Application of high voltage fragmentation to treat end-of-life wind blades

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Abstract. The use of composites is constantly increasing in several sectors, from wind energy to automotive, thanks to their mechanical properties, lightweight, and resistance to corrosion. Despite this, the recycling and reuse of these materials in high-added value applications is not yet performed at the industrial level. In particular, End-of-Life (EoL) products are sent to landfills (if possible), incinerated, or inserted in co-processing in cement plants. This work presents an experimental approach to treat End-of-Life wind blades based on High Voltage Fragmentation (HVF). This technology, based on the creation of electric spark channels, is able to generate localized shock waves at the interface between two different materials. The potential of its application has been shown in the literature, but an experimental campaign is needed to find the optimal parameters to obtain an output material with proper characteristics to feed specific output products, following a demand-driven approach.

Introduction

In the last years, the necessity to reduce carbon emissions and to become less dependent on fossil fuels has led to the wide exploitation of renewable energy, reaching a share of 22% of the European energy mix in 2021 [1]. Among them, wind energy is one of the most used. As an example, in the last decade wind power installations doubled in Europe with 236 GW of wind turbines (considering both onshore and offshore) [2]. To achieve the goal, defined in the European Green Deal, to become a climate-neutral continent by 2050, the EU has set a target of 32% of renewable energy by 2030 [3]. Wind Europe, the European Wind Energy Association, estimated in a realistic scenario the installation of more than 23 GW/y in the next five years [2]. However, as the typical life of a wind turbine is of 20/25 years, the issue of End-of-Life treatment of their components, especially the blades, has become increasingly pressing to satisfy future growth plans.

Wind turbine blades are made from composite materials that are difficult to recycle, leading to concerns about the environmental impact of wind turbine decommissioning. According to the European Union, around 80,000 wind turbines will need to be decommissioned in the EU alone by 2030, creating a significant waste management challenge [4]. Currently, most of the EoL wind blades are landfilled. This results not only in a massive environmental impact but also in a relevant loss of economic opportunities, as these products have a considerable residual value.

Composite materials can be recycled through mechanical, thermal, or chemical recycling [5]. Mechanical recycling allows to obtain granules composed of both fibers and resin that can be reprocessed for the manufacturing of new products with lower mechanical properties. Even if these processes are competitive in terms of cost, the obtained material cannot be reused for the same application, leading to a downgrade [6]. Thermal treatments exploit the temperature to volatilize the polymeric part leading to clean fibers and, using innovative processes, also liquid resin. Also in this case, due to the depolimerazion temperature, the fibers degrade, leading to a downcycling of the material, together with the relatively high cost of the process (mainly dependent on its energy-consuming nature) [7]. Chemical processes such as solvolysis are able to clean fibers with relatively low degradation but the costs to obtain them are high, mainly due to the solvents [8]. Independently from the adopted solutions, two different concepts have to be considered to enable robust and reliable recycling processes [9]. The first one is the so-called cross-sectorial approach. Materials obtained through the recycling of products in a specific sector have to be reused in another sector which requires lower mechanical properties, but with high-added value. In this way, recycled particles from wind energy can be reused in sectors such as automotive, avoiding their use as fillers or in the co-processing of cement. This can be enhanced by considering a second concept: the demand-driven approach. Traditionally, an EoL product is recycled and, only after that, an application for the obtained material is found. This, even if allows to have rigid but fast traditional processes, leads to the loss of the greatest part of the residual value. The demand-driven approach reverses the traditional chain. First of all, a product embedding recycled material is designed. As a consequence, the characteristics of the recycled material that enable to obtain the desired mechanical, physical, and aesthetical properties of the product are derived. On the basis of them, the recycling process is optimized to maximize the quantity of target material, minimizing, at the same time, the costs to obtain it.

Innovative technologies are studied at the research level. Among them, High Voltage Fragmentation (HVF) is one of the most promising. Exploiting the difference in electric conductivity of different materials, it is able to create local shockwaves to detach them at their interface. Due to the nature of composites, the application of HVF to their recycling is interesting to obtain homogeneous and, in the future, pure fractions of material. This work presents an experimental approach to preliminary investigate the potentiality of the innovative technology of HVF in the recycling of EoL wind blades, fostering the adoption of the demand-driven approach, to enable reliable and robust circular economy solutions for this kind of product.

