CARBON COMPOSITES RECYCLING STRATEGIES AND THEIR REALIZATION FOR NEW PRODUCTS

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Abstract

Carbon waste is difficult to process on textile equipment due to a lack of "typical textile" properties like crimp, friction and torque. It is therefore necessary to modify all machines and working elements in a typical textile recycling line to achieve acceptable processing behavior.

In order to allow fundamental studies a flexible and compact recycling line has been installed at the Institute für Textiltechnik Augsburg. Based on intensive research and first industrial experience a lot of modifications were already executed and will allow to find the most proper line configurations and settings for developing the right strategy for suitable products.

As a first result a matrix will be presented which provides a systematical overview of all known technologies for the single steps of composites recycling. The overview matrix starts with the specifications needed for a given final application and is based on different specification of recyclable "raw" materials. For every step the potential technologies are listed, evaluated and applications described.

1. Introduction

Recycling of waste from composites products or fabrication waste is a must reflecting the economic potential of recycled material on the one hand and the need for reuse resulting from the prohibition of depositing carbon composites waste in most of the European countries.

It is more and more a decisive discussion to justify the use of CFRP in certain products by providing a sound and specific solution how to process waste from CFRP production into new and useful products. There are only a few – but growing – number of end uses known for recycled carbon fiber products, which is mainly due to several reasons:

- recycling processes have not been evaluated properly related to carbon waste processing
- there are only limited applications for recycled composites known from industrial use
- standards for specifying properties and processes have not been adapted to materials and semi products for recycling
- design principles for recycling products have not been adapted

Applying systematical analysis and transferring methods from other areas of successful recycling procedures i.e. textile recycling in the nonwoven industry may show a promising approach to solve the problem of the low rate of recycling efforts applied to composite waste.

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2. Raw Material Sources for Recycling

Under the given circumstances that still up to 35% waste is produced in composite manufacturing there is a growing focus in the industry on avoiding waste by proper design of the products and waste reduction in processing. However, despite waste optimization the total waste amount grows on worldwide base due to the growing production and use of CFRP products. Therefore the focus of r&d will have to stay on developing suitable recycling strategies and processes in order to face the challenge of optimizing raw material utilization and of course under the aspect that disposal of composite waste is forbidden by law in most of the western countries.

A reasonable analysis of the situation has to start by a proper definition of the different waste specifications, which calls for adapted procedures of recycling processes. We have to differentiate between 3 major groups of composite waste:

- Final product waste (End of Life, defective goods)
- Laminated waste (mainly prepreg waste)
- Dry waste from production (i.e. stacks, fabric waste, roving waste)

Going more in detail means that we have to choose the appropriate recycling procedure not only on the material structure and properties but also reflecting the economics. It is obvious that recycling costs may not exceed the costs of virgin material. For CFRPs this allows a separation of matrix and fibers, while for GRP the biggest economical obstacle is that the costs for separating the fibers and the matrix exceeds the purchasing costs for new glass fibers. When in this case only mechanical separation i.e. milling or impact crushers are possible only compound use of waste is a suitable method but with very limited economical potential (i.e. use as filling material in cement production or building structures).

Due to the high costs of carbon fibers CFRP recycling has a higher potential for textile recycling processes which consequently preserve fiber length. The future of successful recycling applications therefore has to first separate the fibers in the best length saving procedure as this opens up the way of using the recycled fiber again in composite products instead of only using very short fibers i.e. in filling material in plastic molding.

Carbon Fibers show limited “textile” behavior and therefore calls for an adaptation of machines of textile recycling. Carbon is also very sensitive to mechanical stress, which does not allow the application of textile processing without major modifications. As Carbon is also conductive the whole electrical components and control elements of the recycling line has to be properly protected. The high dust creation in mechanical processing calls for special means in order to keep the working elements in proper shape.

Summarizing all these special aspects of carbon products leads to the statement that: Opening should be applied “as much as necessary but as little as possible”! This principle will be the guideline to design a new carbon recycling line.

3. Processing Steps

The adaptation of existing textile recycling processes has to be done based on the above mentioned principles, carefully analyzed and applied to every single process step of converting waste to recycled fibers formed to suitable web structures. As a guideline for adapting this analysis the scheme shown in **Figure 1** will guide us through the following chapters.

