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Energy consumption assessment and modeling of a comminution process: The glass fibers reinforced composites case-study

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A R T I C L E I N F O

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A B S T R A C T

The implementation of circular economy concept is necessary to obtain sustainable processes. Meanwhile, End-of-Life composite products is one of the most rapidly increasing waste flow. Mechanical recycling, due to low cost and reduced environmental impact, is one of the most promising solutions for composite waste treatment, in which shredding plays a fundamental role. To compete with low cost of virgin fibers, an energy assessment and modeling of the process is mandatory. This work aims to evaluate the energy consumption of a shredding process of End-of-Life composite materials, aiming to its optimization, to enable a competitive and attractive value chain.

1. Introduction

The relevance of Circular Economy principles has been outlined in the last 50 years for the reduction of the environmental impact of industries and manufacturing (Stahel and Reday-Mulvey, 1981; Pearce and Turner, 1989). In the meanwhile, Ellen MacArthur Foundation underlines few years ago the economic opportunities of the implementation of this concept, summarizing and homogenizing all the different existing approaches (Ellen Mac Arthur Foundation 2017).

Among the different principles of Circular Economy, one of the most important is to increase the lifetime of products and materials, considering waste as raw materials. This could be achieved through several approaches as re-use, repair, remanufacturing and, finally, recycling.

Recycling processes could be grouped in mechanical, thermal and chemical processes (Oliveaux et al., 2015). Mechanical ones are able to obtain output materials with good quality and low energy consumption, environmental impact and less by-products. One of the most fundamental step in mechanical recycling is the size reduction of End-of-Life products to obtain high liberated particles (composed by a small number of materials (Colledani and Tolio, 2013)). The result is a homogeneous flow with a specific dimensional distribution.

Granulometry of the particles in output is strongly correlated to the liberation of target material and it determines also the possibility to directly re-use shredded particles in new products. On the other hand, the operational costs are key factors to obtain recycled materials with competitive price with respect to virgin ones.

In the meanwhile, End-of-Life composite products flow is one of the most rapidly increasing with a worldwide growth rate of 5% with 95% composed by glass fibers reinforced plastics (GFRP) with a total amount of about 2.8 million tons of GFRP (Witten et al., 2017). This results in relevant future waste flows with GFRP that are currently about 98% in weight of total recycled composite materials (Gutiérrez and Bono, 2013). As an example, the amount of End-of-Life GFRP wind turbine blades is expected to reach an amount of up to 30,000 tons per year between 2020 and 2030 (Faulstich et al., 2016).

As for other materials, also End-of-Life composites could be recycled through mechanical, thermal and chemical processes (Ribeiro et al., 2016). Due to the low costs of virgin glass fibers, mechanical recycling is the only economically feasible way (Cunliffe and Williams, 2003), in particular considering a cross-sectorial approach, in which shredded GFRP from sectors with higher requirements on mechanical properties could be re-used in new products with lower mechanical properties as shown in Fig. 1 (11).

To enable this approach, the minimization of process costs is fundamental. This work aims to present the energy assessment of a shredding process in composite sector, proposing a new model for energy costs prediction and optimization.

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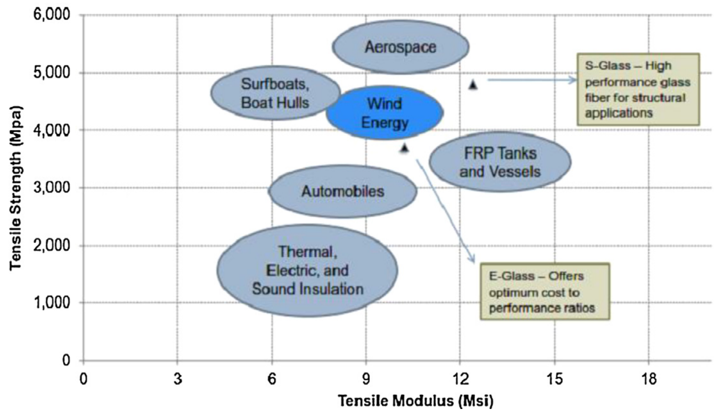

Fig. 1. Glass fibers composite materials application (11).

