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INVESTIGATIONS OF TECHNICAL CHALLENGES IN COMPOUNDING OF RECYCLED CARBON FIBERS

Azmin Hannan[1], Holger Seidlitz[1,2,3], Jonas Krenz[1], Marco Müller[1]

[1] *Chair of Polymer-based Lightweight Design, Brandenburg University of Technology Cottbus – Senftenberg (BTU), Germany*
[2] *Research division Polymeric Materials and Composites PYCO, Fraunhofer Institute for Applied Polymer Research IAP, Germany*
[3] *Strukturwandel-Clusters SpreeTec neXt*

Corresponding author:
Holger Seidlitz
Brandenburg University of Technology Cottbus – Senftenberg (BTU)
Konrad-Wachsmann-Allee 13, 03046 Cottbus, Germany
phone: (+49) 355 69 5001
e-mail: fg-leichtbau@b-tu.de

Abstract

Carbon fiber reinforced plastics (CFRP) owing to its excellent properties have found its extensive application in various fields ranging from medical to automobile and aerospace industries. This has thereby led to ever-increasing demand of carbon fiber production and as well as resulting in tonnes of carbon fiber wastes in the landfills [5]. Due to the high positive impacts of using carbon fibers, the energy intensive and cost intensive production of virgin fibers and the growing landfills are often overlooked. Hence, the need for recycling and repurposing of carbon fiber wastes have gained the significance at present day. Although various recycling technologies have been developed yet, various challenges are faced with processing of recycled carbon fibers (rCF). Besides, the desired application specific properties are not compromised for high cost and high-energy requirement. Therefore, an overall development of processing rCF is sought from not only a sustainability point but also an economic point [7]. Various efficient recycling technologies are currently operating. The challenges arises in commercializing the recycled fibers after the recycling process. The recycled fibers often require various post-processing of fibers and undergoes fiber degradation. This induces a skeptical mindset for the buyers to introduce the recycled fibers in the material ecosystem. This paper currently discusses the processing challenges of long rCF in a compounding plant. To form a closed loop, the recycled fibers are obtained from the novel thermocatalytic degassing process from the CFRP recycling pioneers in Germany, Global EnerTec AG, Guben. This plant in Guben not only recycles carbon fibers from automotive CFRP wastes but also repurposes the epoxy matrices into secondary energy sources. This paper focuses in investigating the processing of rCF obtained from a 100% recycling technology. The aim is to investigate the possible technical challenges so that the rCF can be repurposed to new product manufacturing. Thereby, addressing the concerns with the development of closed loop circular economy in recycling CFRP wastes.

Keywords
CFRP, rCF, recycling, circular economy, compounding, carbon fibers.

1. Introduction

Epoxy based carbon fiber composites owing to its excellent properties finds its wide applications in the fields of automotive, microelectronics and aerospace, aviation, and high-speed rail industries. In 2022, it was estimated to have a world production demand of 199,000t [2]. However, these petrochemical derived epoxy resins for high performance applications have negative environmental impacts. Additionally, their inherent cross-linked structures makes them resistant to recycling [4, 9]. Hence, a long-standing challenge is prevalent for recycling of epoxy resins. Therefore, there arises a need for recycling and reforming these ever-increasing epoxy-based composites both on the economic and as well as environmental aspects.

Recycling methods and possibilities of material recovery has existed for several years now. However, what has been lacking, is the acceptance for recycled materials and their stigma of poor quality. In addition to trust their reliabilities to offer continuous supply [1, 2]. Since, this paper focuses on a complete sustainable circular economy, the source of receiving the carbon fibers is also taken into consideration.

In this regard, Global EnerTec AG, Guben, Germany have developed a novel thermocatalytic degassing process to recycle carbon fiber reinforced plastics waste from automotive sectors. The epoxy matrices through this process are repurposed as secondary energy sources. This process additionally is performed in a closed chamber, lower operating temperatures and offers 100% recycling of CFRP wastes. Therefore, it combats the challenges of high temperature conventional pyrolysis process of recycling [3]. In conventional pyrolysis process, around 80% of the matrix material are burnt off during recycling of CFRP wastes. As well as, due to the closed chambers, the fiber flight are no more a concern. Thereby preventing the short circuit of machine components unlike in conventional pyrolysis processes. Hence, it assured the rCF are obtained from a sustainable and efficient source.

