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125 Indirect 3D Printing of recycled glass fibres from end-of-life products: towards a design engineering approach to circular design

Alessia Romani[1], Marinella Levi[2]

[1]Department of Chemistry, Materials and Chemical Engineering "Giulio Natta", Politecnico di Milano – Piazza Leonardo Da Vinci 32, 20131 Milano Italy - Department of Design, Politecnico di Milano – Via Durando 38/A, 20158 Milano Italy, alessia.romani@polimi.it

[2]Department of Chemistry, Materials and Chemical Engineering "Giulio Natta", Politecnico di Milano – Piazza Leonardo Da Vinci 32, 20131 Milano Italy, marinella.levi@polimi.it

Abstract

Sustainability is increasingly becoming a key aspect for the design of new products and services. Within this context, digital technologies represent a reliable way for the development of new circular economy models. Basically, Additive Manufacturing (or 3D printing) allows to implement not only distributed production strategies but also the reuse and recycle of products at their end of life. In the last years, the development of new recycled materials for additive manufacturing has received much attention from both industry and academia, especially considering the most common materials (i.e. thermoplastics). Only few studies are actually focused on the recycling of less conventional products and wastes, as in the case of glass fibre composite materials. Since recycled fibres shall often fulfil specific requirements for the development of a new 3D printable material, coarse recycled fibres are not generally considered for the design of new products with additive manufacturing. Furthermore, designers are not fully aware of the existence of these new recycled materials, and their potential use for new applications may not be completely figured out during the design process. Especially for recycled composites, new materials are usually developed considering quantifiable physical properties as a priority at the expense of expressive-sensorial qualities related to human perception.

How could the use of these circular materials be encouraged for the design of new products? Is it possible to develop new recycled materials for real applications by considering a different approach to additive manufacturing? The aim of this work is to define a strategy for the design and production of new products from recycled composites through low cost and accessible 3D printing technologies.

Firstly, a new thermally-curable epoxy-based material filled with coarse shredded end-of-life wind blades was characterised taking in consideration both physical and expressive-sensorial qualities. At this purpose, a preliminary mechanical characterisation was performed, as well as different samples were created and compared according to the main visual and tactile properties. Contemporarily, a suitable process for the production of customizable pieces was defined through an indirect approach, which means by pouring the material in moulds made from a Fused Filament Fabrication 3D printer (Indirect 3D Printing).

Afterwards, the whole experimentation was validated thanks to the design and prototyping of a product for temporary exhibitions and stands, which can be reused as urban furniture or interior design element after its life cycle. To conclude, this strategy allows to design and produce customized long-lasting products from a waste-based material with an accessible technology, giving to the designer more flexibility for the development of new sustainable solutions. Further efforts should be done in order to better define an integrated approach for the development of new circular materials merging product design and material engineering expertise. In addition, other end-of-life products and materials could be potentially considered, as well as the use of biobased matrixes. Finally, the use of low-cost additive manufacturing technologies may lead to new bottom-up circular economy models for real applications from end-of-life products and common wastes.

Keywords: Product Design, Additive Manufacturing, Circular Economy, Glass Fiber Reinforced Polymers, 3D Printed Molds

Introduction

According to the main policymakers and stakeholders, sustainability has become a central aspect to reach responsible models of production and consumption (United Nations, 2015). In particular, Circular Economy is able to keep products and materials in use by preserving resources through the generation of closed loops (Ellen MacArthur Foundation, 2013). Different strategies, namely the "R-imperatives", are fostering the transition toward circular economy models such as recycle, reuse, and repair (Reike et al., 2018). Consequently, designers have a crucial role in this practical transition through the design of new sustainable products and services (Camocho et al., 2018; Stegall, 2006).

