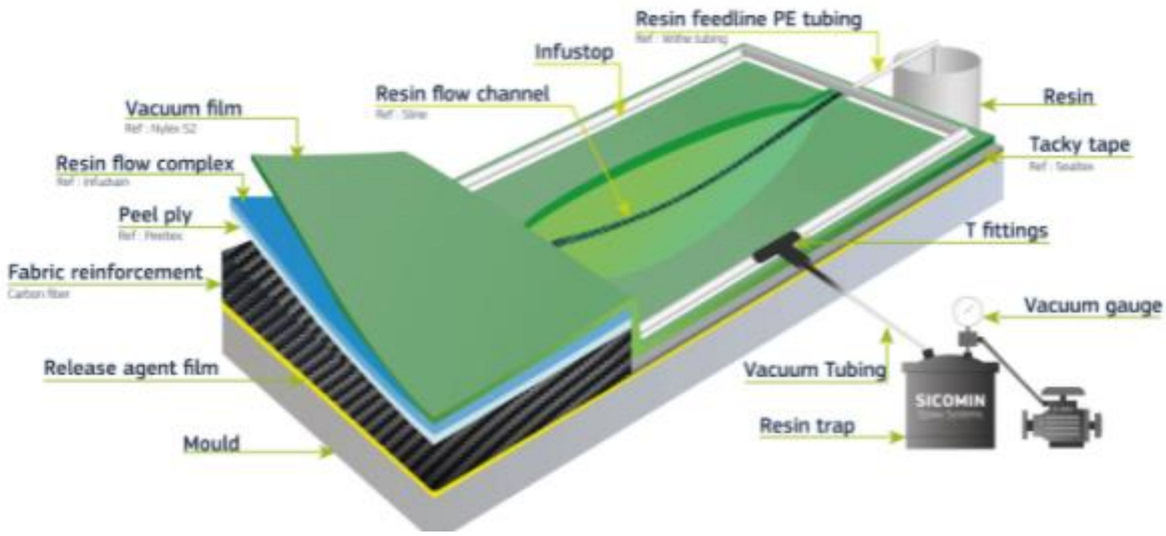

Figure 2. Vacuum Infusion Process – Scheme (Source: SICOMIN [7])

Figure 3. Lay-up fibres in the molds

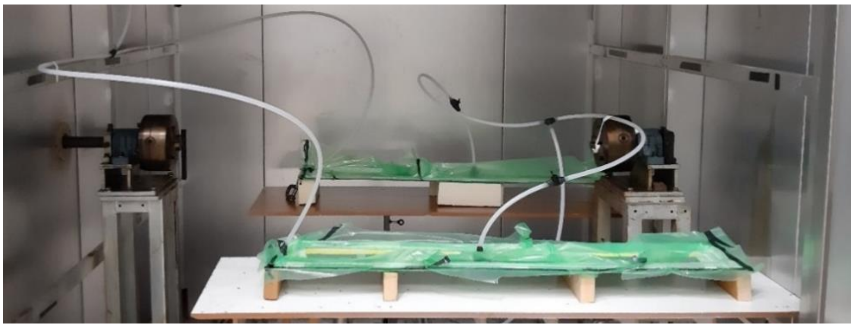

Figure 4. Vacuum Infusion Process

Figure 5. Fill and glue two blade halves

Figure 6. Small recyclable wind blade WB-AKE-1

2.4. Testing of the materials

The flexural properties and the interlaminar shear strength (ILSS) by short beam 3-point bending of the coupon-scale laminates were evaluated according to ASTM D-790 and ASTM D-2344 standard, respectively. These tests were performed on an Instron model 2204 universal testing machine.

The structural characterization of the wind turbine blades was evaluated through property, flap direction static (Figure 7) and centrifugal testing (Figure 8). Static loads and centrifugal force were estimated according to the simplified load model of IEC 61400-2 Standard [8-9]. Table 1 provides uncertainty for the test measurements with a 95% level of confidence (k=2).

In addition, the performance testing of two Sicomin wind turbine blades (WB-SIC-1 and WB-SIC-2), together with one Akelite wind turbine blade (WB-AKE-1) were evaluated on a 1 kW small wind turbine for 4 months.