Without marketability, the recycling fiber will have no profitability [1, 2]. The automotive industry is viewed as one of the potential market opening for recycled materials. Low weight carbon fibers with good surface finish makes it suitable for many interior components and body panels applications.

Besides, the inclusivity of recycled raw materials is evidently observed in the automotive fields. For instance, the series production of BMW i3 and i8 since 2013 [1, 2].

In order to have a circular economy, it is important to have an investigation on the further processing of these recycling carbon fibers to manufacture a new product and these fibers can be commercialized into the market to assure the supply chain security.

The recovered carbon fibers can be post-processed and use to create a new product chain. The question is to widen processibility of long rCF and not restrict to typical processes with short carbon fibers such as Sheet Moulding Compounds (SMC) and Bulk Moulding Coumpounds (BMC) semi-finished product processes. Besides, long non-continuous fibers show better properties than short fiber injection moulded materials [11]. Hence, this paper investigates the processing requirements for a compounding and injection moulding process with a view to develop rCF suitable for other processes and product chains.

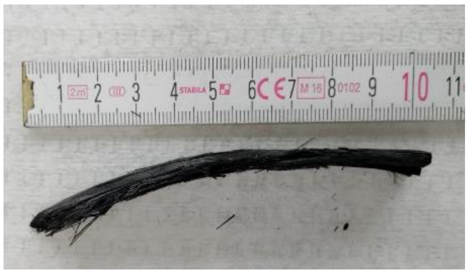
2. Challenges in compounding of long fibers

The rCF were obtained from Global EnerTec AG, Guben, Germany. A mini-compounding plant from Collin solutions was used for the compounding process. The challenge for the compounding of long rCF occurred due to mainly, fiber sizes and the smaller screws in the mini-compounder. Hence, an introduction to the fiber sizes and illustrations of the screws and compounding plant is shown in the following texts.

The rCF were first fed into the compounder directly without any post-processing such as shredding or surface treatment. The fiber length were inhomogeneous and of fiber sizes ranging from 10–100 mm (Fig. 1). The fibers had thickness of around 1–10 mm (Fig. 2).

Fiber length – 10 cm

Fig. 1. Fiber size along the length.



Fiber thickness – 0.5 cm

Fig. 2. Fiber size along the thickness.

The compounding feed had two feeding unit with co-rotating twin screws with different cuts. The size of the screws were as follows:

Screw Diameter of Dosing Unit – 10 mm (inner)
20 mm (outer)

Length of screws are – 24 cm

Distance between the screws – 18 mm.

Each dosing unit in the feeding unit consists of two co-rotating screws. The distance between the screws are of 18 mm.

The types of screws of both the dosing unit are depicted in Figs. 3 and 4.

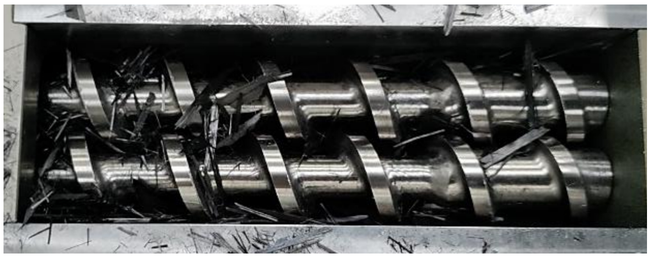


Fig. 3. Screw type 1 in dosing unit 1.

Fig. 4. Screw type 2 in dosing unit 2.

The mini-compounder from Collins solution (Fig. 5) is a continuous plant from feeding hopper to cooling bath where the drawn polymer filament is cooled. This filament can then continuously be fed into the pelletizer to collect the granulates.