Similarly, digital technologies actively support the implementation of new circular economy strategies. In particular, Additive Manufacturing (also known as 3D printing) shows the potential to implement distributed production strategies and allows the reuse and recycle of products and materials at their end of life (EoL) (Colorado et al., 2020; Despeisse et al., 2017; Sauerwein et al., 2019). Furthermore, new recycled materials from EoL products or waste have been progressively developed for additive manufacturing, especially considering Fused Filament Fabrication processes (FFF, also called Fused Deposition Modelling, FDM). In this emerging context, the most common waste materials (i.e. thermoplastics) have been receiving much attention from both industry and academic research (Cruz Sanchez et al., 2020). However, only few studies are dealing with the recycling of less conventional products and wastes, such as composites. In particular, Glass Fibre Reinforced Polymers (GFRPs) represent a good opportunity for new circular economy strategies based on Additive Manufacturing considering the future amount of products made with GFRPs at their EoL (Deeney et al., 2021; Witten and Mathes, 2019). Recently, some works focused on the development of new products from EoL wind turbine blades (Bank et al., 2018; Jensen and Skelton, 2018; Joustra et al., 2021), or 3D printable materials after the mechanical recycling of these composite waste (Romani et al., 2020). In this case, recycled fibres from mechanical processes have to fulfil some specific requirements to develop a new 3D printable material, for example a maximum size of the fibres related to the nozzle diameter. As a consequence, coarse recyclate powders with significant variations in particle dimensions are less considered for the development of new materials for additive manufacturing and, consequently, for new products.

Currently, the knowledge of these recycled 3D printable materials for new applications is not well-established amongst designers and practitioners, even though their role is crucial to enlarge the range of application of those kinds of materials (Romani et al., 2021). In addition, the development of new recycled composite materials mainly considers the quantifiable physical and technical properties due to the predominant use of composites for high-performing products. The expressive-sensorial qualities of these kinds of materials are scarcely considered through the whole development process despite their significant contribution in the perception of new products from waste (Sauerwein et al., 2017; Veelaert et al., 2020).

This work aims at defining a preliminary strategy for the design of new products starting from the development of new recycled composites. For this reason, the characterization of a rGFRP from shredded EoL wind turbine blades was performed by taking into consideration the mechanical properties and expressive-sensorial qualities. At a later stage, the goal of this work is to show a possible way to use accessible FFF technologies for the development of new products from EoL wastes that allows to use coarse recyclate powders.

In this work, a preliminary mechanical characterization was carried out on two different material formulations based on an epoxy resin matrix filled with coarse shredded powders from EoL GFRPs. Visive and visuo-tactile qualities were characterized through the comparison of different samples obtained from 3D printed casting moulds. As a preliminary validation, a plausible application field was then detected for this indirect approach to 3D printing considering the results from the characterization. The life cycle of a temporary customizable element for stands and exhibitions was then defined by considering the recycle and reuse R-imperatives to generate possible closed loops in urban furniture and interior design fields. Afterwards, the scaled model of a possible configuration was designed and prototyped as a proof-of-concept of the strategy. Despite the preliminary nature of this work, this strategy fosters the development of new customized and long-lasting products with materials from composite waste considering both technical properties and expressive-sensorial qualities through design prototyping. Designers and practitioners can therefore directly experience with these new materials to understand how to best use the experiential knowledge for the design of new value-added products. Moreover, this work sets the stage for the development of a new integrated approach for circular materials merging product design and materials engineering expertise, as well as bottom-up projects for new application fields from EoL products and materials.

Methods

Material (rGFRPs)

In this study, mechanically recycled GFs from EoL wind turbine blades were used as reinforcement for the new rGFRP samples and prototypes. EoL blades were provided by Siemens Gamesa Renewable Energy S.A. whereas the mechanical recycling was carried out by STIIMA-CNR (Istituto di Tecnologie Industriali e Automazione – Consiglio Nazionale delle Ricerche). EoL wind turbine blades were composed by an epoxy resin matrix reinforced with continuous GFs. A coarse powder (hereinafter called recyclate) was obtained by shredding these EoL parts through grid holes of 1 mm. As a consequence, the recyclate powder was composed by the shredded epoxy matrix and GFs with a variable dimension of around 1 mm.