2. Literature review and scope of this work

Recycling processes of End-of-Life composite materials could be grouped in three main groups: thermal, chemical and mechanical (Oliveaux et al., 2015).

Most used thermal processes are pyrolysis (Cunliffe and Williams, 2003; Oliveira Nunes et al., 2014), fluidised-bed pyrolysis (Pickering et al., 2000) and microwave pyrolysis (Åkesson et al., 2012). These techniques are suitable for Carbon Fiber Reinforced Plastics (CFRP) due to the high value of virgin materials and low degradation of recycled fibers with optimized processes (Oliveaux et al., 2015). On the contrary, pyrolysis is not suitable for GFRP due to the degradation at high temperatures and relatively high costs (Cunliffe and Williams, 2003).

Chemical treatments are mainly performed through solvolysis. The objective is to degrade the resin matrix using different solvents (Yoon et al., 1997). Despite the widely use of solvolysis for CFRP, only one work is present in literature regarding chemical recycling of GFRP (Oliveux et al., 2012). This is due to the low resistance of GFRP to acidic and alkaline conditions and to the high costs of solvents with respect to the price of virgin fibers.

Mechanical recycling has been applied in particular on GFRP. This is due to the low cost of mechanical processes that results in recycled fibers with prices comparable to virgin ones. Exploiting the cross-sectorial concept shown in Section 1, mechanical recycled GFRP could be reinserted as reinforcement through different manufacturing processes as, in particular, Sheet Moulding Compound (SMC) and Bulk Moulding Compound (BMC) (Pickering, 2016), in new products. The possibility to have a real closed-loop recycling of thermoset composites with recycled GFRP as smart reinforcement in SMC and BMC has been demonstrated in automotive sector (Palmer et al., 2009).

Despite of the relevant results obtained in re-use of shredded particles in new composite products, only few works in literature deal with energy assessment of size reduction processes. Most of it have explored the relationship between energy consumption and target size reduction, not considering the operational parameters. This topic has been firstly investigated in 1957 (Charles, 1957), based on the empirical “third theory” comminution proposed in 1952 (Bond, 1952). This approach has been improved and applied to different comminution processes in the following years (Bond, 1960; Austin, 1973; Morrell, 2008). The pillar of this theory is that the higher is the difference between the dimensions of input and output particles, the higher is the energy consumption. On the other hand, a non-empirical relationship has been proposed in 1972 (Kapur, 1972) based on size-mass balance considerations and validated in 2013 (Gupta, 2013). All these models have been developed for shredding in mineral sector, considering only batch processes.

Recycling is a continuous process with variability in input materials, both in conditions and models. Only few works consider these aspects in energy assessment and modeling. Energy consumption of continuous processes depends not only on the difference between input and output dimensions of the particles, but on several factors. Adapting the assumption introduced by Gutowski in machining (Gutowski et al., 2006), the direct energy demand for comminution could be divided in two terms, one related to power at zero load and the other for the power absorbed by the shredding process (Shuaib and Mativenga, 2016).

The objective of this work is to present a complete energy assessment of a shredding process. The dependence on several factors will be shown, underling the impacts on the process. A model for energy consumption process will be presented and the preliminary validation will be shown.

3. Energy assessment

Energy consumption in a shredding process depends on several factors as following:

- *Cost of electric energy.* It is Country and Region dependent. It is also function of the availability of renewable energy and of the accessibility of supply.
- *Absorbed power.* It is technology and machine dependent.
- *Residence time.* The longer the particles remains in the chamber, the higher is the energy consumption to comminute them.
- *Rotational speed.* Higher rotational speeds typically means higher energy consumption but in a shorter time and vice versa.
- *Throughput.* It influences the particles residence time and, as a consequence, the energy consumption.
- *Material.* Harder materials requires higher power while softer materials have to be shredded for longer time.
- *Saturation of the chamber.* It influences the throughput.
- *Input/output dimension gap.* Higher differences in the dimensions between input and output particles result in higher energy consumption.