Table 1. Uncertainty of test measurements

Instrument	Manufacturer	Model	Serial number	Uncertainty	Unit
Weighing hook	Kern	FCB 24K2	WD080033792	2.00	gr
Tape measure	Medid	Elephant 2640	F1019FZP	1.50	mm
Acelerometer	PCB	352C33	45095	0.03	Hz
Load Cell	Bongshin	DBBP-3t	K24449	36.87	N
Load Cell	Bongshin	DBBP-0.5t	10217	3.43	N
String Pot	ASM	WS17KT-1500	200846256145	1.56	mm
Strain Gage	HBM	6/350	K-LY41-350	7.50	me
Temeperature	Comet	T0210	8962656	1.20	%
Humidity	Comet	T0210	8962656	0.25	ºC

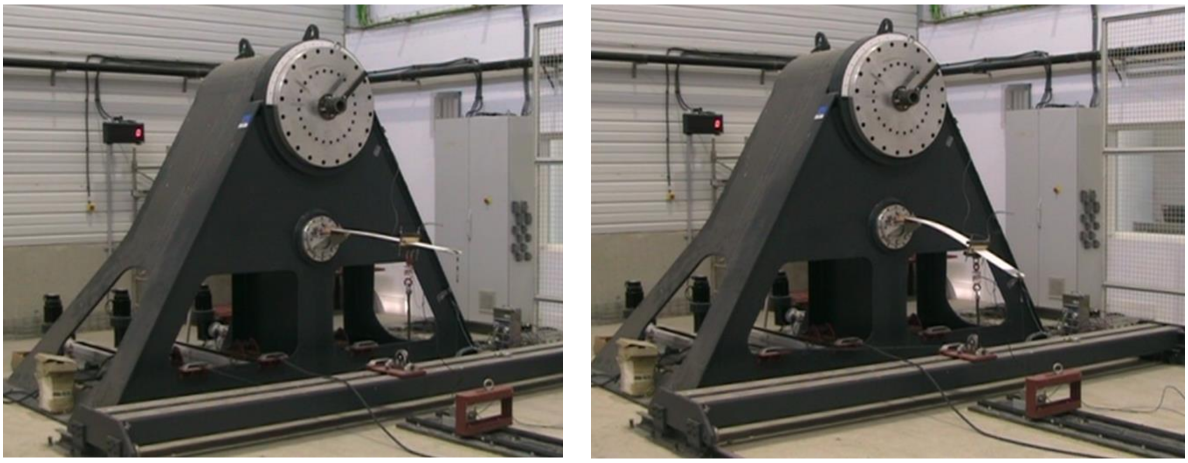

Figure 7. Static test (initial and final steps) of small wind turbine blade WB-SIC-3

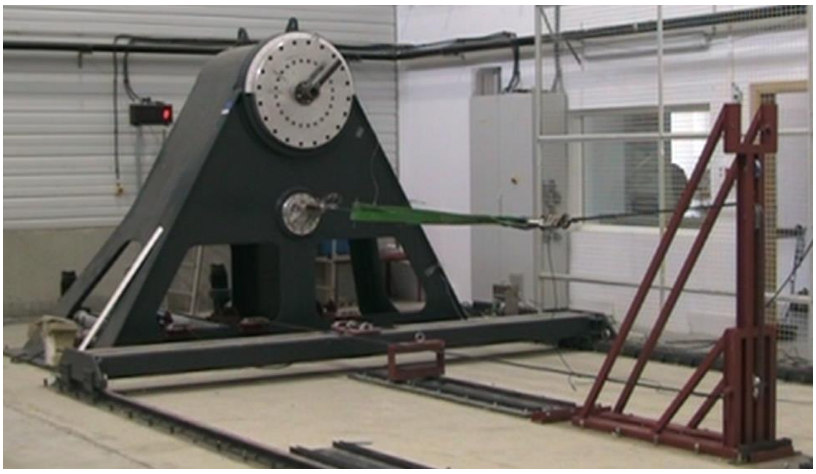

Figure 8. Centrifugal test of small wind turbine blade WB-AKE-2

3. Results and discussion

The certification of new materials, as thermoplastic resin, for wind turbine blades requires its validation on different scales. Table 2 presents the mechanical properties, tensile, bending, and interlaminar strength to the coupon-scale laminates. No significant differences are found between both composites, indicating that the thermoplastic resin can be used as polymeric matrix for the manufacturing of fibre reinforced polymer composites. Importantly, this is achieved by using commercial fibres without any specific treatment for thermoplastic resins, and using the same conventional processing techniques for the production of FRP with epoxy resins.