The new matrix was composed by an epoxy-based resin (Araldite BY158, Huntsman International LCC, USA). A curing agent (Aradur 21, Huntsman International LCC, USA) was added to Araldite BY158 with a weight ratio of 100/28 for the crosslinking, reaching a gel time of approximately 80 minutes. The recyclate powder was added to the matrix with a nominal percentage from 15% to 45% wt. and mixed for 10 minutes with a mechanical stirrer at 50 rpm. The mixture was then poured into 3D printed moulds and the samples were demoulded after 24h at room temperature. Finally, a thermal post-curing was carried out at 100°C for 1h to complete the crosslinking.

3D Modeling and Indirect 3D Printing

Different samples were designed and produced for the preliminary experimentation of this work: the tensile specimens for the mechanical characterization, six 3D models with complex curved surfaces for the experiential characterization of the expressive-sensorial qualities (“3D Tiles”), and three open, closed and full parts for the proof-of-concept of the product application (“Bricks”). “Fusion 360” (Autodesk, USA) and

“Rhinoceros” (Robert McNeel & Associates, USA) CAD software were used to produce the 3D models of the samples and the moulds.

A Prusa i3 MK3S FFF 3D printer equipped with a nozzle diameter of 0.4 mm was used to 3D print the moulds (Prusa Research, Czech Republic). The Gcode files for the production were obtained with the open source software “Prusa Slicer” (Prusa Research, Czech Republic). In this case, a water-solvable filament was used for the 3D printed moulds, which is a BVOH (Butenediol Vinyl Alcohol Co-polymer) filament from Verbatim Italia S.p.A., Italy. This material is generally used as support material for FFF multimaterial 3D printing. A minimum 20/1 water dilution ratio is required for the disposal of this material with the household effluent for a maximum of 2 kg of dissolved BVOH per day (Verbatim, 2018). Considering other water-solvable materials (i.e. PVA, Polyvinyl Alcohol), lower temperatures and times are required for the dissolution of the 3D printed parts. Moreover, it absorbs less humidity during the storage, therefore it causes less clogging issues during the material extrusion.

The 3D tiles had a nominal length of 40 mm, a height of 40 mm and a width of 6, 8, 10 or 16 mm according to the specific sample for the experiential characterization. Considering the proof-of-concept, 1:10 prototypes were made, and the bricks had an overall dimension of 58x25x30 mm. A layer height of 0.10 mm was chosen for all the specimen moulds, which were 3D printed with the vase mode to reduce the overall amount of BVOH to dissolve.

The rGFRP samples were made by pouring the liquid mixture into the moulds made with the BVOH filament. In other words, 3D printing was used to create the tooling parts rather than the final pieces. Complex shapes with a wide range of materials can be obtained thanks to this approach, also known as “Indirect 3D Printing”. As a matter of fact, thermosettings and composites that cannot be directly 3D printed can be processed by using 3D printed moulds. Among those materials, silicones represent the most spread materials for moulds and countermoulds, especially in electronics and medicine (He et al., 2020). Other applications have been recently explored in different fields (i.e. architectural design), including the use of sacrificial water-solvable moulds for complex parts with overhangs or multimaterial pieces (Burger et al., 2020; Leschok and Dillenburger, 2020; Montero et al., 2020; Naboni and Breseghello, 2018; Rossing et al., 2020).

As previously mentioned, the rGFRP samples were obtained starting from an epoxy-based thermosetting resin filled with the shredded recyclate. After the first curing phase of 24h at room temperature, the moulds were dissolved by immersion in a beaker filled with cold water for 3h. The parts were manually washed every about 1h to remove the residues of BVOH, and then re-immersed in fresh water following the above-mentioned water dilution ratio. At the end, the thermal post-curing was performed to complete the crosslinking reactions of the final samples. The mould of a 3D tile with the corresponding casted shape are shown in Figure 1a, whereas the mould and the casted shape of an open brick are visible in Figure 1b.

