Article

Influences on textile and mechanical properties of recycled carbon fiber nonwovens produced by carding

Frank Manis* [1] and Georg Stegschuster [2]

[1] Fraunhofer Institute for Casting, Composite and Processing Technology IGCV; frank.manis@igcv.fraunhofer.de
[2] Institut für Textiltechnik Augsburg gGmbH; georg.stegschuster@ita-augsburg.de
* Correspondence: frank.manis@igcv.fraunhofer.de

Abstract:

Nonwovens made of recycled carbon fibers (rCF) and thermoplastic (TP) fibers have excellent economic and ecological potential. In contrast to new fibers, recycled carbon fibers are significantly cheaper and the CO2 footprint is mostly compensated by energy savings in the first product life cycle. The next step for this promising material is its industrial serial use.

Therefore the process chain from fiber to composite material is analyzed. Initially rCF length at different positions during the carding process is measured. Thereafter the influence of the TP fibers onto processing, fiber shortening and mechanical properties is evaluated. At last several nonwovens with different TP fibers and fiber volume contents between 15 vol.-% and 30 vol.-% are produced, consolidated by hot pressing and tested by 4-point bending to determine the mechanical values. The fiber length reduction ranges from 20.6 % to 28.4 %. TP fibers cushion the rCF against mechanical stress but hold rCF fragments back due to their crimp. The resulting bending strength varies from 301 MPa to 405 MPa and the stiffness from 16.3 GPa to 30.1 GPa. Design recommendations for reduced fiber shortening are derived as well as material mixtures which offer better homogeneity and higher mechanical properties.

Keywords: Carbon fiber, recycling, nonwoven, carding, hot pressing, Polyamide 6, Polyethylene terephthalate

---

1. Introduction

Composite materials showed a strong increase in their versatility in the recent years as well as a strong increase in demand. Especially the wind energy and aerospace market cannot be imagined without fiber reinforced polymers (FRP) like glass fibers reinforced (GFRP) or carbon fibers reinforced plastics (CFRP). Carbon fibers are widely used because of their high specific strength and stiffness, which are superior to those of conventional metals and glass fiber composites. Therefore carbon fiber reinforced plastics show an increase in demand by 8.84 % (Compound Annual Growth Rate 2010 - 2020) [1]. New production sites are built as well as new applications are found and marketed [1].

Negative impact to usage of this lightweight material is given by its limited recyclability and limited possibility of circularity. Both pre-consumer waste as well as post-consumer waste are increasing and the availability of secondary fibers is higher than the demand for recycled carbon fibers (rCF). Some of the reasons are low or unknown mechanical properties, inhomogeneous material behavior, limited possibility of simulation and a high material price just to name a few. For this reason, the technologies of recycle carbon fibers are under steady investigation for many years starting with the work of Pickering et al. and Pimenta et al. [2-5]. First scientific works were mostly related to the fiber-matrix separation by pyrolysis and oxidation [6-8]. In the last years more papers containing the solvolysis were published [9-12] and lab and medium scale devices were built-up [13-14].

After the fibers are chopped and reclaimed, they can be used for textile processes like carding and wet laid technologies. Those processes are called dry laying and wet laying. The carding process offers a higher technology readiness level (TRL) as well as productivity and many companies have started to rebuilt and change their carding design to improve carbon fiber handling [15-20].

Fiber breakage and unstable textile properties like the coefficient of variation (CV-value) of the area weight or varying fiber volume contents still pose great challenges for the market access of this material.

The main advantages of the nonwoven process are excellent economic efficiency due to high production output and high flexibility regarding properties like area weight, isotropy and degree of compaction. In order to be able to successfully process recycled carbon fibers on a nonwoven line, the line is modified to minimize fiber damage. The compact carding process combines several conversion processes to produce a homogeneous textile surface from a fiber blend.

One major goal of recycling is to keep the fiber length as long as possible to enable future recycling cycles and be able to contribute to a circular economy. Furthermore longer CF can contribute to better mechanical properties of the composite [21, 22]. The minimum fiber length for carding is around 30 mm therefore in this paper this threshold is chosen for the evaluation of the process.

The fibers are successively separated along the process into single fibers, which are parallelized. In technical jargon, those processes are called opening and carding. These processes are carried out by rollers which are covered with a saw-tooth-wire – the clothing. The clothing enhances the grip between fibers and rollers [23]. The carded fibers are finally accumulated on the doffer roller and a coherent, uniform fiber mat forms: the carding web. The carding web builds the basis for the nonwoven fabric. As the area weight of the carding web ranges from only 10 to 40 g/m^2, it is layered and stacked to achieve the desired area weight and improve the handling. The stacked webs are bonded together by needling with a needle loom. The fibres are intertwined by the needles and the resulting frictional connection with the surrounding fibers creates an irreversible bond [24].

The production of needle punched nonwovens has been developed and optimized for thermoplastic and/or staple fibers of natural origin. The use of fiber blend with carbon and thermoplastic fibers offers multiple advantages in the production process. The thermoplastic fibers act as carriers for the carbon fibers, which reduces the fiber length reduction [25]. Furthermore the blending achieves an essential goal of composite manufacturing already during nonwoven production: the impregnation of the matrix material. High-viscosity thermoplastics are typically impregnated into textile surfaces by high pressure and temperature [26]. Nonwovens from carbon thermoplastic fiber blends do not require this step. The thorough mixing during nonwoven formation results in minimal flow paths for the matrix [27].

Nonwovens from rCF can be processed in many ways. If thermoplastic fibers are added to the carding or wet laid process the hybrid nonwovens can be consolidated directly by variothermal hotpressing or isothermal pressing. Pure CF nonwovens are suitable for infiltration processes like resin transfer molding or wet compression molding [28]. Because hybrid nonwovens already have their polymer included, process time and costs can be saved. Furthermore the thermoplastic components are formable and weldable and can be further functionalized by injection molding.