Table 2. Mechanical properties of laminates with thermoplastic and epoxy resin

	Akelite	**Sicomin**	**Standard**
Flexural strength (MPa)	713.4±11.4	724.0±7.4	ASTM D-790
Flexural modulus (GPa)	20.6±1.5	19.9±0.8	ASTM D-790
ILSS (MPa)	41.8±1.7	40.1±2.2	ASTM D-2344

3.1. Property test

The temporal response for Akelite wind turbine blade (WB-AKE-2) during property test is shown in Figure 9.

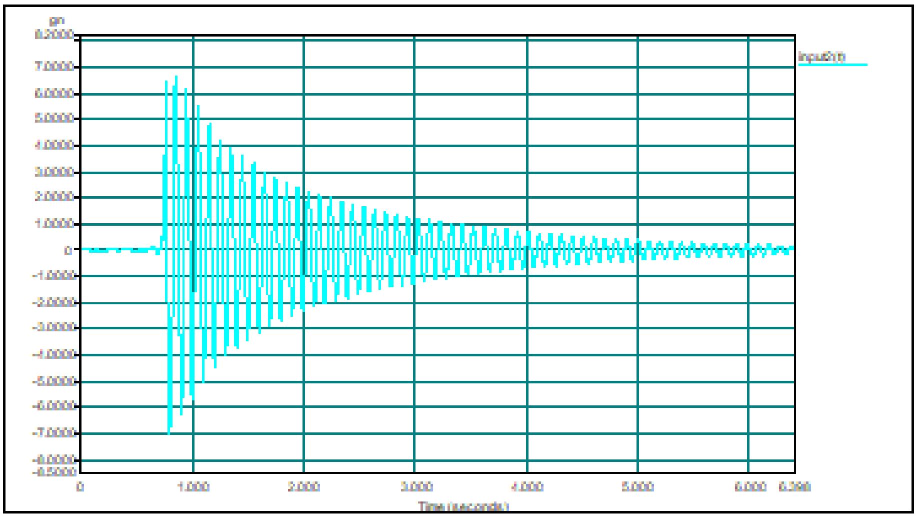

Figure 9. Temporal response of WB-AKE-2 during property test

Table 3 shows the characteristics such as length, mass, centre of gravity and natural frequencies of the blades. Thermoplastic blade weighed slightly less than the epoxy blade, with the centre of gravity being further toward the blade root for the thermoplastic blade. It was due to epoxy blades were painted with a white gelcoat to discern blades. An approximately 5% difference in weight and stiffness is acceptable. Interestingly, the natural frequency in both the at flap and lead-lag directions were higher than 5% for two blades. As lay-up of both blades was the same, it suggests that the difference of these parameters was due to the foam epoxy (Sicomin PB170+DM03) used to fill two halves blade. A small difference of quantity (expansion 1:6) could produce a big change in weight and stiffness on the blade.

Table 3. Results of the property tests

Wind turbine blade	Length, mm	Mass, gr	Centre of gravity, mm	1ª Flap Frequency, Hz	1ª Lead-lag Frequency, Hz
WB-SIC-1	1212	1032	613	7.81	41.00
WB-SIC-2	1212	1092	607	5.94	40.62
WB-SIC-3	1212	1052	615	7.76	41.17
WB-AKE-1	1212	946	617	10.15	48.45
WB-AKE-2	1212	958	601	11.09	47.93

3.2. Static test

An estimation of the static load was done according IEC 61400-2 Standard. Table 4 shows the results of the static test at different loads (Figure 7). The maximum tip deflection, measured with a string potentiometer situated at blade tip, was 192 mm and 312 mm for WB-AKE-2 and WB-SIC-3, respectively. Thus, the displacement of the thermoplastic blade was 38% lower than the epoxy blade at the tip blade station. This difference at the tip deflection suggests that the overall stiffness between the epoxy and thermoplastic blade were not similar. This increase in the displacement of the epoxy blade is attributed to the differences in the resins, but mainly the foam epoxy, as was mentioned before.