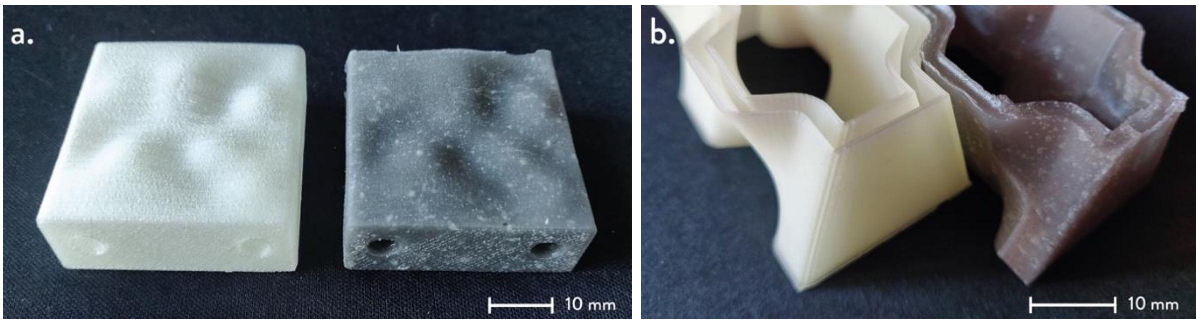

Figure 1. Samples of the 3D printed solvable mould and final shape of the (a) 3D Tiles for the preliminary experiential characterization and of the (b) Bricks.

Mechanical properties and expressive-sensorial qualities

A preliminary mechanical and experiential characterization was performed in order to consider both the technical properties and expressive-sensorial qualities of the new rGFRPs for the definition of a suitable application field. As a result, both aspects can be considered during the design phase of new products from EoL GFRPs although this holistic approach should be further developed for a practical implementation.

Figure 2. Tensile test specimens with 35% wt. of GF recyclate after the removal of the 3D printed mould according to the ASTM ISO 3039 standard.

Tensile tests were carried out by means of Zwick Roell Z010 equipped with a 10 kN cell load (ZwickRoell GmbH & Co, Germany) to evaluate the Elastic modulus, tensile strength and elongation at break of the rGFRPs. The tests were performed according to the ASTM D3039/D3039M-17 standard (ASTM International, 2017) at a speed of 1 mm/min. In particular, the elastic moduli were assessed in the starting slope of the linear elastic region. Experimental data were used to calculate a mean value and a standard deviation for each mechanical property. Two batches of at least five specimens each were prepared with a recyclate percentage of 35% wt. and 45% wt., respectively. Each specimen had an overall length of 100 mm, a width of 10 mm, a thickness of 2.5 mm and a nominal gauge length of 40 mm. A manual polishing was then performed to remove the asperities related to the fibers, reaching a constant cross-section. The tensile specimens with 35% wt of recyclate are visible in Figure 2.

Two batches of 3D tiles were produced for the experiential characterization. In detail, the first batch aimed at showing the variation of the visive qualities of the recycled material through 18 3D tiles according to the thickness of the sample (6, 8 and 10 mm), the recyclate percentage (15% wt., 20% wt., 25% wt., 30% wt., and 35% wt) and the different light exposition (direct or indirect light). The second batch focused on the investigation of the visuo-tactile qualities by modifying the recyclate percentage (25% wt., 30% wt., and 35% wt.) and the surface details (curved surfaces, engraves and embosses). The samples were then placed to create two different matrixes of comparison that can be useful for designers and practitioners to evaluate the different perception of the recycled material according to the selected variables.

Results and Discussion

Mechanical properties and expressive-sensorial qualities

Tensile tests were performed to evaluate the experimental elastic moduli, tensile strength and elongation at break for two batches of specimens with different rGFRP percentages. This evaluation step was useful to choose a possible field of application for these rGFRPs. In detail, two material formulations with 35% wt. and 45% wt. of recyclate powder were used for Batch 1 and 2, respectively. The main results are shown in Table 1.