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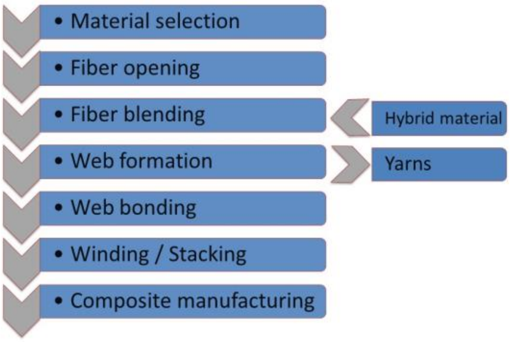

Figure 1. Composite Recycling - technology matrix -

4. Description of Processing Steps

4.1 Waste Preparation

Starting with a proper waste preparation is the foundation for a successful application of recycling procedures. Depending on the sort of waste we have to apply different waste preparation procedures:

4.1.1 Dry waste (manufacturing)

First of all waste parts has to be sorted according to size, length of parts and sort of textile (woven, braided, etc.) to allow specific further processing and proper blending for uniform properties. As a next step a cutting process (lengthwise, crosswise) needs to be applied to allow uniform feeding to the further processes. Finally the preparation for further fiber opening needs to be started.

4.1.2 Hardened waste, (pre)laminated waste

For the separation of fibers and matrix different methods are available depending on the type of composite – either duroplastic or thermoplastic matrix system. Thermical or chemical elimination of resin components by Pyrolysis, Solvolysis or use of supercritical fluids allow the complete separation of fibers from the composite structure. By selection of cut length the fibers are sorted to different end uses, while the conservation of best possible fiber length will allow optimum possible end use properties.

The first step to the mechanical textile recycling process is the uniform and appropriate feeding to the recycling process. This can be done by intermediate storage in form of bales, which can be produced by suitable bale press installations with adapted production features. The bale press allows homogenous material flow, simplifies blending of fibers with different specifications and represents a compact material storage. Alternately direct or by bale laydown the material is then fed to the line by bale openers, which allow a first blending of the fibers. In case of dry composite fabrication waste a cross cutter minimizes and harmonizes waste dimensions then linked to the bale opener by air flow or mechanical feeding.

As a next step blending and mixing units with variable size allow continued blending and storage for smoothening production flow. Especially in case of hybrid material use, where the additional material component is realized in fiber form an optimum blend of the components can be achieved via blending and mixing boxes.

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For carbon waste recycling the proven statement that “proper blending and sorting is mandatory for uniform product properties” becomes true, too.

4.2 Fiber Opening and Blending

In order to create uniform products the opening degree of the carbon waste is decisive to achieve good fabric properties or fiber volume content. Depending on the desired end use a high degree of fiber alignment may be desired for optimum fabric strength as well as an isotropic structure of the fibers in the final product. This feature strongly correlates with the fiber opening degree ideally up to the single filament opening. In textile applications this is achieved by use of tearing and opening machines. Most of these machines have a feeding unit for uniform production and the opening work is done by cylinders with adapted working elements like nose bars, pins or saw tooth wire. Considering the brittle structure of carbon fibers against mechanical stress the opening work is extremely sensitive, as using not modified machines from textile processing will destroy the carbon fibers and a severe fiber damage will be caused. By modifying working gaps, cylinder speed and choosing the optimum working element the right compromise between necessary opening and low fiber damage can be achieved. **Figure 2** shows a modified tearing machine, which was successfully adapted to carbon processing.

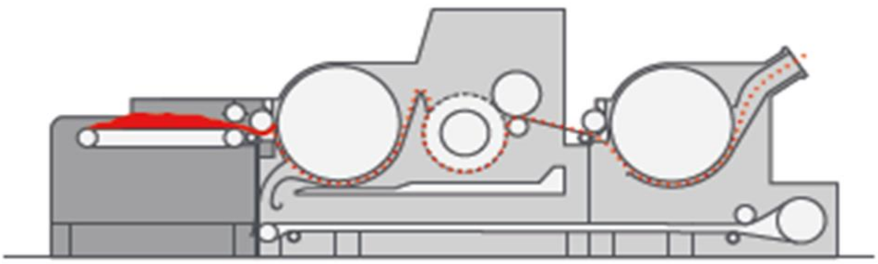

Figure 2. Intensive Fiber Opening (modified tearing)
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4.3 Web Formation

Similar to textile recycling the fabric formation by nonwoven webs is the most suitable process to be considered for carbon recycling, too. As nonwoven processes are the most direct way from fiber to fabric this process combines low production cost with variable fiber design in the final product from light web as 5 g/m² to coarse webs of 5000 g/m², from condensed to open structures and from aligned to isotropic web configuration, all with variable fabric width.