This study is investigating possible improvements for dry-laid nonwovens from recycled carbon fibers on two different levels: fiber and composite. The aims on the fiber level are the investigation of the degree of fiber breakage on the one hand in dependence of the web formation process in the carding machine and the amount of worker stripper pairs. And on the other hand in dependence of the thermoplastic fiber properties as well as their weight proportion in a fiber blend with carbon fibers. The aims on the composite lever are the investigation of the mechanical influence of the fiber type as well as the fiber volume content on the mechanical properties.

2. Materials and Methods

The materials and methods used to determine the influences on the fiber level and the composite level are presented.

2.1 Material and Method for the effects of webv formation and machine setup on carbon fiber shortening

Two kinds of carbon fiber are used for the trials. Carbon fibers from dry cut processes and pyrolized carbon fibers. The CarboNXT chopped 60,000 NP5 R (VCF) from CarboNXT GmbH, Stade, is a carbon fiber from dry cut and still has an intact sizing attached from the carbon fiber production. These fibers mainly originate from processing waste by textile fabric production. The carbon fiber VCF is used in two different length classes that differ in the amount of cutting procedures:

- 3-fold cutting by guillotine cutting (see Figure 1) with 60 mm blade distance (VCF3x)
- 1-fold cutting by guillotine cutting with 60 mm blade distance (VCF1x)

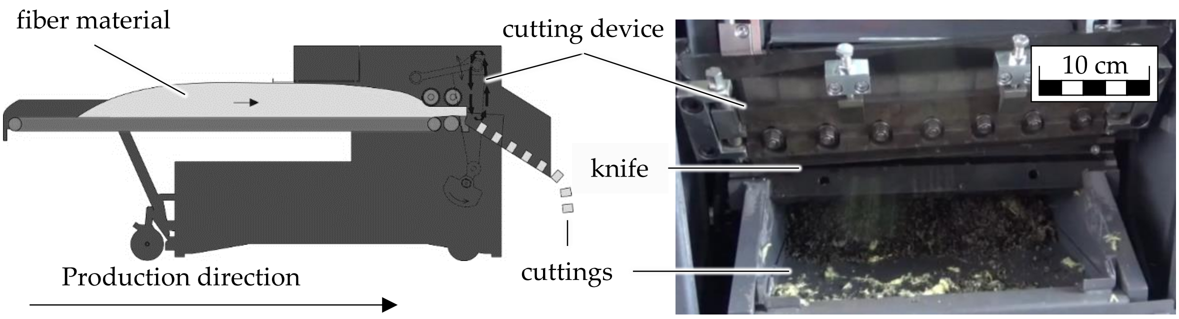

Figure 1. Schematic representation of the guillotine cutting [29].

The pyrolized carbon fiber is a Carbiso C SM45R 60/90 (PCF) from the ELG Carbon Fibre Ltd., Coseley, England. According to the manufacturer the fibers are between 60 mm and 90 mm long and do not have any sizing left on the fibers.

Four thermoplastic (TP) fibers are used in the study. The types P300 and P301 are polyamide 6 (PA6) fibers with different textile properties and are produced by the company EMS-CHEMIE HOLDING AG, Dormat/Ems, Switzerland. In addition two polyethylene terephthalate (PET) fibers type TREVIRA® 290 from Trevira GmbH, Bobingen, Germany, are employed. The PET-fiber properties differ in length, fineness and crimp and are summarized in Table 1. Fineness is a measure for the weight of textile fibers in regard to their length. The unit dtex describes the weight in gram per 10,000 km of fiber length. The crimp is a unit for the amount of curls per centimeter that a textile fiber possesses. Those curls lead to a better grip between fibers and wires.

Table 1. Thermoplastic fibers and their textile properties.

Type	Length [mm]	Fineness [dtex]	Crimp [B/cm]	Code
P300	40	1.7	8	PA6-40-1.7-8
P301	60	6.7	6	PA6-60-6.7-6
TREVIRA® 290	60	6.7	4	PET-60-6.7-4
TREVIRA® 290	38	1.7	6	PET-38-1.7-6

The fibers are processed at ITA Augsburg on the nonwoven line KC11 2-4 SD / MEK 11 from Dilo Systems GmbH, Eberbach with two different trial setups. First three different fiber blends are processed with the nonwoven line using a fixed set machine parameters to determine the influence of the nonwoven formation on the carbon fiber length.

Therefore the carbon fiber, which is cut three times VCF3x is processed pure and as a blend with 60 wt% of the polyamid6 fiber PA6-40-1.7. The pyrolized carbon fiber PCF is processed as a blend with 60 wt% of the PA6-40-1.7 as well. The materials and the ratio of mixture are shown in Table 2.

Table 2. Processed fiber blends for fiber length measurement regarding web formation.

Carbon fiber	wt%	TP fiber	wt%	Worker-Stripper Pair	Material Code
VCF3x	100	-	-	3	VCF3x
VCF3x	40	PA6-40-1.7-8	60	3	VCF3x_PA6
PCF	40	PA6-40-1.7-8	60	3	PCF_PA6

The influence of the web formation by the carding machine is analyzed by measuring the fiber length at four positions along the process. The fiber sampling positions as well as the machine setup are shown in Figure 2.