Table 1. Elastic Modulus, Tensile Strength and Elongation at Break for two different batches of tensile specimens (35% wt. and 45% wt. of recyclate)

Batch	Recyclate percentage (% wt.)	Elastic Modulus (GPa)	Tensile Strength (MPa)	Elongation at Break (%)
1	35	4,5 ± 0,6	42,6 ± 6,2	1,2 ± 0,2
2	45	5,0 ± 1,1	36,7 ± 12,4	0,9 ± 0,2

Comparable values of elastic moduli, tensile strength and elongation at break are exhibited from the two material formulations. This can be due to the standard deviation values linked to the variability of recyclate powders. In general, the properties of composites filled with mechanically recycled reinforcements may significantly change from one batch to another, since the particle dimensions and distribution of the recyclate are influenced not only by the specific material waste but also by the conditions of the recycling setup. Moreover, further experimentation should be done to test other batches with different recyclate percentages, as well as to predict the effect of this misaligned short GF reinforcement on the mechanical properties of the composite (Fu and Lauke, 1998).

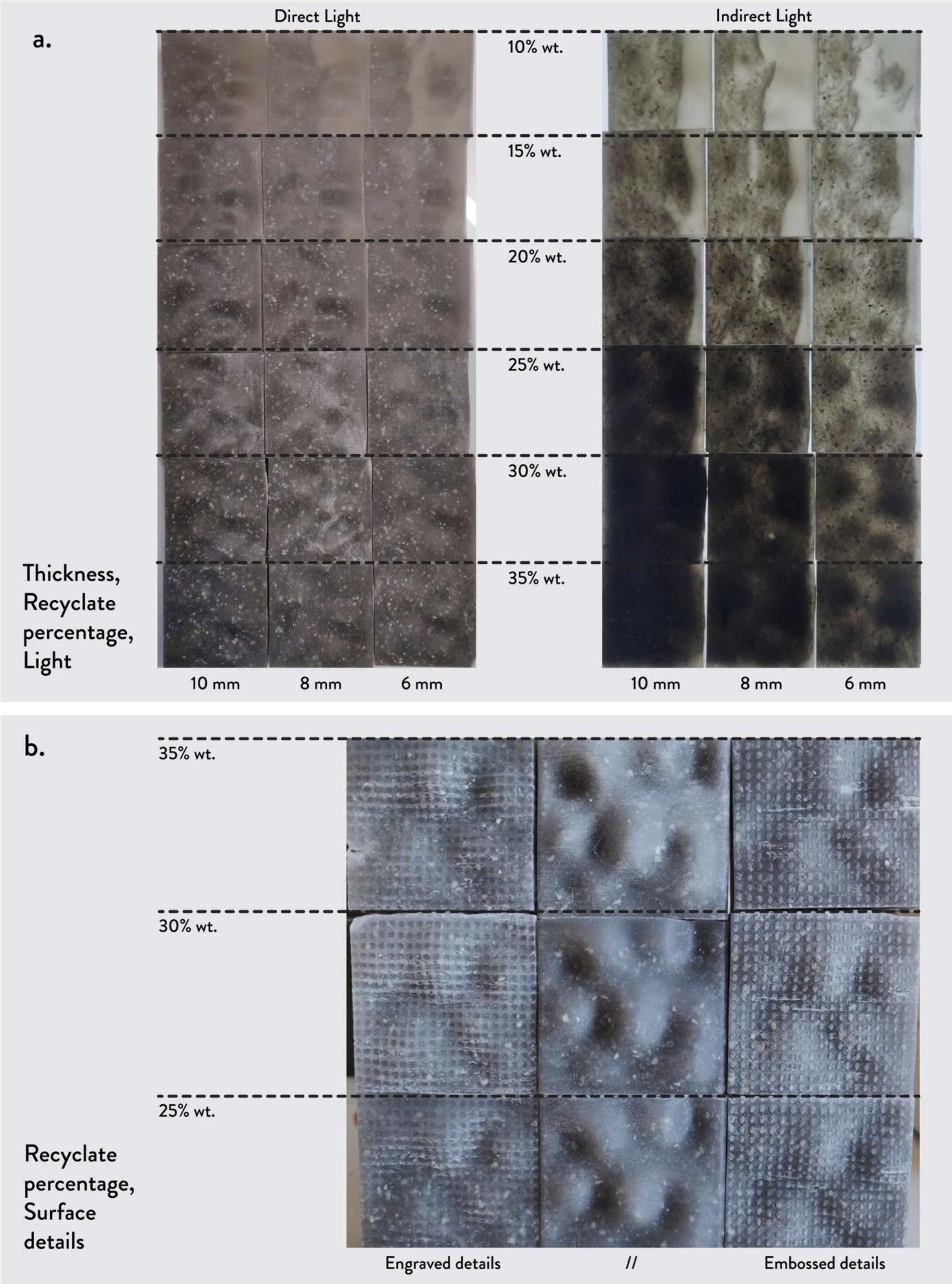

Figure 3. Samples for the preliminary experiential characterization: expressive-sensorial qualities related to (a) the thickness, the recyclate percentage and the light variation; and (b) to the recyclate percentage and different surface details.