In the next sub-sections, the dependency of energy consumption on some of these factors is shown.

All the acquisitions have been done using plug-in energy sensors with a customized software to obtain real-time measurements. The shredded material comes from End-of-Life sanitary products composed by glass fibers in a polyester resin and End-of-Life wind blades made of glass fibers and epoxy resin.

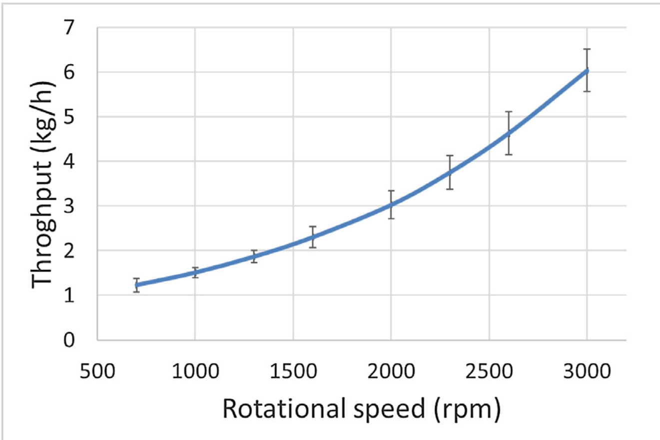

Fig. 2. Influence of rotational speed on throughput.

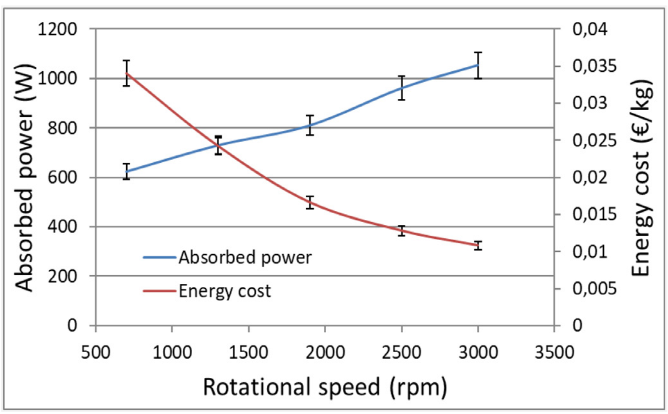

Fig. 3. Power absorbed (in blue) and energy cost (in red) for shredding of EoL glass fibers reinforced sanitary products. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.1. Throughput

In Fig. 2 dependency of throughput on rotational speed is shown. Higher rotational speeds result in higher throughput. For this reason, even if increasing rotational speed corresponds to larger power absorption, the cost for energy may not follow the same behavior as in Fig. 3.

The high throughput compensate the absorbed power. The result is that is more convenient to shred at maximum possible speed to reduce cost due to energy consumption. Other materials have different behavior as shown in Section 3.4.

3.2. Saturation

The saturation of the chamber is defined as

$$S(t) = \frac{M^{IN}(t) + M^{CH}(t)}{m_{max}}$$

Where M^{IN} is the input mass at time t, M^{CH} is the mass in chamber at time t and m_{max} is the maximum mass acceptable by the chamber (depending on the volume of the chamber and the density of material).

In Fig. 4 the effect of saturation of the chamber on the absorbed power is shown. The absorbed power increases linearly with the saturation of the chamber. Higher saturation results in higher probability to break particles at every breakage time step, increasing both aborbed power and throughput.