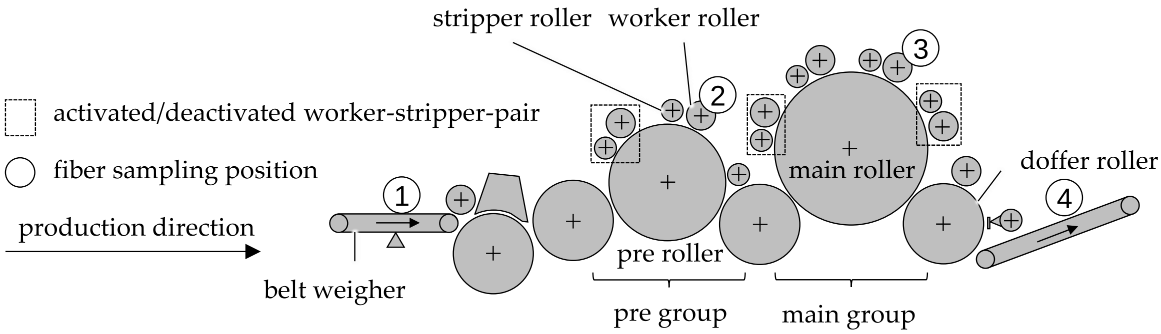

Figure 2. Schematic representation of the carding machine and sampling positions [34].

The fiber sampling positions are the belt weigher, the second worker roll of the pre group, the third worker roll of the main group and the web.

In a second trial two different machine setups are compared where three and six worker stripper pairs are employed. Between the worker rollers and the main rollers the fibers are carded. Carding is a trade-off between fiber orientation and fiber damage, why the amount of worker-stripper-pairs is of significant importance. To analyze the influence samples are taken on the belt weigher and the web for fiber length measurements. The influence of the machine setup is investigated with pure carbon fibers and in a blend with thermoplastic fibers. The carbon fiber, which is cut once, VCF1x is processed pure with three and six active worker-stripper-pairs. Furthermore blend with 10 wt% of the of the polyamid6 fiber PA6-60-6.7-6 is processed with six active worker-stripper-pairs. At last a trial is conducted which combines a high proportion of 60 wt% thermoplastic fibers and three worker-stripper-pairs to investigate the least amount of fiber damage.

Table 3. Processed fiber blends for fiber length measurement regarding machine setup and proportion of thermoplastic fiber of the blend.

Carbon fiber	wt%	wt% of the thermoplastic fiber	Worker-Stripper Pair	Material Code
VCF1x	100	-	3	VCF1x_100wt%_3
VCF1x	100	-	6	VCF1x_100wt%_6
VCF1x	90	10	6	VCF1x_90wt%_6
VCF1x	40	60	3	VCF1x_40wt%_3

The length of the carbon fibers from each position is measured by the two-tweezers method according to DIN 53808-1 [30]. The sample size includes 200 measurements. The results are sorted into length classes of 5 mm width. Thus the mean fiber length and the fiber length distribution are determined. Due to the manual procedure and the subjective selection of carbon fibers by hand as well as the fracture behavior of the recycled carbon fibers under mechanical load, this procedure is prone to errors. Therefore the fiber length measurement is carried out by a designated person in order to minimize the subjective influence during testing. Since individual carbon fibers break easily during handling with tweezers, the measuring concentrates on rovings – carbon fiber bundles consisting of several thousand individual fibers – instead (Figure 3).

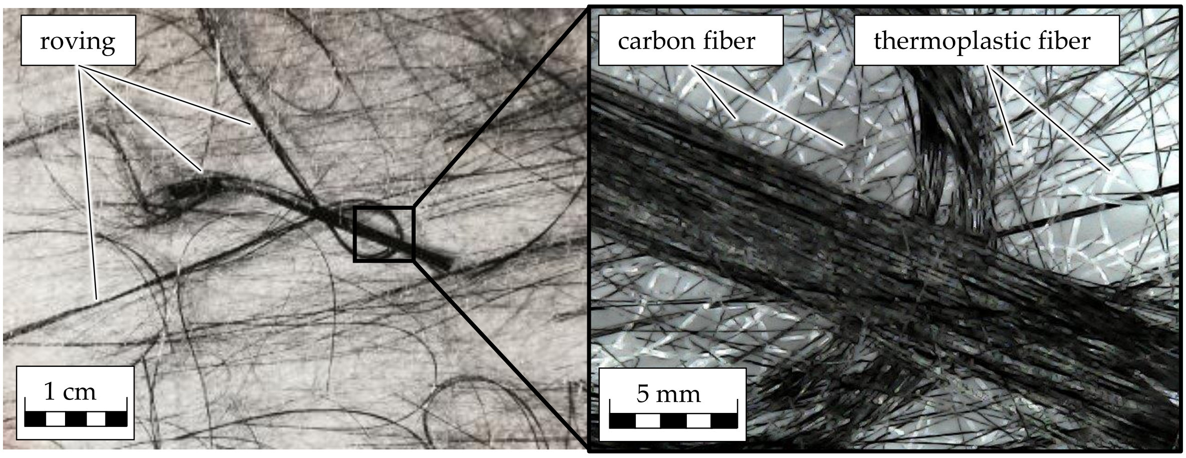

Figure 3. Schematic representation of the carding machine and sampling positions [34].

In order to assess the significance between the fiber lengths at different positions statistical methods are employed. The Kolmogorov-Smirnov test is used to determine whether the data is normally distributed, which does not apply to the fiber length measurement. Therefore the Mann-Whitney test is used [33]. The probability of the null hypothesis (pH0) is calculated. Zero hypothesis (H0) states that the calculated mean values do not show any significant difference between them. The alternative hypothesis (H1) states that the calculated mean values show a significant difference between them. The significance level is 5 %. If the probability of occurrence of the null hypothesis (pH0) is less than 5% the significance level is fulfilled and the null hypothesis can be rejected.

2.2. Material and Methods for bending properties of rCF nonwoven panels

The second part of our investigation focuses on the composite properties of carbon fiber nonwoven reinforced plastics. The nonwovens are processed to panels at Fraunhofer IGCV in Augsburg. A complete list of the used materials is shown in Table 3. The variable parameters are carbon fibers from cut VCF and pyrolized carbon fibers PCF, the amount of worker-stripper-pairs, the properties of the thermoplastic fibers and the proportion of thermoplastic fibers of the blends.