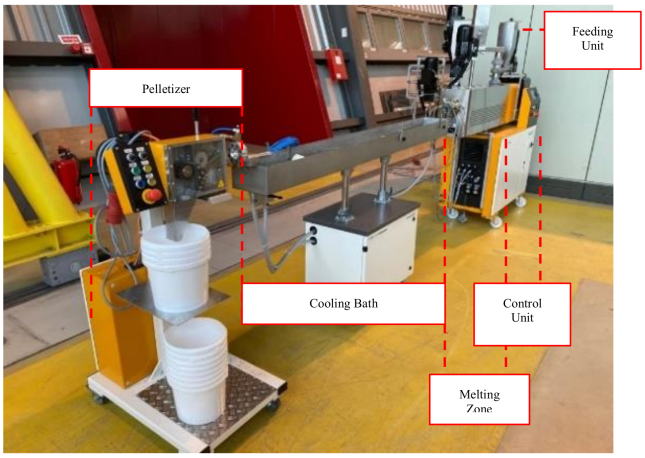


Fig. 5. Mini-compounder plant from Collins Solutions.

As depicted in the Fig. 5, the polymer and the fibers are fed together after weighing them in one of the feed unit. Once the materials are fed, it goes through the melting zone where the screws rotate to mix and melt the mixture under the effect of shear and heat. The control unit controls the feed rate, rotation of the screws and the temperature. The melt filament is drawn through the cooling bath for hardening and is fed continuously to the pelletizer. The filaments are cut into pellets and collected. This pellets or granulates are then dried and made ready for the injection molding process. During the feeding, the major challenge that have been observed is the blockage of screws. This is due to the fiber size. The fibers are long and thick to pass through the feeding screws easily. Additionally, the inhomogeneous fiber sizes in rCF resulted in an inconsistent through-put. Therefore, the ratio of fiber to polymer were difficult to identify in the pelletized granulates.

The change of screws in the dosing units were not feasible because more than the effect of geometry of the screws, the dimension of the screws affected the process. As the fibers when fed to either of the dosing unit showed blockage of screws resulting in no constant throughput. Therefore, in order to switch to bigger screws, counter-rotating screws or single screws for flakes, it has to fit the dimension of the dosing unit accordingly. Hence, the distance between the screws will remain unchanged. Therefore, the challenge remains prevalent until the fiber sizes remains unchanged for a lab scale mini-compounding plant. Figure 6 depicts the blockage of screws by the lump build-up of rCF hindering the material flow into the mixing and melting zone of the compounding plant.

Hence, the assumed solutions were to be opted to identify the fiber size that would be able to pass through the screws easily without blocking the screws. Followed by shredding the carbon fibers to the required length. Therefore, various experimental work had to be performed to tackle this technical solution by post-processing the fibers. These experimental works are discussed in the next section in detail.

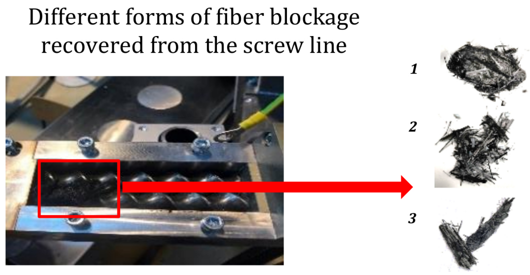


Fig. 6. Fiber Lumps in between screws.

3. Experimental investigation

The experimental work is planned for the identification of process requirements in a lab scale mini-compounder (Fig. 5). Initially, a set of preliminary experiment were carried out without post-processing of rCF in the mini-compounder. The gauging of the rCF were monitored. Preliminary gauging tests showed better gauging of feed material through dosing unit 1 with screw geometry 1. Hence, further experiments were carried forward with dosing unit 1. However, the technical challenges with fiber gauging were prevalent. It was found that without the shortening of fibers, it was not possible to gauge the fibers through the screws without any blockage. Two main possible reasons for the blockage of screws were – fiber sizes as well as the texture of fibers after shredding processes. Hence, different shredding processes were carried out and the gauging was monitored successively after post-processing.

Mainly, three shredding process were performed: ball mill, grindomixer, cutting mill. Figure 7 shows the fibers after the milling process. The gauging process were carried out to observe the effect of milling process. The summary is listed in Table 1.