Literature review

High Voltage Fragmentation (or electrodynamic fragmentation) was initially designed during the 1960s [10] for mineral extraction from ore. Since the technology exploits different electrical permittivity of material to separate them at the phase boundaries, it was traditionally used for obtaining high-value minerals, like gold, from its ore mineral extractions. Considering the shown high efficiency in treating rocks and ores, together with the possibility to control a wide range of parameters, the potentiality to apply HVF for other applications like the treatment of Municipal Solid Waste (MSW) ashes has been investigated. Examples of using HVF technology for the recovery of metals and immobilization of heavy metals from ashes generated by the thermal treatment of MSWs can be seen in [10]. After treatment, the ashes have been used as an aggregate to produce reinforced concrete.

Considering the similarity of minerals with concrete, made up of an aggregate structure, HVF technology has been applied to the recycling of building materials, primarily concrete and fiber-reinforced concrete [10] [11]. The HVF technology has been seen to be both very effective and energy efficient [11] in breaking down and separating its various components. Tests carried out on Ultra-High-Performance Fiber Reinforced Concrete (UHPFRC) have shown the potential of this technology. The results can be seen in [12], where concrete with different compression strengths was tested with HVF and it was seen the process was not only viable but the change in compression strength had little to no effect on the liberation.

HVF technology has recently been tested for the recycling of Printed Circuit Boards (PCBs) and photovoltaic panels [13] as well. For PCBs, HVF technology produces, in comparison with size reduction processes, a better liberation of metal fractions, but it was found to be significantly more energy-consuming [14]. HVF has proven to be a viable option also for recycling and dismantling of photovoltaic panels. It is comparatively better than mechanical recycling since it is less energy-consuming [13] and it produces specific size fractions of the target metallic materials.

It also has benefits over chemical recycling methods since it reduces further contamination with chemicals and it is environmentally friendly due to the absence of solvents [15].

Considering fiber-reinforced plastics, it is possible to find some examples in the literature on the application of High Voltage Fragmentation to their recycling [16]. There have been researches conducted into the viability of the technology with thermoplastics with carbon fiber (CF) reinforcement [17]. Door hinges made from thermoplastics with CF reinforcement have been tested with HVF and the process was seen to be largely viable in terms of mechanical qualities of the recycled fibers. There was only a 17% reduction in the mechanical properties of the recycled fibers with respect to the virgin ones [17], and a new door hinge was manufactured with 100% recycled material with little to no post-treatment. Considering Glass Fiber Reinforced Plastics (GFRPs), the most present material in wind blades, some work can be found in the literature. High Voltage Fragmentation has been seen as a competitor of mechanical recycling [18] [19] of GFRP due to comparable comminution principles, but mechanical recycling by itself almost always results in short fibers with a lot of resin material, limiting the utilization of recycled particles as secondary raw materials in products. Also, the tensile strength and Young's Modulus of recycled particles obtained with HVF were slightly higher compared to mechanical recycling. It can also be seen that by increasing the number of pulses (discharges), the percentage of mixed particles (with fibers and resin still joined together) in the recycled material can be reduced [19]. However, the specific energy requirements for HVF recycling are considerably higher in comparison to mechanical recycling (at least 2,6 times higher) as seen in [19] [16].

Materials & methods

The experiments have been conducted using a High Voltage Fragmentation machine of SelFrag AG (laboratory-scale model) has been used. The machine works on the principle of the selective breakdown of material with the help of high-voltage electrical pulses. At the top of the working vessel, which contains the sample in a liquid (typically deionized water), there is an electrode, while at the bottom the counter-electrode is placed. The machine produces high-voltage electric discharges between the two electrodes in a nitrogen atmosphere. During the process, a plasma channel is created by an electrical discharge with high energy which leads to high temperatures, greater than 10^4 K, and high pressure, about 10^9-10^{10} Pa, which is able to pass through the sample to be treated, concentrating at the interface between two materials with two different electric permittivity. This generates stresses which usually exceed the strength of solid material. When the electrical pulse rises time goes down as low as 500 ns the ionization stops and the breakdown path in the plasma ends. All of these effects generate a localized shock wave, similar to that of a lightning strike, at the phase boundaries of the solid material leading to cracks. After multiple discharges, the cracks that have been created expand and reach the edges of the material that in the end causes fragmentation. Since the electrons are in the material boundaries, the fragmentation energy is situated along with the interface of the material [20]. This leads to high liberation and selective fragmentation of the product.