Table 3. Parameters of hybrid nonwovens for the hot pressing process.

Carbon fiber	Vol.-% (rCF)	TP fiber	Worker-stripper-pairs	Code
PCF	32	P300	6	PCF_P300_WS6
PCF	33	P300	3	PCF_P300_WS3
PCF	32	P301	3	PCF_P301_WS3
PCF	30	TREVIRA® 290	3	PCF_T290_WS3
VCF1x	15	TREVIRA® 290	3	15%_VCF1x_85%_PET
VCF1x	18	TREVIRA® 290	3	18%_VCF1x_82%_PET
VCF1x	25	TREVIRA® 290	3	25%_VCF1x_75%_PET
VCF1x	29	TREVIRA® 290	3	29%_VCF1x_71%_PET

A LZT-OK-130-L press from the company Langzauner GmbH, Lambrechten (AUT), with a maximum force of 1,370 kN was used to manufacture 2 mm thick samples which are mechanically characterized afterwards. The TK 350 mm x 350 mm tooling was used for the production of the samples. For PA6 and PET hybrid nonwovens a pressing temperature of 290°C was set. The temperature was controlled at the top and bottom part of the tooling as well as inside the sample. The maximum deviation of Temperature is about 10 K. For the pressing a variothermal process was used starting at room temperature and compressing the material with 50 kN (4 bar). Afterwards the material is heated until it reached the maximum temperature. Then the maximum pressure up to 50 bar was applied to the material. In dependence of fiber volume content, homogeneity and polymer viscosity those parameters were slightly changed to achieve the optimal result. After the consolidation the thickness of each panel was measured and the surface quality was evaluated. If the panel met the required quality criteria, it was used for mechanical testing.

After the consolidation the samples were cut from the panel by water jet cutting. Ten samples in 0°, +45°, -45° and 90° were cut from the panel. Six were used for the bending test. The others were used for the fiber volume content determination. The bending tests were carried out according to DIN EN ISO 14125 and in compliance with the 4-point bending set-up. Material class II was assumed and therefore samples of 40 mm x 15 mm x 2 mm manufactured. After the testing the average value as well as the standard deviation were calculated. Broken samples were used for cross section images to gather more information regarding the quality of the impregnation.

3. Results

The results are discussed in two chapters. First the influence of the web formation, machine setup and proportion of thermoplastic fibers of the blend are presented. The second part shows the results for the investigation of the mechanic properties of nonwoven reinforced plastics in regard to the carbon fiber raw material, the amount of worker-stripper-pairs, the properties of the thermoplastic fibers and the proportion of thermoplastic fibers of the blends.

3.1. Effects of process step and machine setup on the shortening of carbon fibers

The results of the fiber length measurement are shown in Table 4. The average carbon fiber length prior to the carding process ranges from 59 mm to 62.3 mm with more than 72.6 % of fibers being over 30 mm long. During the process the fibers lose between 20.6 % up to 28.4 % of length. Pure carbon fibers and pyrolized carbon fibers show a higher reduction in length. The addition of thermoplastic fibers reduces the fiber shortening by almost 28 % for VCF.

Table 4. Fiber length of VCF, VCF_PA6 and PCF_PA6.

Parameter	Avg. starting length	Avg. length in the web	Length reduction	Fibers over 30 mm (start)	Fibers over 30 mm (web)
VCF	62.3 mm	44.6 mm	28.4 %	78.6 %	71.6 %
VCF_PA6x	62.3 mm	46.0 mm	20.6 %	72.6 %	69.2 %
PCF_PA6	59.0 mm	42.7 mm	27.6 %	75.6 %	63.2 %

The amount of fibers over 30 mm decreases for all tested blends during the process. The VCF_PA6 showing the least reduction (3.4 %) and PCF_PA6 showing the highest reduction (12.4 %).

Figure 4 features the staple fiber diagrams of the three different blends. The optimal length for the used nonwoven process is between 30 mm and 90 mm. The curves for VCF3x, VCF3x_PA6 and PCF_PA6 show a shift to the left with consecutive positions (pos.) indicating a loss in fiber length due to the mechanical stress exerted onto the fibers by the carding process. The VCF3x graphs show a strong left shift from pos. 1 to pos. 2 for fibers above 40 mm. The pos. 2 and pos. 3 are similar for fibers below 70 mm. Above this threshold the amount of longer fibers is reduced. From pos. 3 to pos. 4 a distinct decrease is observed between 35 mm and 60 mm and the amount of longer fibers decreases even further. All changes are significant as stated in Table 5 except for pos. 2 to pos. 3, which are almost identical.

The graphs for VCF3x_PA6 indicate an overall lower left shift. Between pos. 1 and pos. 2 differences occur only above 70 mm and are not significant. The thermoplastic fibers show a clear cushioning effect against fiber damage at this specific position. Pos. 3 and pos. 4 are very similar and almost no further reduction in fiber length occurs. The difference between the consecutive positions is not significant (Table 5).