Since expressive-sensorial qualities play a key role in the perception of a product (Karlsson and Velasco, 2007; Whitaker et al., 2008), a preliminary experiential characterization was set through two batches of samples from 3D printed moulds. According to Material Driven Design, an experience-oriented perspective should be considered to design new experiences starting from a material (Karana et al., 2015).

To this purpose, the 3D tiles were useful to tinker with the material and to directly experience with the variation of different parameters. The first batch (Figure 3a) was useful to assess the qualitative variation according to the different thickness of the samples, the recyclate percentage and the effect of the light exposition. A variation of 2 mm was designed for the 3D tiles thickness (from 6 to 10 mm), and an increase of 5% wt. was chosen for the recyclate percentage (from 15% wt. to 35% wt.). A matrix was then created for the qualitative comparison, and two different light setup were used. As shown in the matrix of Figure 3b, the second batch is linked to the variation of the visuo-tactile qualities according to the different recyclate percentage and the surface details. Also in this case, an increase of 5% wt. was chosen for the recyclate content (from 25% wt. to 35% wt.), and the superficial texture was modified by adding engraved or embossed details.

As a result, different translucencies and visive effects can be reached, as well as different textures could be added to the surface. A random pattern was visible in both cases, mainly related to the variability of the recyclate particle size. The creation of physical samples can be considered a powerful tool for the designers in order to fully exploit the potentials of new materials from wastes from an experiential point of view. Future works should be focused on the investigation of different expressive-sensorial qualities, also involving the users to assess their perception for the design of new value-added products (Veelaert et al., 2020).

Indirect 3D printing process

As previously mentioned, FFF 3D printing process was used for the creation of water-solvable moulds made in BVOH. Since this material is biodegradable and non-toxic, it could be considered one of the most suitable alternatives for sacrificial moulds. Moreover, BVOH could be recycled by collecting the material during the demoulding phase, that can be dried and shredded for the production of new moulds with pellet-based FFF 3D printers (Leschok and Dillenburger, 2020).

The use of 3D printed moulds may allow to select the most suitable shredding process or to avoid some steps for the mechanical recycling of EoL composites, i.e. fine shredding and sieving, reducing the overall impact of this process. As a matter of fact, the development of new extrudable reinforced materials for a direct approach to 3D printing shows some constraints related to the dimensions of the reinforcing particles. In particular, the nozzle diameter plays a crucial role in determining the maximum dimensions of the particles that can be successfully extruded. As an example, the maximum fibre length value for a nozzle with a diameter of 1 mm corresponds to 160 µm, and different steps or processes could be required to reach this dimension (Romani et al., 2020). Furthermore, the variability of different recyclate batches could significantly affect the printability of a composite material from EoL waste, while a lower effect might be noticed using a coarse recyclate as a reinforcement for poured rGFRPs.

Finally, indirect 3D printing for new rGFRPs could be a suitable way to produce large-format parts with complex shapes, especially considering that further work is needed to reach a scale up of new 3D printable materials from EoL GFRPs (Burger et al., 2020; Naboni and Breseghello, 2018; Nieto and Molina, 2019; Romani et al., 2020). However, some limitations may be related to possible entrapped air bubbles in the material during the casting or to deformations of the BVOH moulds for the exothermic reaction during the resin crosslinking.