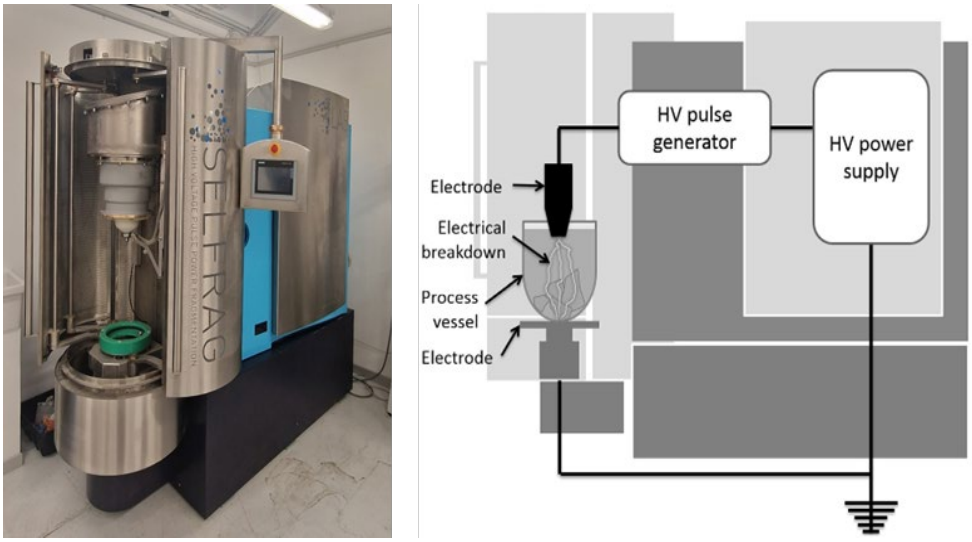

Fig. 1: High voltage fragmentation machine of SelFrag AG (functioning scheme on the right)

The process vessel in which the sample is processed can be of open or closed type. In the open type, a sieve inlay (grid) can be added to allow material that has reached the sieve size to fall into a rubber container. In the closed-type vessel, the material stays inside till the end of the process. The different controllable parameters of this process are the voltage, which ranges between 90-200 KV, the distance between the electrodes, which can be between 10-40 mm, the pulse repetition rate, which ranges between 1-5 Hz, and the number of electric pulses, and a peak power consumption of 6 kW.

To analyze the material obtained with this process, a particle analyzer has been used, in particular Camsizer P4 of Microtrac, which uses a dual-camera imaging system to capture real-time images of material. The results obtained give information on the dimensional characteristics like the length and width of the material, together with morphological details like sphericity and elongation, with a wide dynamic range that extends from 20 microns to 30 millimeters. The software is able to elaborate the images, providing several dimensional parameters, like Feret Diameter (useful to evaluate fibers), and morphological parameters, such as the aspect ratio. For the experiments, samples with dimensions of 50x50x15 mm with a weight of about 65 g obtained cutting an EoL wind blade have been used. They were composed of glass fibers in an epoxy resin with an intermediate layer made of polyurethane (PU) of about 10 mm.