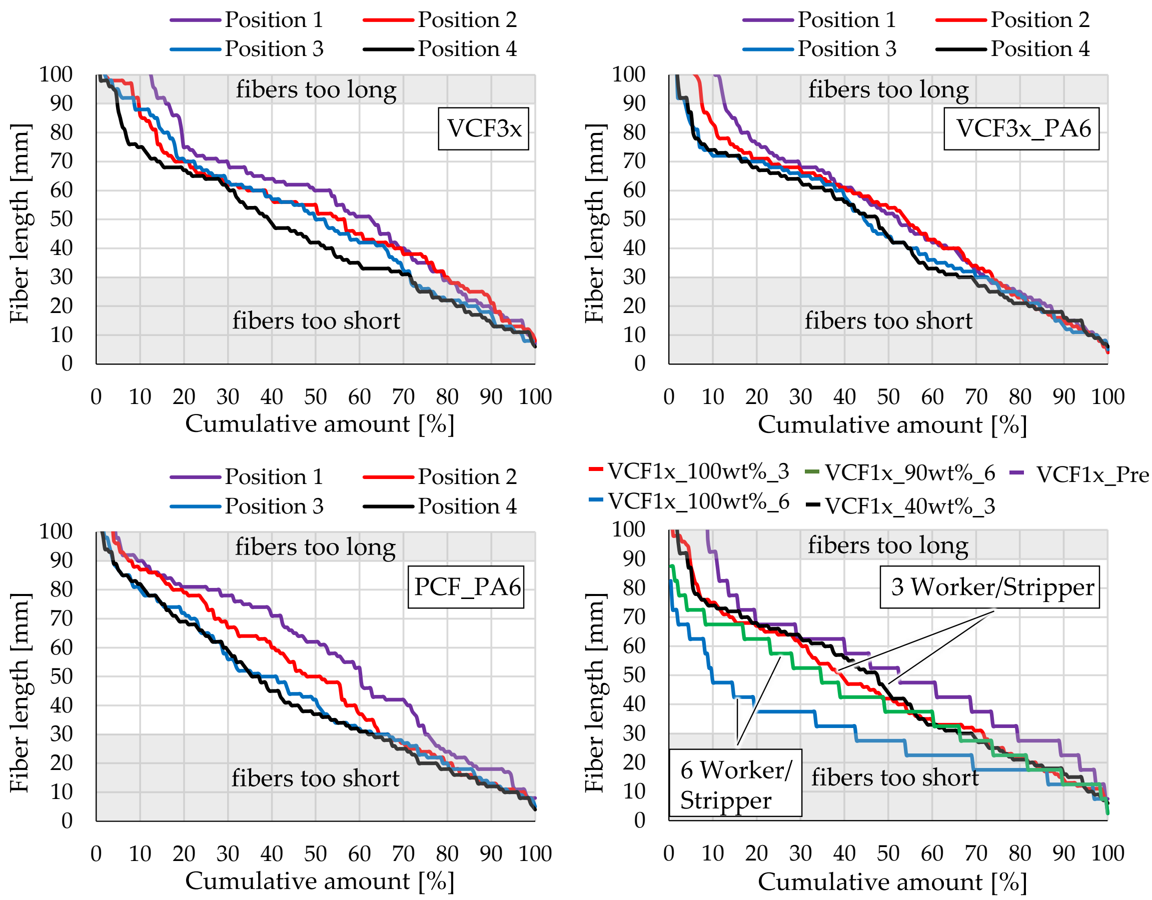

Figure 4. Staple fiber diagram for VCF and VCF_PA6 and PCF_PA6 and fibers processed by different machine setups.

The length reduction is greatly reduced and the doffing between pos. 3 and pos. 4 shows almost no shortening of the fibers. At the same time more fibers are below 30 mm. The reason is the crimp of the thermoplastic fibers. Short carbon fibers are held back in the web and the suction system of the carding machine extracts lesser short fibers in the mixture.

Table 5. Statistical significance between the fiber lengths of the positions (Significant difference indicated as "+", no difference indicated as "-").

Parameter	pos. 1 to pos. 2	pos. 1 to pos. 3	pos. 1 to pos. 4	pos. 2 to pos. 3	pos. 2 to pos. 4	pos. 3 to pos. 4
VCF3x	+	+	+	-	+	+
VCF3x_PA6x	-	+	+	-	-	-
PCF_PA6	+	+	+	-	+	-

PCF_PA6 has longer fibers then VCF. The reduction from pos. 1 to pos. 2 is visible by a prominent left shift for all fibers shorter than 80 mm. Fibers above are not affected. A shortening between pos. 2 and pos. 3 is visible for fibers above 30 mm. Nevertheless, no significant difference can be proven. Pos. 3 and pos. 4 are almost identical.

The diagram at the lower right presents the fiber lengths before and after the nonwoven process using different machine setups. The processing of the pure carbon fiber VCF1x_100wt%_6 with six active pairs of workers and strippers exhibits an average fiber length reduction of 49 %. The processing with three worker stripper pairs leads to a length reduction of 28.4 %. The addition of thermoplastic fibers reduces the shortening further to 21.5 %. The lowest length reduction of 20.6 % is achieved with the blend of 60 wt% thermoplastic fibers and only three active worker-stripper-pairs.

3.2. Mechanical bending test results of rCF nonwoven panels

The produced panels were tested by 4-point bending. The results of each test were used to calculate an average mechanical value in each of the four directions and its standard deviation. For the investigation of the orientation and isotropy, different approaches can be found in literature. In this paper, the orientation ratio of a nonwoven material is described as the ratio of the highest average stiffness divided by the lowest. For carded material that usually means bending strength in 90° direction σ_{90° divided by bending strength in 0° direction σ_{0° because of the higher orientation in 90° due to the cross lapping process. For the investigation the average values were calculated by the mean values of all four testing directions (0°, +45°, -45° and 90°) and compared to the ratio of the 90° value divided by the 0° value. Those values show the same order of magnitude, therefore the 90° to 0° average value was used in this study. The influence of the fiber volume content was investigated. Therefore the mechanical properties of the samples were not normalized to a fixed fiber volume content, which is usually done with a linear recalculation to be able to directly compare samples of different fiber content.