Application Proof-of-concept

After the preliminary characterization of the rGFRP presented in this work, a suitable application field was chosen considering the material properties and the possibilities enhanced through 3D printing. From a technological point of view, 3D printed moulds allow to produce complex and customizable parts with a good control of the overall shape thanks to the digitalization of the mould construction. This aspect is particularly noticeable in large format applications such as building and furniture sectors, where the use of 3D printed moulds (or formworks) is increasingly gaining attention (Burger et al., 2020; Leschok and Dillenburger, 2020; Naboni and Breseghello, 2018). Moreover, furniture making represents one of the most sustainable solutions to recycle waste from wind turbine blades according to the Sustainable Development Goals (Deeney et al., 2021; United Nations, 2015).

For these reasons, exhibition and furniture sectors were chosen as a case study to define the life cycle of new customizable products for new closed loops based on recycle and reuse. A conceptual scheme for the design of customizable and reusable exhibition – furniture structures from rGFs is shown in Figure 4a. Starting from the mechanically rGFRPs coarse powders (1), new composite materials can be developed and characterized from a technical and an experiential point of view to fully exploit the potentials for new products (2). New customizable products can be designed and produced through indirect 3D printing based on FFF processes (3). After their first life cycle, these products can be reused multiple times for similar applications (A) or in different contexts and sectors (B), generating new closed loops. This strategy could be also useful to foster a behavioural change in local communities using these products as a tangible medium to involve users and citizens in the transition toward circular economy practices (Camocho et al., 2018). Within this context, designers and practitioners can actively contribute to this change, adding value to recycled composite materials through design (Romani et al., 2021).