Table 4. Static test of the small wind turbine blade

WB-AKE-2			**WB-SIC-3**		
Winch, N	Root moment, Nm	Tip deflection, mm	Winch, N	Root moment, Nm	Tip deflection, mm
8	14	0	8	14	0
53	51	-23	17	22	-24
103	90	-55	115	100	-167
177	150	-114	171	145	-240
248	206	-192	242	202	-312

3.3. Centrifugal test

A centrifugal test was developed applying a load of, approximately, 3500 N, and measured with a load cell from a saddle situated at 800 mm from the blade root. The applied load was 3900 N and 3200 N for WB-SIC-3 and WB-AKE-2, respectively. Both wind turbine blades passed the test correctly, overcoming the initial target of 3000N, without any breakage (Figure 8).

3.4. Performance test of wind turbine

Two Sicomin wind turbine blades (WB-SIC-1 and WB-SIC-2), together with one Akelite wind turbine blade (WB-AKE-1) were installed on a 1 kW small wind turbine at lab roof to check different parameters included in IEC 61400-2 Standard, such as power curve, functionality and security (Figure 10).

Figure 10. Small wind turbine installation at roof lab and measuring board

Wind speed was measured with a cup anemometer 4 meters from the top of the building and electrical parameters were measured with a DC voltage sensor and a current shunt. The small wind turbine was in operation from August to December 2021, showing normal behavior without any functionality or safety issues. The performance test showed the normal behavior of these installations and presented two electrical curves depending on the battery charge level (Figure 11).

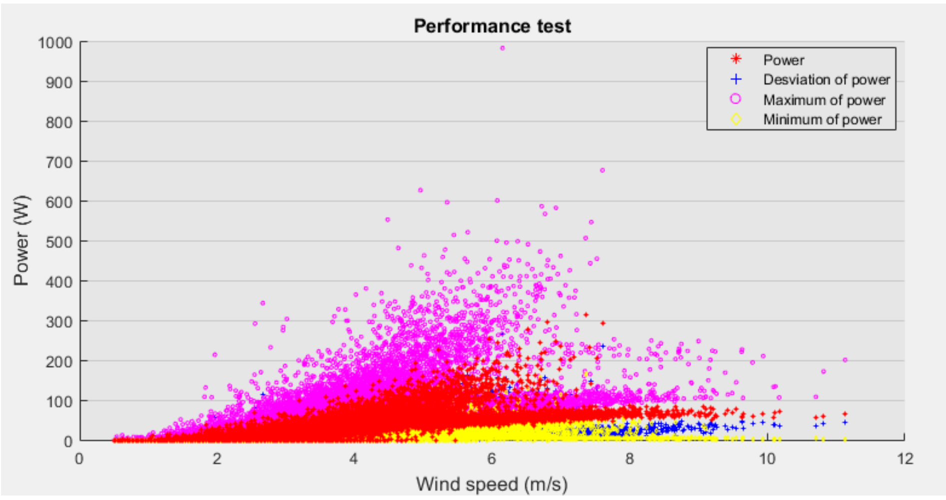

Figure 11. Performance curve of the small wind turbine

3.5. Recycling of small recyclable wind blade

At the end of the lab tests, Akelite wind turbine blade (WB-AKE-2) was recycled by immersion in acetone at room temperature for 24 h. The recycling process was done in order to recover the main raw materials (fibres and thermoplastic resin) (Figure 12). All plies were separated by gently pulling by hand and left at room temperature to dry. The recovered solvent was introduced in a rotavapor equipment at 50 °C to separate the dissolved polymer and solvent for their reuse.

Coupon level recycling experiments showed more than 95% of recycled thermoplastic resin was recovered measured by weight differences. Recovered fibres of small wind blade can be reused in other new composites.