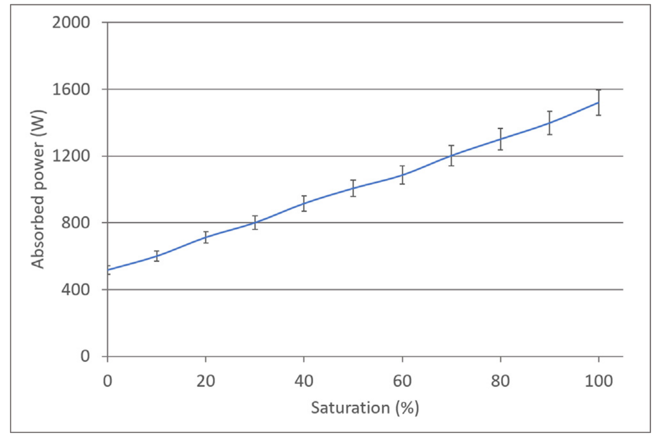

Fig. 4. Influence of saturation of the chamber on the absorbed power.

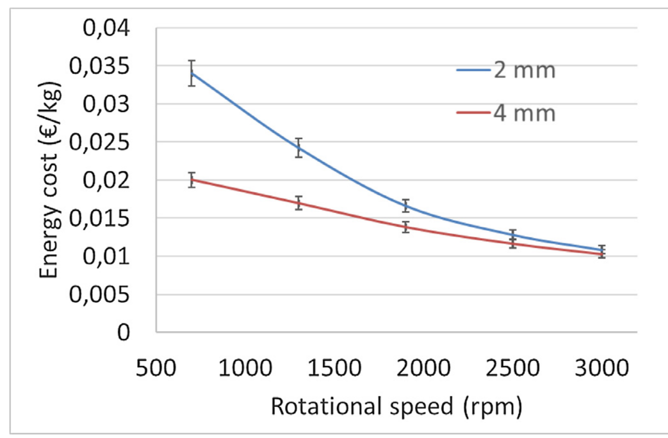

Fig. 5. Influence of difference between input and output particles dimensions for grate size of 4 mm (red line) and 2 mm (blue line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.3. Input/output gap

In Fig. 5 the dependency of energy consumption on the grid size is shown. The experiments have been performed with shredded particles from End-of-Life sanitary products at 10 mm with two different grids, one with size of 4 mm (red line) and one of 2 mm (blue line).

Higher differences in input and output dimensions result in longer residence times. As a consequence, throughput decreases and energy consumption increases. At highest rotational speeds residence time differences reduce and, as a consequence, energy costs become similar.

3.4. Material

In Fig. 6 energy consumption (in €/kg) for two different composite materials is shown. In particular red line is for End-of-Life wind blades made of glass fibers in epoxy resin and blue line is for waste from sanitary composed by glass fibers with polyester resin. The two materials have a glass fibers content, respectively, of 65% and 30%. This results in a different material behavior in terms of hardness (higher for wind blades). The first one shows a slight increase in energy consumption but always lower than the second one which decreases with increasing in rotational speed. This is because comminution of soft material requires longer times. This effect seems to be compensated by higher rotational speeds.

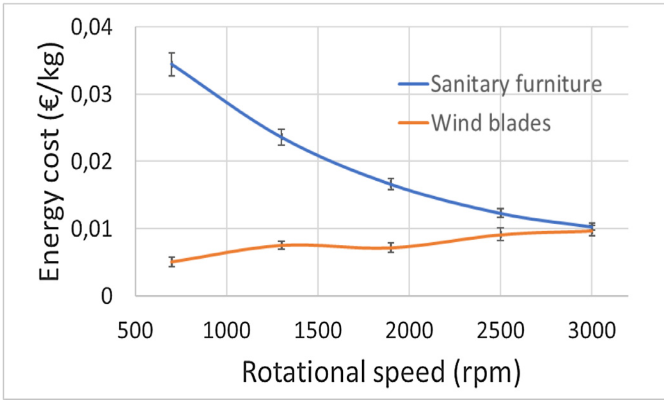

Fig. 6. Energy consumption for End-of-Life wind blades (in red) and waste from sanitary furniture (in blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. Energy consumption model

A model for the energy costs has been developed, considering that the energy consumption is defined as the power absorbed by the process multiplied by the time needed for the process itself, and knowing from Shuaib and Mativenga (2016) that the absorbed power could be divided in two terms, one at zero load and one for the actual shredding.