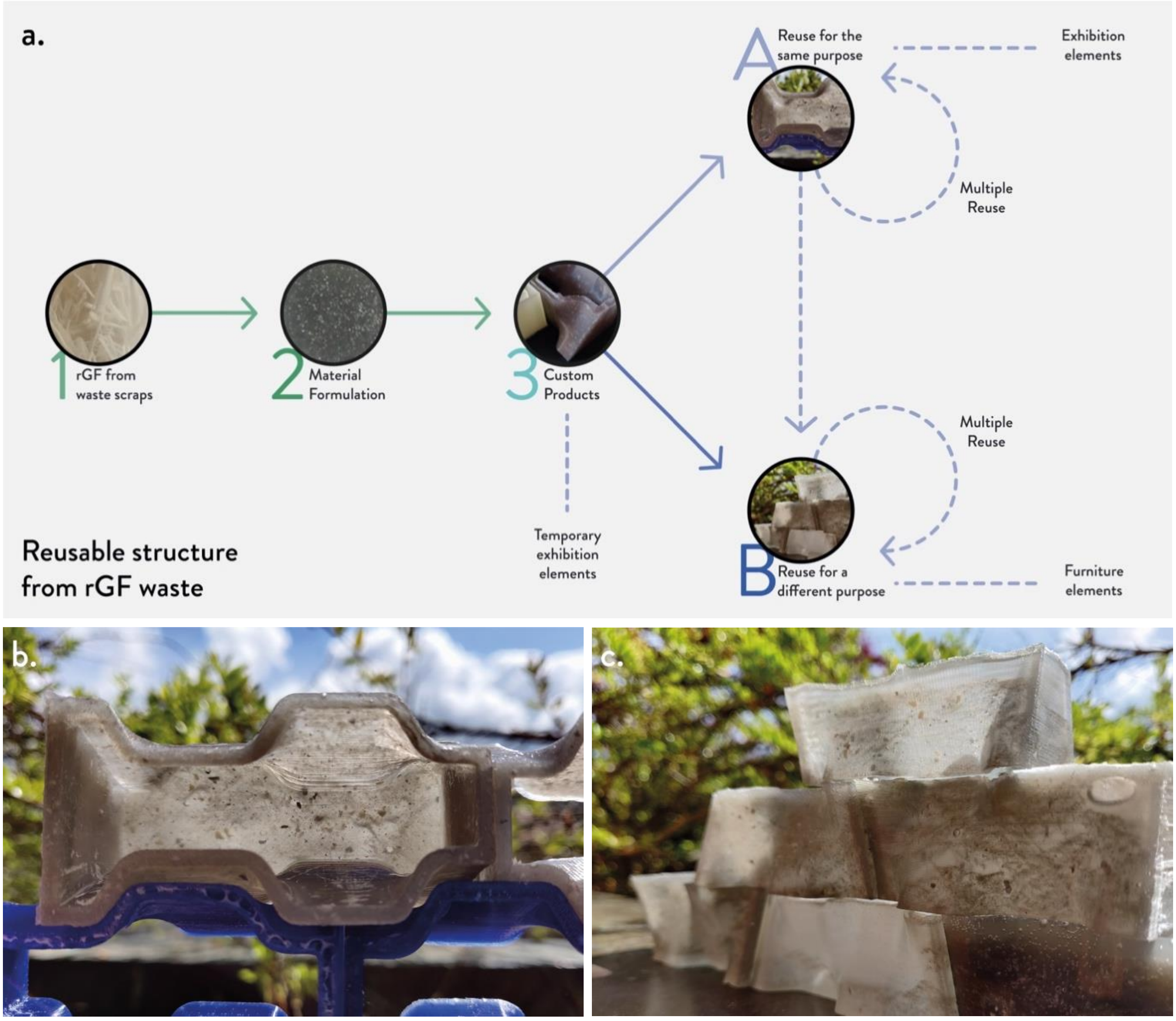

Figure 4. Concept of the reusable custom exhibition – furniture structure from rGFs: (a) concept of the life cycle; (b) detail of the "Brick" single element (1:10 prototype); and (c) possible configuration of the exhibition elements (1:10 prototype).

As a proof-of-concept, a temporary customizable element for stands and exhibition was designed. Following the scheme in Figure 4a, the exhibition element can be produced with 3D printed moulds by pouring the rGFRPs from EoL turbine wind blades. After its first life cycle, the product can be reused for other exhibitions and/or in local community public spaces as urban furniture or interior design elements. The 1:10 prototypes of three different configurations of the "Brick" sample (open shape, closed shape and full shape) were created to validate the overall strategy. Through this preliminary prototype shown in Figure 4b and 4c, some possible stand configurations using the exhibition elements were created, also considering the preliminary experiential characterization. This design prototype demonstrates that this strategy is able to foster the generation of new closed loops following an experiential and practical approach to new circular materials from EoL waste. Furthermore, FFF 3D printing technology allows designers to develop new customized and sustainable solutions.

Considering the preliminary stage of this work, further investigations should be done to assess other intrinsic features of the material or to develop other sustainable alternatives based on bio-based matrixes or different EoL composites. Additional work could be linked to evaluate the safety issues of these rGFRPs for real products. Finally, an integrated and holistic approach for new circular materials could be developed by merging product design and materials engineering expertise including a wider range of technical properties, expressive-sensorial qualities and a well-structured workflow.

Conclusions

To sum up, this work presented a possible approach to design new products starting from the development of new circular materials from EoL waste. A preliminary characterization of the mechanical properties and of some visive and visuo-tactile qualities was performed on rGFRPs filled with coarse recyclate powders from mechanically recycled GFs. An indirect approach to FFF 3D printing was adopted for the production of the samples that were poured in 3D printed water-solvable moulds made with a BVOH filament. In this way, designers and practitioners can directly tinker with new circular materials to better exploit their potentials for new products.

Afterwards, a conceptual scheme for new closed loops was designed considering the recycling of EoL composites and the reuse of the new developed products (Recycle and Reuse R-imperatives). Starting from the developed rGFRPs and the FFF technology, a proof-of-concept was designed and prototyped to validate the whole strategy. Exhibition and furniture sectors were chosen as suitable fields for new customizable elements for multiple reuse that aim to foster the behavioural change towards more sustainable models of production and consumption. Therefore, the designer has the opportunity to enhance this transition through the design of new products from EoL waste considering this behavioural change as an intrinsic added value. Even though this approach should be further developed, this work paves the way to a new holistic approach that considers design and engineering for new products starting from EoL waste. At a later stage, new bottom-up initiatives and applications may be detected and investigated with this approach to foster the transition towards circular economy models and a paradigm-shift in the behaviours of users and local communities.

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