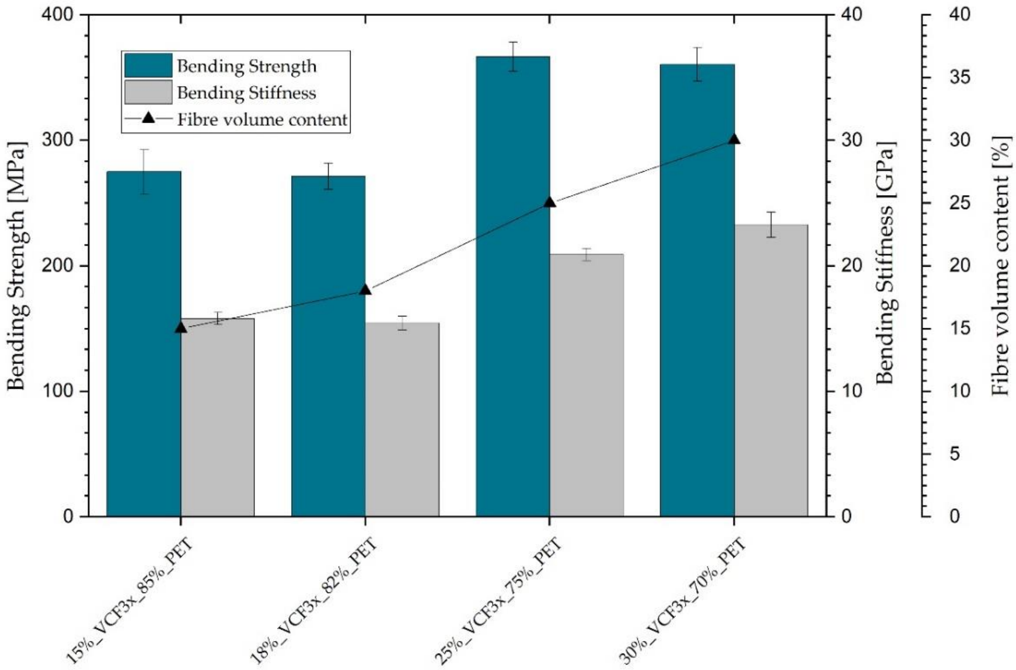

Figure 5. Bending strength and bending stiffness of four PET nonwoven with 15%, 18%, 25% and 30% fiber volume content.

The investigated PET materials (figure 5) have a fiber volume content of 15 %, 18 %, 25 % and 30 %. The properties of the 15 % and 18 % material are very similar. This similarity highlights that the deviation of the material is higher than the theoretical increase of performance by adding 3 % of carbon fiber. With a higher fiber volume content of 25 % the stiffness and strength increase by 32 % - 33 %. The material with 30 % content of fibers does however not show any further increase of its strength and a slight increase in stiffness. Overall a stiffness of 15.8 GPa for the 15 % material and 23.3 GPa for the 30 % FVC material can be reported. The bending strength shows a minimum of 271 MPa and a maximum value of 366 MPa for the 18 % and 30 % material, respectively. In addition to the mechanical properties cross section images are made to determine the quality of impregnation and fiber breakage (Figure 6).

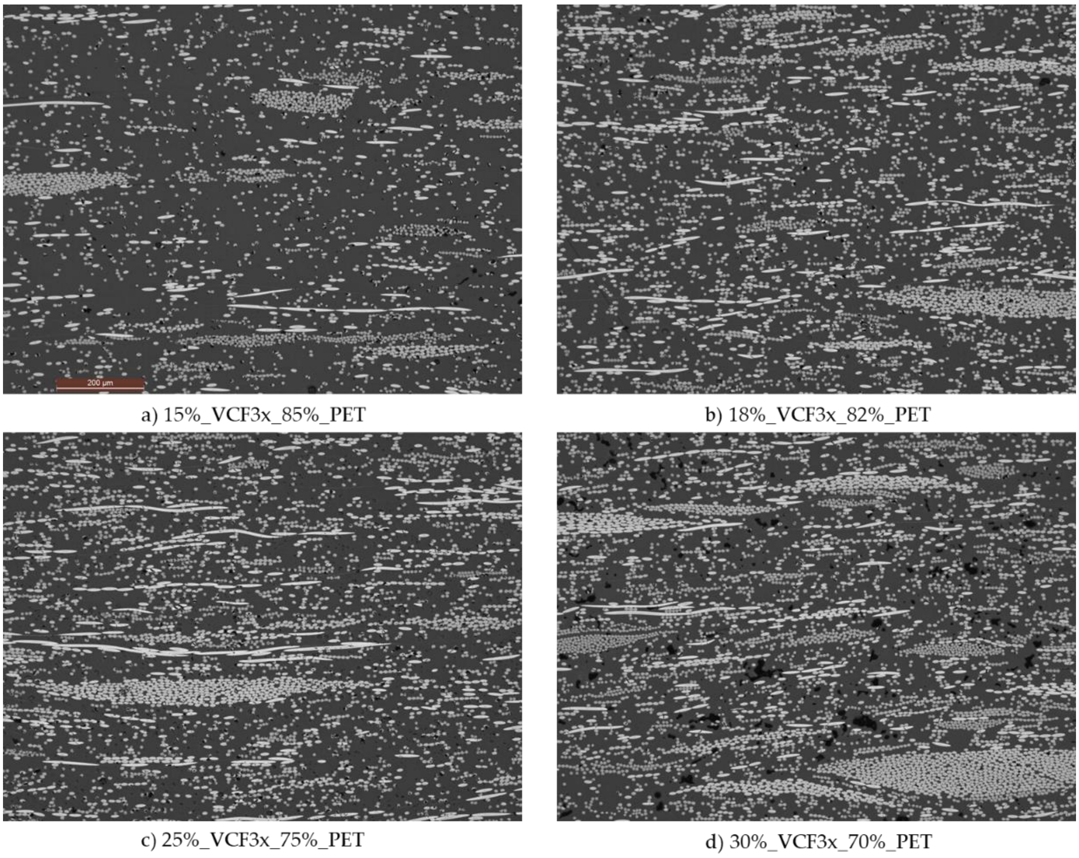

Figure 6. Cross section images of PET nonwoven with different fiber volume contents. a) 15%, b) 18%, c) 25% and c) 30% fiber volume content.