The notation for the different terms, based on the factors listed in Section 3 is as follows.

- C_{energy} is the cost due to electric energy consumption.
- $C_{e.\,e.\,fixed\ cost}$ is the fixed cost of electric energy that depends on several factors as the Country, the availability of renewable energy and the accessibility of energy supply.
- P_0 is the power at zero load to run both mechanical and electrical parts of the machine and it depends on the rotational speed.
- ω is the rotational speed.
- P_{sh} is the power absorbed for the shredding physical process, function of material to treat, size reduction technology and tools (this quantity is equal to the total absorbed power minus the power at zero load). P_{sh} is also function of the rotational speed. Considering the two materials seen in Section 3.4, P_{sh} is constant for sanitary products while for wind blades it increases linearly with ω.
- *Sat* is the saturation of the chamber.
- m_{tot} is the total mass acceptable by the chamber depending on the volume of the chamber and the density of the material.
- *Th* is the throughput of the process in kilograms per time unit which is function of the grid size and the rotational speed; it also depends on the material under treatment. It is calculated using the model in (Diani et al., 2019).
- n_{tools} is the number of tools involved in the process.

Finally, modeling the time of the process considering a discrete interval as in (Diani et al., 2019), the cost for energy consumption could be written as

$$C_{energy} = C_{e.e.\,fixed\ cost} \cdot (P_0 + P_{sh}(\omega) \cdot Sat) \cdot \frac{m_{tot}}{Th(tu)} \cdot \frac{1}{n_{tools} \cdot \omega}$$

This cost function contains all the trends seen in Section 3. In particular, the cost for electric consumption strongly depends on both rotational speed and throughput and, as a consequence, on the difference in dimensions of input and output particles. At the same time, the dependency on the material characteristic is represented by the total mass to treat and the power needed for the actual shredding process.

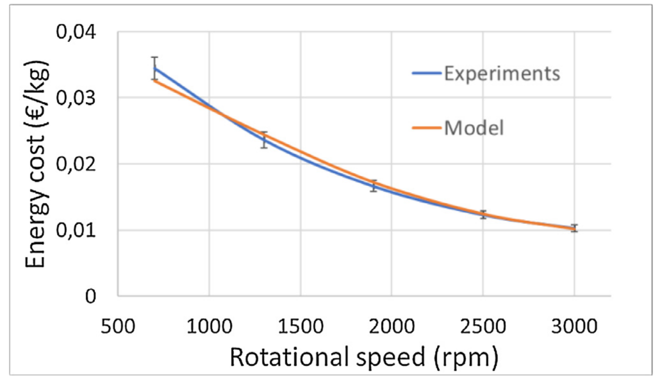

Fig. 7. Comparison between experimental (in blue) and model (in red) data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4.1. Validation

This model has been validated using waste from sanitary furniture with 30% glass fibers in a polyester resin. The data have been acquired in real-time through plug-in power sensors and a customized software. Three repetitions have been performed at five different rotational speeds (e.g. 700, 1300, 1900, 2500 and 3000 rpm). The results are in Fig. 7. A good adhesion of the model data to the experimental ones is shown, with slow difference only for lowest rotational speeds.

5. Conclusions and future perspectives

Energy assessment of a shredding process has been shown. Different factors have been considered as the throughput, the saturation of the chamber, the differences in initial and final dimensions of the particles and the material. To achieve a real circular economy in composite sector, minimization of the cost is fundamental. For this reason, the energy consumption for a comminution process has been developed and preliminary validated. The result underlines the importance of rotational speed. In particular, higher rotational speeds lead to lower energy consumption per kg (depending on the material). This concept is widely accepted in literature but to obtain the real process cost also tool wear must be considered. A deep study and modeling of tool wear considering several process factors has to be done.

CRediT authorship contribution statement

Marco Diani: Conceptualization, Methodology, Validation, Investigation, Writing - original draft, Writing - review & editing, Visualization. **Marcello Colledani:** Conceptualization, Validation, Investigation, Writing - review & editing, Visualization, Supervision, Project administration.

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