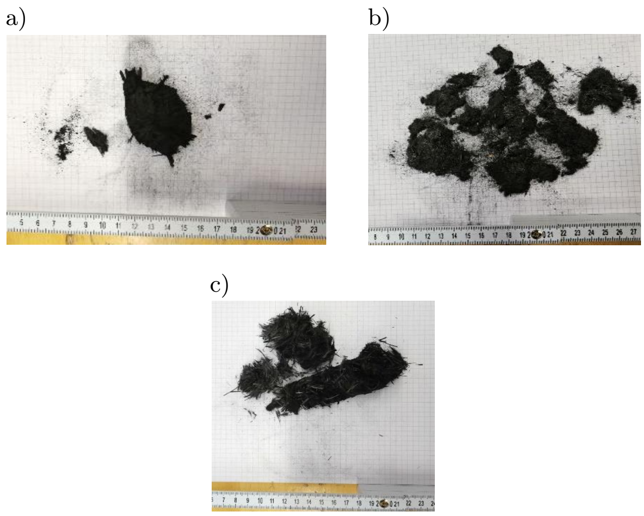


Fig. 7. Fibers after milling process:
a) ball mill, b) grindomixer, c) cutting mill.

As evident from Table 1, the milled fibers were not successfully gauged homogeneously through the dosing screws. This identifies that the fibers are supposed be not matted or lumped.

Tabela 1
Gauging of fibers after milling.

Milling process	Results from gauging process
Ball mill	• Flakes have been broken up to a large extent, some fibers are still long, and many have been crushed to powder. • Some fibers are heavily matted, the metering screws on the compounder convey only individual matted lumps. • Build-up of a fiber pile in the hopper that is not conveyed. • The processed quantity is not sufficient to fill the hopper sufficiently (dosing screws only half in contact with fibers).
Grindomix	• Fibers were not cut during preparation, flocks were partially broken up and slightly matted. • Conveying of the fibers with the metering screws of the compounder not possible. • Fibers are not "grabbed", unbroken flocks lie between the wall and the screws and are not conveyed. • Very low throughput, regardless of speed.
Cutting mill	• Fibers were cut during preparation, approx. 12–0.2 mm, flakes are almost completely broken up, short fibers are felted. • The matted fibers formed "cotton lumps" about 5–30 mm in size, which were conveyed relatively uniformly. • After the test, a single heavily felted fiber lump (40–50 mm) could be removed from the hopper and could no longer be conveyed. • At speeds >60% a relatively uniform material flow could be observed. • Most of the material is conveyed in felted lumps. • Possibly uneven distribution in the compound.

The matted (fluffy and wool like) texture of fibers are depicted in Fig. 8.

Fig. 8. Matted texture of fibers.

Besides milled carbon fibers (mCF) loses its structural strength when compared to continuous or discontinuous long fibers [6]. Thus, microscopic investigation of some of these milled fibers were performed. From the microscopic images in Figs. 9 and 10. Damage can be seen in both the fibers from the grindomixer and the fibers from the ball mill.

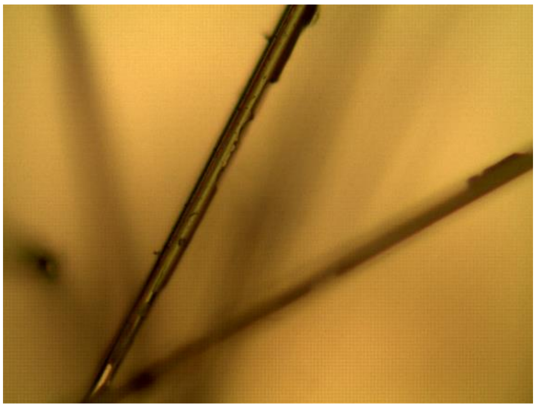


Fig. 9. Microscopic image (Grindomixer mCF).

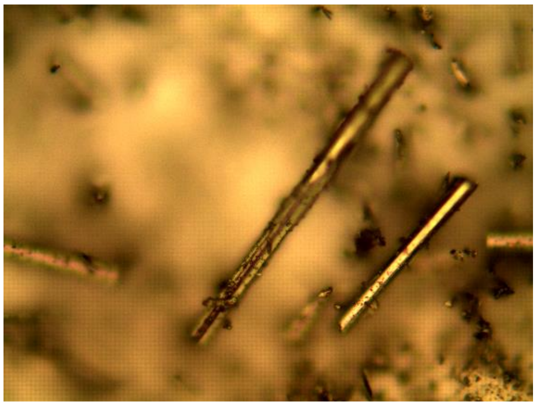


Fig. 10. Microscopic image (Ball mill mCF).