The variability of nonwoven is also characterized by a broad variety of different web formation machines. Especially under the aspect of fiber length, web weight, opening degree and fiber orientation there are four major processes to be considered, which will be described in the next paragraph.

4.3.1 Chute Feeder

This machine (shown as feeding unit in **Figure 3**) is normally used to feed web formation machines like cards or Airlay machines. The opening degree is relatively low and thus the fiber alignment,

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combined with a rather coarse web weight but enabling processing of fibers with higher fiber length. For isotropic structures this process combines a short and low damage process with a uniform web structure for light weight designs with lower requirement of strength properties. This machine is available with useful tools like closed loop control and profiling to enable very good length and crosswise uniformity.

4.3.2 Aerodynamic Card (Airlay)

The aerodynamic card, commonly described as Airlay (**Figure 3**) is a small carding machine using air doffing to a suction belt mainly applied to produce high bulk webs with higher opening degree of the fibers and intensive fiber blending compared to just using the chute feeder. The main additional feature is the possibility to additionally create a 3D-orientation by means of an additional Hi-Loft roller positioned on top of the suction belt in the outlet. Typical products in conventional textile processing are isotropic webs for car interior end use. Similar to this application Airlay makes sense when heading for coarser web weights with isotropic properties in the web. (As an alternative to a separate machine an air doffing unit can also be used in conventional carding to create similar web structures.)

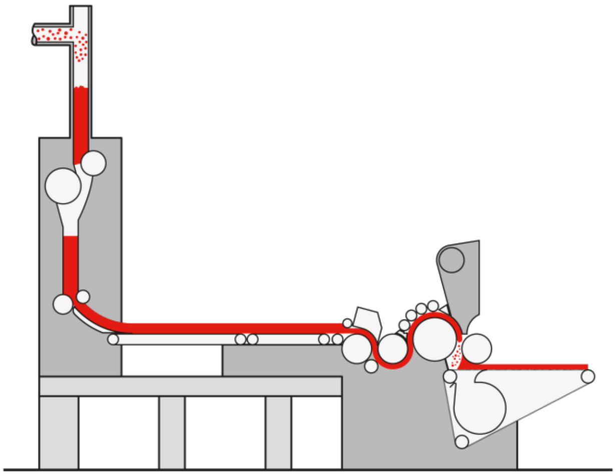

Figure 3. Aerodynamic Web Forming (Airlay) with Chute Feeder
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4.3.3 Carding

Carding is the mainly applied process for producing nonwoven webs and the most universal process compared to all other web forming machines. The machine (**Figure 4**) offers a wide range of processable fibers regarding length and fiber type. The machine provides the highest possible fiber opening and alignment but calls for strong modifications in carbon processing to reduce the risk of fiber damage. As the process is optimized for “typical textile” fibers, carbon fiber processing asks for strong modification regarding roller configuration, speeds, working nips, configuration and execution of working elements, especially wires. First industrial applications show that using carding principal for web formation opens the chance to produce very competitive products regarding web properties but there is still a wide gap open in modifying and optimizing the machine, when you consider the production window for carbon fiber compared to other textile fibers. It also has to be noted that there is a strong correlation between low web weight and achievable orientation of fibers in the web. Therefore as in conventional textile processing higher web weight calls for the crosslapper as an additional machine. But similar as in other nonwoven applications the crosslapper adds useful features

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as enabling higher web weight, adjustable MD:CD ratio in properties, better uniformity and wider fabric width.