Two different experimental campaigns have been conducted. The objective of the first one was to evaluate the potentiality of the HVF to liberate the PU. As a matter of fact, contamination of polyurethane can reduce the reuse possibilities of recycled material in high-added value products. In this case, the only parameter that has been changed is the number of discharges, with values of 50, 100, 250, 500, 1000, and 2000, while the voltage, the repetition rate, and the distance between the electrodes were fixed at, respectively, 200 kV, 5 Hz, and 20 mm. The second experimental campaign focused on the differences using a vessel with or without a grid. This is interesting not only in terms of final distribution but also to understand the potentiality of this technology to be used at an industrial scale. In this case, the considered factor was the presence of a 1 mm grid, while the voltage was of 200 kV, the repetition rate of 5 Hz, 1000 discharges, and the distance between the electrodes of 20 mm. Finally, the results obtained with the grid have been compared with historical data from a previous shredding campaign of the same material with a cutting mill of Retsch model SM300 with a 1 mm grate size.

Results and discussion

The obtained results will be presented and discussed in the following three subsections.

Separation of polyurethane.
For this first set of experiments, the results have been evaluated through visual analysis as the PU is easily recognizable from GRFP. The obtained results are shown in Fig. 2. From these pictures, it is possible to say that high voltage fragmentation is able to completely liberate the polyurethane insert from the fiber matrix of the wind blade also with very few pulses (even 50). This effect can be explained by considering the physics of HVF. Since the machine works on the principle of selective fragmentation, which exploits the different electric permittivity of a material, the PU insert is distinctively different from the fiber-matrix component of the composite. However, with an increasing number of pulses the size of the PU reduces (mainly due to shockwave side effect that propagates in the medium), increasing the energy consumption and making its separation more difficult, requiring more complex technology with respect to, as an example, traditional optic separation. The high voltage fragmentation technology can hence be used for preliminary coarse process to separate different components, the target of which can be further processed through the same technology or through more traditional ones (as size reduction).

Fig. 2: Material obtained with (from the left) 50 pulses, 250 pulses, 1000 pulses.

Influence of the grid.
An interesting result was observed when the sample was processed with and without a sieve inlay. The grid has a unique effect on the process since all of the material that passes through it below is no longer processed. The distribution of the recycled particles is narrower around 1mm and the dimensions of the particles were in general smaller than processing the same sample without a sieve (see Fig. 3). This behavior can be explained by considering that since the material passes through the grid, less material remains inside the process vessel. As a consequence, treating less material with the same quantity of energy make the process more efficient as we have more energy per volume unit. Without the grid, all of the material remains inside the vessel till the end of the process. This disperses the energy in a more diffused manner and the material retains larger dimensions. In addition, when a particle is fragmented during the process, an higher number of smaller particles is generated, resulting in less efficient process at the subsequent step.

This behavior is of particular interest considering the already introduced demand-driven approach. Using a grid it seems to be possible to obtain narrower distribution, resulting in a larger quantity of material respecting the target characteristics to be reused in high-added value products. Different experiments will be conducted in the next future to better understand the repeatability of these results and the effect of grids with different dimensions.

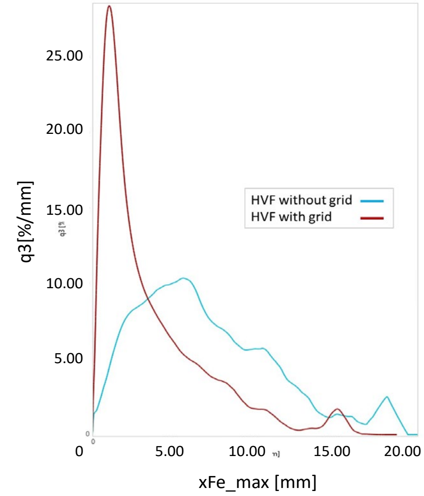

Fig. 3: Dimensional distributions obtained through HVF without (in blue) and with (in red) a 1 mm grid.

Comparison with a traditional mechanical process (shredding).

The material obtained with high voltage fragmentation with the sieve inlay (the most promising one) was also compared with the one obtained through a cutting mill in previous research, using also in this case a 1 mm grid. The results are reported in Fig. 4. The material processed with HVF is narrower around 1 mm, while the fibers mechanically recycled had a wider spread in terms of length, even if most of the particles are around 1 mm. In addition, considering the aspect ratio of the two samples, high voltage fragmentation seems to be able to obtain more elongated particles, while the ones obtained with shredding are more circular, suggesting an higher presence of powder. For sake of completeness, also at a visual inspection, the material obtained with shredding has a considerable quantity of powder material (even if cutting mill is one of the size reduction technologies that minimizes powder production), opposite with the one obtained with HVF, due to the physics behind the mechanical process, based both on impact and cutting. Also in this case, these results are not good or bad in an absolute way, as the shape of the material is also an important factor for the demand-driven recycling. The desired distribution depends on the reuse purposes (e.g. longer particles will have better mechanical properties while powder can substitute typical additives in composite formulation as calcium carbonate).