The "dust" of the fibers from the ball mill consists of many fragments of the fibers and remnants of the matrix material [8].

The remnants of the fibers from the grindomixer consist of fewer fiber remnants, but snippets of fibers were prevalent here. On one hand, it is foreseen that surface treatment of fiber surfaces after milling process might be necessary. On the other hand, the fiber remnants can offer better roughness and thereby better interfacial adhesion [10]. Hence, further investigations are required to be able to mitigate such challenges for rCF to be remanufactured. This enhances the concerns to potential application of rCF in regard to circular economy. In this paper, the work is focused to investigate the probable technical challenges faced to compound long rCF.

Once the texture of fibers were identified, further lab based investigation were performed to identify better, the requirement of suitable fiber feed size. This was done through sieving the rCF without any post-process. The sieving was performed with 150–250 μm. Sieving amplitudes of 60 for 20 min, 30 min and 60 min. The fiber size achieved were ranging from 0.5–1 mm (Fig. 11). These fibers sieved were dry and separated (not sticky, lumped, matted). However, this step was only performed to identify the suitable fiber length of the feed material.

Fig. 11. Sieved fibers.

These sieved fibers passed through without any blockage through the dosing screws. Gradual increase in fiber sizes were tested. It was observed that if the fibers are non-sticky and dry, an optimal fiber size up to 6 mm could be easily compounded in a mini – compounding plant. Although sieving is not a feasible solution for post-processing, yet it helped to identify the suitable fiber length and fiber texture for the measured screw dimension of the dosing unit. Therefore, a feasible solution for post-processing of rCF has to be developed for easy compounding of carbon fibers.

4. Conclusion

In this paper, the investigation of technical challenges faced during processing rCF through a mini-compounding plant was done. To ensure a closed loop and a sustainable economy, rCF were recovered by a 100% recycling technology (Global EnerTec AG). The optimization of this recycling process for rCF recovery at Global EnerTec AG was supported by Brandenburg Technical University, Department of polymer based lightweight construction. This was done through fiber and matrix analysis.

The processing of rCF had been investigated further. The main challenge identified was – inhomogeneous fiber size of rCF. This indicated necessary post-processing steps before the compounds could be remanufactured. The post-processing included shortening of fibers from 10–1 mm. Various post-processing methods such as ball mill, grindomixer, cutting mill and sieving were performed. The fiber gauging in the compounding dosing unit were studied before and after shortening of fibers. Significant lumping of rCF were observed which aided in blocking of screws in the dosing unit. Thus, resulting in an inconsistent through-put as well as inconsistent fiber to matrix ratio in the end compound. Therefore, a suitable fiber length and fiber texture requirement had to be identified for processing in the lab-scale mini-compounding plant.

This further required investigation of the screw dimension and screw geometry which allowed easy material flow. The screw geometry type 1, dosing unit 1 showed better material flow. This was observed by monitoring gauging of material.

Comparatively, the cutting milled rCF showed better gauging of material through the screws. However, after a certain processing time, the milled fibers built up a lump due to mixing and electrostatic charges on rCF. Milled fibers also showed fiber surface degradation under microscope.

Thus, it required further investigations. Besides, the texture of fibers (fluffy, wool-like) after milling were not suitable as it aided to faster lump formation and thereby blockage of screws. The fibers were then sieved to different fiber sizes and without post-processing. These fibers of fiber size up to 1 mm and dried, non-sticky texture showed optimal material gauging for screw dimensions of 20 mm outer diameter, 24 cm in length and 18 mm distance between the two screws.

Since, the identification of material feed requirement for the lab-scale mini-compounding plant were achieved. Further research works aim at compounding these rCF with recycled thermoplastics. This would enable the remanufacturing of possibly a fully recycled new product. This would help to achieve a closed loop circular economy from waste to recycled remanufactured product.

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