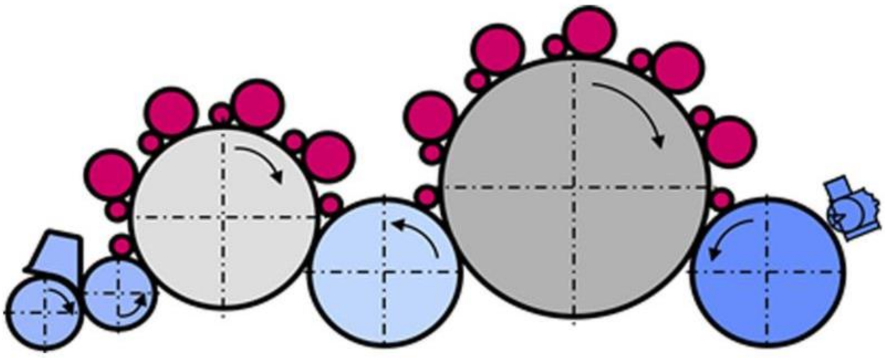

Figure 4. Carding machine
Source and copyright: Dilo Group

4.3.4 Wet Laid Process

As an adaptation of the paper making process wet laid nonwoven machines offer the chance to produce very fine web weights down to 5 g/m². The process shows best performance when processing shorter fibers and offers excellent web uniformity compared to other nonwoven web forming machines. Due to its principle the forming of the web in an emulsion of water and fibers offer a major advantage by eliminating dust creation in the process as well at the same time a disadvantage by the need of an additional energy consuming dryer. There are some first light webs available for decoration purposes with very nice property features.

4.3.5 Selection Criteria

Table 1 shows a first list of selection criteria for the optimum web forming process based on development experience so far available.

Table 1. Web formation principles for carbon waste

Web formation	*Fiber length* (mm)	*Web weight* (g/m²)	*Fiber orientation* (-)	*Fiber opening* (-)
Chute Feeder	< 80	400 - 6000	Low	Low
Airlay	< 120	20 - 5000	Medium; Isotropic	Medium
Card	< 140	20 - 200	High	High
Wet Laid	< 40	5 - 50	Medium	High

4.4 Web Bonding

A specific of nonwoven processing is the fact that the web forming process does not create a structure which is able to carry load of further processing. Therefore a web bonding procedure has to follow web forming in order to allow proper transport to further processing, even when the final bonding is done by composite manufacturing.
There are two suitable bonding principles available:

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Mechanical Bonding can be realized by needling, although this process just uses the same principle as felt needling but with extremely reduced needling intensity just creating a still soft protection needling for transport. Alternately thermobonding can be used for the same purpose.

Table 2 offers some guidelines for selection of the suitable method.

Table 2. Web bonding principles for carbon waste

	NEEDLING	THERMOBONDING
advantage	stress-reduced bonding No additional bonding material Low energy consumption	density stays on constant “seals surface”
disadvantage	creates compacting effect	Additional melt fiber necessary Higher energy consumption

4.5 Make Up

Depending on web weight and thickness semi-finished products makeup can be realized by winding or stacking. Longitudinal and crosswise cutting devices are available in great variety. High wear of cutting knifes needs to be considered.

4.6 Direct Forming

Instead of producing semi-finished products a direct feeding of open fibers into the mold for final processing is an option with some decisive advantages. The process can be applied to products where a molding procedure is the final step of product’s shape forming and calls for a certain minimum web weight in order to ensure a certain uniformity. It is based on the shortest possible process and consequently eliminates primary and secondary waste. Double layers in certain areas of the product or stiffening zones can be realized in direct mode by feeding more material to certain zones of the perforated mold (**Figure 5**).

Uniform feeding is a challenge, where further development efforts may improve product properties and suitable fiber orientation. The cost of molds maybe a limitation factor in certain applications.

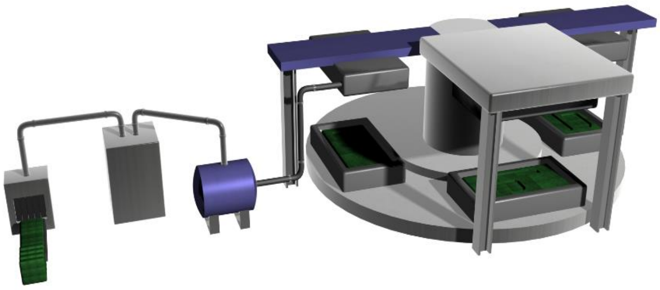

Figure 5. Direct Forming Installation
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4.7 Yarn Processing

The process of yarn manufacturing is more or less identical in regard to preparation and carding until the web take-off unit. But instead of producing a nonwoven web directly the yarn making process calls for additional processes with cost plus and risk of additional fiber damage.