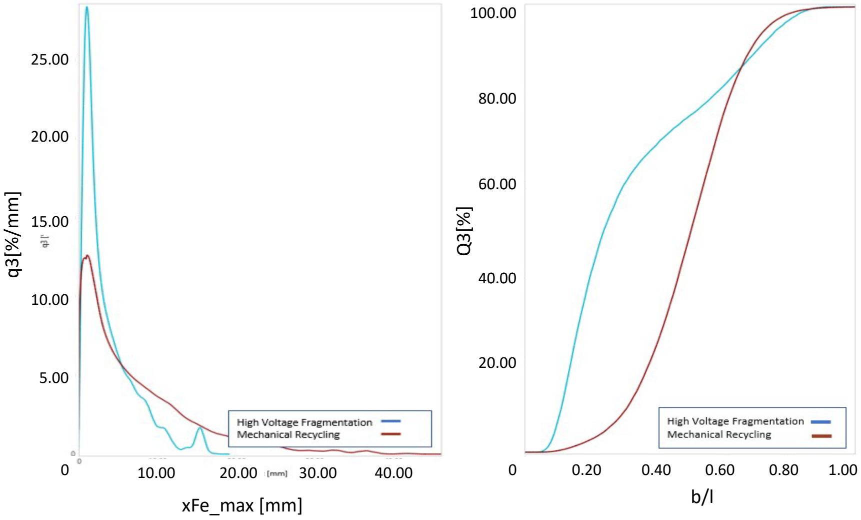

Fig. 4: Comparison of the results obtained with HVF (in blue) and with shredding (in red), both for dimensional distribution (on the left) and aspect ratio (on the right).

Conclusions

The recycling of End-of-Life wind blades is becoming urgent. The constant adoption of this technology to increase the share of green energy in the EU energy mix, together with their typical life of 20/25 years, is pushing the necessity to find reliable solutions to treat these products. Considering that most of the wind blades are made with glass fiber reinforced plastics, mechanical recycling is the current solution that allows obtaining a material competitive with virgin one. This can be reached only if both cross-sectorial and demand-driven approaches are applied. To enhance the beneficial effects of these approaches, innovative technologies can be exploited. Among them, one of the most promising is High Voltage Fragmentation. Using a fast-rising electric field with high voltage, it is able to act at the interface between two different materials, thanks to their difference in electric permittivity, liberating them. Composites, which have fibers in a resin matrix, seem to be the right candidate to be treated with this technology.

This work presented the results of two preliminary experimental campaigns to treat EoL wind blades. The first one was dedicated to the removal of undesired materials, while the objective of the second one was to investigate the potentiality of exploiting the presence of a grid to better select the target material. The results seem promising in both directions. The first experimental campaign showed that the polyurethane layer, which, if present in the recycled material, can reduce its reuse possibilities, can be completely liberated also after a few discharges, obtaining a purer material to be sent to subsequent processes. The second one suggested the improvement in obtaining material with specific target dimensions, in particular using a sieve inlay, with respect to shredding, fostering the demand-driven approach (increasing in addition possible options to treat the material).

Following the obtained results, future research will consider a full factorial design of experiments, including all the controllable parameters, with different levels. This will allow to better understand the effect of this technology on composite materials and to find the optimal parameters considering both the target characteristics of the material in output and the cost to obtain it. Also, in addition to the characterization of the material in terms of dimensions and morphology, the analysis with a Scanning Electron Microscope has to be done to see the cleanliness level of the fibers. Finally, the development and implementation of a model, physics or AI-based, of the machine can be interesting, in particular for possible future exploitation to optimize and control the process itself.

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