Besides the investigation of the FVC influence, the effect of different textile properties of the fibers as well as different machine setups on the mechanical properties of nonwoven reinforced composites were evaluated. Four different polymer fibers blended with the same fiber volume content of PCF were used to manufacture nonwovens. The blends are shown in Table 6. The materials were used for sample production by hotpressing and mechanical characterization by 4-point-bending. Figure 7 shows the bending strength and bending stiffness of those materials. The axis of the strength is zoomed in to highlight the effect. The illustrated values are average values of 0° und 90° direction. The PCF_P300_WS6 fiber blend shows the overall lowest properties with 336 MPa bending strength and 19.5 GPa bending stiffness. The reduction of worker stripper pairs from six to three leads on average to an increase of bending strength by 4.4 % to 351 MPa and to an increase of bending stiffness by 1.5 % to 19.8 GPa. By changing the textile properties of the thermoplastic fibers – fiber length, fineness and crimp – an increase to 358 MPa (+6.5 %) for strength and an increase to 20.9 GPa (7.2 %) for stiffness is achieved. The PA6 materials have a similar fiber volume content so that it can be assumed that there should be no influence on the mechanical properties according to the results in the previous trials. Compared to PA6 the use of PET strongly increases the average bending stiffness to 25.6 GPa. This material also has a slightly lower fiber volume content so that the potential of the use of PET for stiffness driven applications is even higher. The strength could not be increased by the use of PET fibers however and the average value is with 355 MPa even lower than PCF_P300. In cross direction (90°) the average tested value was 30.1 GPa and in machine direction 21.2 GPa. The orientation ratio calculates to 1.42 for the PET/rCF nonwoven. In comparison the PCF_P300_WS6 shows an almost isotropic behavior with an orientation ratio of 1.13. The orientation ratio is increased to 1.56 by changing PA6 properties using fiber type P301, which is longer, less fine and less crimped. Longer, thicker and less crimped fibers not only increase the overall properties but also the orientation degree of the web and therefore influence the overall nonwoven orientation and orientation ratio.

Table 6. 0° und 90° properties of nonwoven by using different polymer types.

Material code	Bending strength 0° [MPa]	Bending strength 90° [MPa]	Average strength [MPa]	Bending stiffness 0° [GPa]	Bending stiffness 90° [GPa]	Average stiffness [GPa]
PCF_P300_WS6	328	344	336	18,3	20,7	19,5
PCF_P300_WS3	341	360	351	19,2	20,4	19,8
PCF_P301_WS3	301	415	358	16,3	25,4	20,9
PCF_T290_WS3	305	405	355	21,2	30,1	25,6

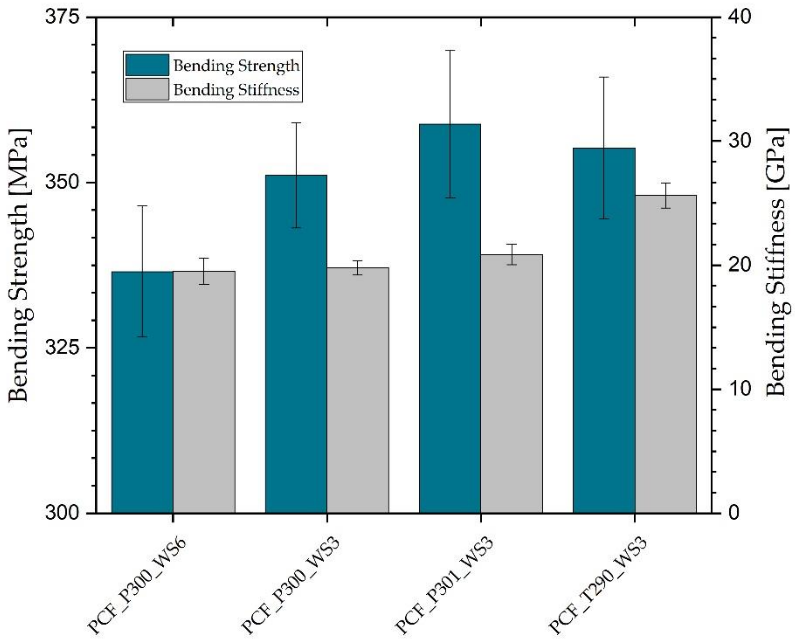

Figure 6. Bending Strength and Bending Stiffness of different machine set-up and different TP fibers. (P300 and P301 are PA6 fibers and T290 the PET fiber). WS3 and WS6 equals the number of worker and stripper pairs within the carding line.

4. Discussion

Carbon fibers always undergo a shortening by the carding process. The amount of reduction depends heavily on the carbon fiber type, if they are blended with thermoplastic fibers and the machine setup.

A study by Dauner et al. investigated the length reduction by position of the card [25]. Although the setup of the nonwoven machine is not explicitly stated, the carding is similar and roller cards are constructed in similar ways. The results are compared to the current findings in Table 7.

The length reduction is strongest at the beginning of the carding machine for all measured fibers and blends. The length reduction in comparison to previous works shows a lower overall shortening. Concerning fiber blends the subsequent positions are each reduced in their effective shortening. Pure VCF however are shortened by only 4.6 % from pos. 2 to pos. 3 but 10.8 % to pos. 4, reversing the effect.