Under the aspect of price pressure on recycled products a yarn formation may only make sense when the final product calls for a strand or yarn like structure, as it is i.e. given in braiding. In any case the yarn forming should not be realized by twisting the fibers to a yarn, as applied in conventional yarn making as twisting causes stress on carbon in its weakest property. Further research needs to be conducted to find out suitable stress released yarn making procedures, preferably no twist on the fibers.

5. Product Development

The final product defines the optimum recycling procedure. Without detailed knowledge about the requirements of the end use a selection of the optimum recycling procedure is hardly possible. Due to the lack of detailed product design rules and lay out simulation for nonwoven structures a product development without extended trials will not lead to new products with optimized processes.

In order to allow fundamental studies a flexible and compact recycling line (**Figure 6**) has been installed at the Institut für Textiltechnik (ITA) Augsburg. Based on intensive research and first industrial experience a lot of modifications were already executed and will allow to find the most proper line configurations and settings for developing the right strategy for suitable products. With this line it is now possible to process carbon waste in a lot of different ways and vary all the necessary properties of semi-finished products in order to achieve optimum base for further processing.

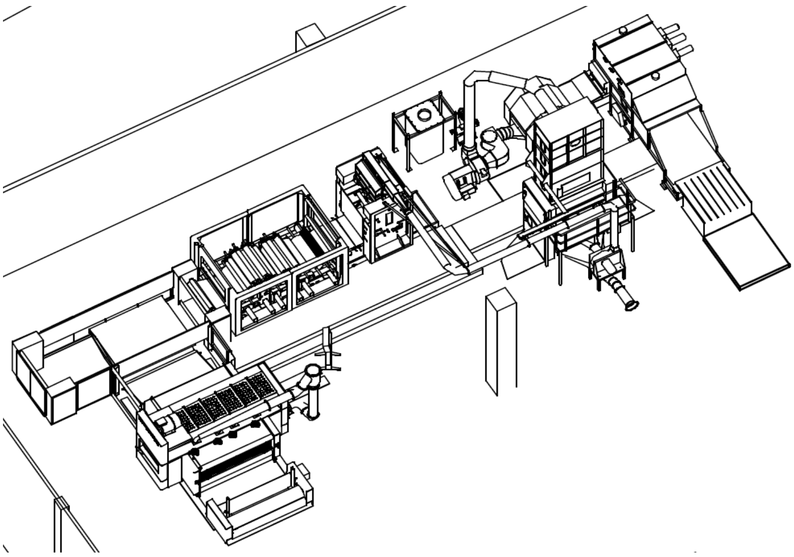

Figure 6. Compact Recycling Line at ITA Augsburg
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Based on the experience so far the following specifications about input material and product properties are needed to allow a successful implementation of this on-process development:

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Type of composite process
- Process (pultrusion, RTM, Tape, etc.)
- Plastic component (thermoplastic, resin)

Orientation of fibers
- aligned
- isotropic

Web weight (g/m²)
Product width (m)
Make up of product (roll goods, stacks, inline)
Hybrids (blends with other fibers)

6. Perspectives

When reflecting the successful use of nonwoven products in applying recycled materials to the car industry the potential of useful product developments can be seen (**Figure 7**) and gives a clear indication where the benefit of using carbon recycled products may lie in the future when further research and development on products and processes will be conducted.

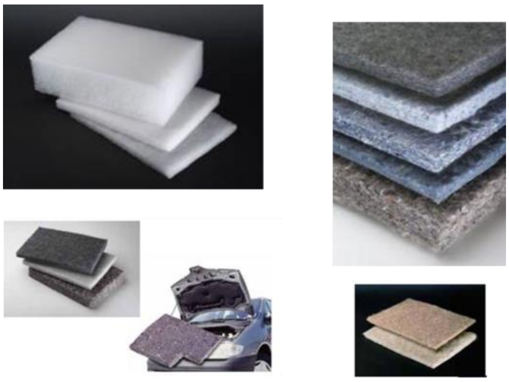

Figure 6. Typical Nonwoven Products from recycled fibers
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