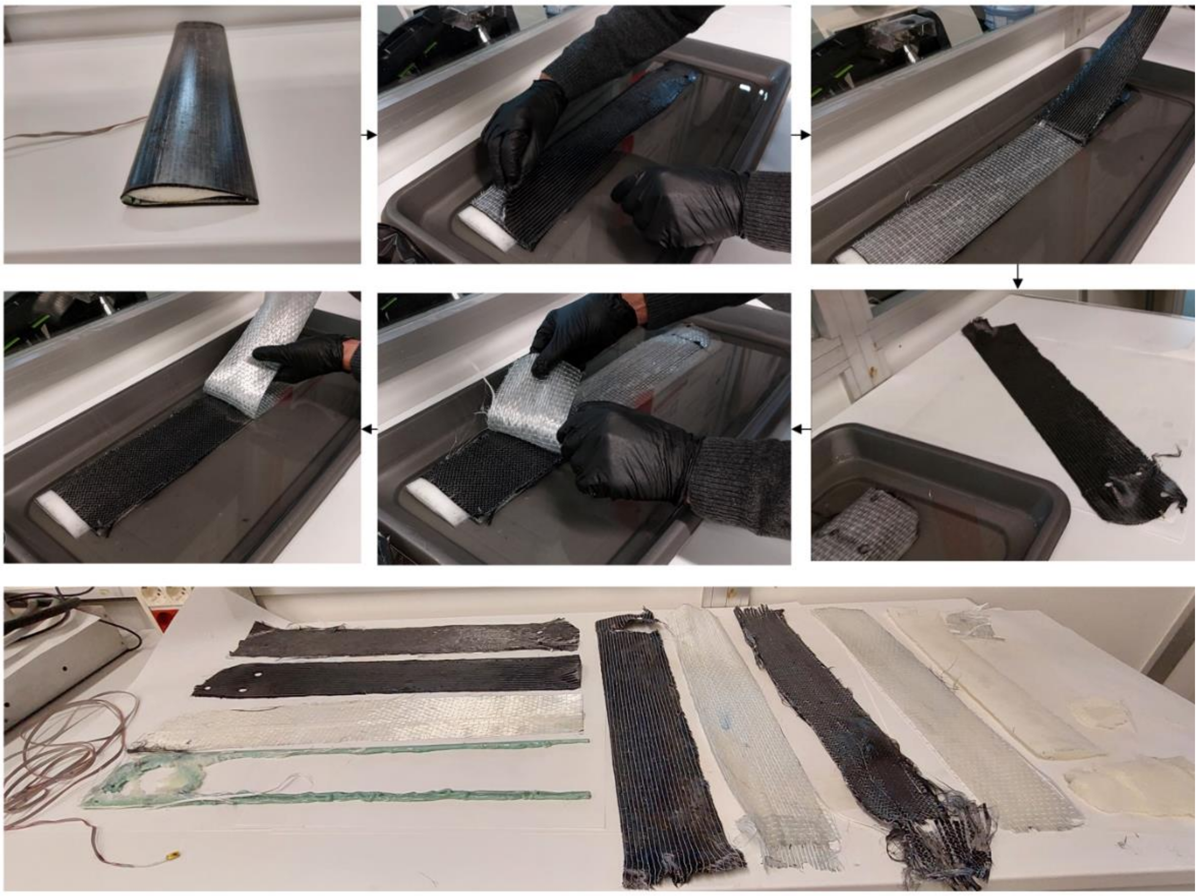

Figure 12. Recycling process of Akelite wind blade WB-AKE-2

4. Conclusions

A thermoplastic composite blade was compared to an equivalent thermoset blade, both manufactured by CIEMAT. The thermoplastic blade polymerized at 60 ºC for 2 hours and did not require any postcure treatment, hence requiring less energy during its manufacturing. Additionally, Akelite wind blade passed both the centrifugal and performance tests showing similar results to conventional thermoset wind turbine blades. However, the static test showed differences in the maximum tip deflection probably related to the epoxy foam used to fill the two halves blade. More tests must be done in order to optimize the blade configuration, for example by using different quantities of foam epoxy to fill the two blade halves. The recyclability of the wind turbine blades was proven through an easily scalable and energy efficient process.

The use of this thermoplastic resin might demonstrate that new cost-efficient, environmentally-friendly materials and manufacturing technologies can be used in the industry in general. Moreover, it will bring clear benefits in terms of reducing raw materials consumption and waste management.

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QR-Code with a short video about the summary of the paper "Manufacturing, Testing and Recycling of a small recyclable wind turbine blade":