Pure carbon fibers and pyrolized carbon fibers show a higher reduction in length. The pyrolized fibers are more brittle after the reclamation process and miss the friction reducing sizing. The thermoplastic fibers in the blends have two opposite effects. On the one hand the fibers function as a cushion for the carbon fibers and reduce fiber damage especially for longer carbon fibers. The effect is shown by the addition of 10 wt% TP fibers in different machine setups, which lead to a reduced fiber shortening up to 58 %.

On the other hand the crimped thermoplastic fibers keep shorter carbon fibers in the web. Therefore increasing the amount of short fibers which are otherwise removed by the suction system of the carding machine. The decreasing amount of fibers over 30 mm proves this effect, which is highest for VCF and significantly lower for the blends with thermoplastic fibers. This could also be the reason for the reversed amount of shortening by position observed for the processing of VCF.

Table 7. Length reduction by position in percent.

	Pos. 1 to pos. 2	pos. 2 to pos. 3	pos. 3 to pos. 4
Dauner et. al. [25]	33.3 %	16.7 %	8.0 %
VCF3x	15.9 %	4.6 %	10.8 %
VCF3x_PA6	11.1 %	9.1 %	1.7 %
PCF_PA6	14.2 %	13.0 %	3.0 %

Another key finding is the positive influence of less worker-stripper-pairs on the fiber length. With three worker-stripper-pairs the length reduction is decreasing substantially while the mechanical results do not show lower orientation values. In fact the mechanical values get higher as shown in Figure 6. The recommendation for the processing of carbon fibers by the carding process is therefore the reduction of worker stripper pairs to a suitable minimum as well as the addition of thermoplastic fibers whenever possible.

The comparison of the measured bending properties in Figure 5 points out, that an increase of the bending strength as well as the bending stiffness occur due to a rising fiber volume content. That fits to the Voigh-Reuss-Hill assumption of an isotropic material [31, 32]. It was shown that a rising fiber volume content has an influence on the mechanical properties especially in terms of bending load. But the observed effect is not always linear and therefore does not follow the rule of mixture for fiber reinforced polymers. One reason is that the deviation of mechanical properties is strongly influenced by the carbon and thermoplastic fiber properties as well as the carding adjustments and is not only based on the principles of load distribution onto the reinforcement fiber. By increasing the FVC from 15 vol.-% to 30 vol.-% of carbon fibers the strength can by increased by 33 % of their original strength and the stiffness by 50 % of its original value. Still the materials with 25 vol.-% show a similar mechanical behavior than the 30 vol.-% material, which proofs that the strength and stiffness are limited. A similar effect was shown by Pickering et al. [3]. He also pointed out that the stiffness of a nonwoven web can be increased by fiber volume content in a linear correlation in certain limits. On the other hand the strength starts to drop at a critical fiber volume content. His measurements were applied to a thermoset material and are however not completely transferable to this thermoplastic nonwoven study. One reason for the non-linearity of correlations could be because of the infiltration quality by the thermoplastic fibers within the hot pressing route. Textile TP fibers have relatively high viscosities due to the spinning process. In the pressing process the polymer chains need to be melted and the viscosity should be reduced as much as possible to achieve a good impregnation behavior. With a higher fiber volume content the isotropic nonwoven material has a lower in-plane permeability and is therefore harder to infiltrate. This leads to dry spots and fiber shorting by pressing onto dry fibers that are not embedded by the resin. This effect can be seen by the cross section images in Figure 6. The 15 %, 18 % and 25 % material does not show many pores but the 30 % materials show a higher density of fibers as well as a higher amount and size of voids within the material cross section.

By increasing the orientation ratio the in-plane permeability can be increased and higher fiber volume contents could be possible. Within the project MAI CC4 Carina [19, 20] the project partners were investigating the correlation of the orientation ratio, the fiber volume content and the mechanical performance. It was shown that up to 38 vol.-% fiber volume content is possible and the mechanical properties can be further increased. However, there are other complications in the thermoplastic processing route for such high fiber volume contents. By using a thermoset polymer or TP powder polymer the infiltration can be improved and higher fiber volume contents are achievable.

The second mechanical investigation in this study is the influence of different TP fiber properties on the bending properties. By the reduction of the worker and stripper pairs the composite strength is increased by 4.5 %. Changing the textile properties to thicker, longer and less crimped fibers the orientation ratio of the web and the nonwoven can be strongly increased. Also the average strength can be increase slightly by 1.9 % and the stiffness by 5.5 %. By using PET instead of PA6 the stiffness is improved by 22.4 %, while the strength stays on the same level. PET exhibits a higher stiffness in comparison to PA6, which also transfers to improved mechanical properties of PET nonwoven panels compared to PA6 nonwoven panels. The high availability of recycled PET and circularity could prefer PET over PA6 for the material choice of future sustainable materials. In conclusion it is shown that the choice of polymer, as well as textile properties and the machine setup have a strong influence on the mechanical properties of nonwoven reinforced composites.

The knowledge of suitable carding and fiber properties leads to the production of enhanced nonwovens. One major issue that has to be solved in future research projects is the high degree of variation in area weight as well as material distribution within blends. Looking forward the industrial serial application and production has to be proven and processing parameters need to be optimized even further.

Author Contributions: Conceptualization, Georg Stegschuster and Frank Manis; methodology, Georg Stegschuster and Frank Manis; validation, Georg Stegschuster and Frank Manis; formal analysis, Georg Stegschuster and Frank Manis.; investigation, Georg Stegschuster and Frank Manis; resources, Georg Stegschuster and Frank Manis; writing—original draft preparation, Georg Stegschuster and Frank Manis; writing—review and editing, Georg Stegschuster, Frank Manis, Stefan Schlichter and Jakob Wölling; visualization, Georg Stegschuster and Frank Manis; project administration, Frank Manis (Project leader) and Georg Stegschuster (Work package textile); funding acquisition, Georg Stegschuster and Frank Manis. All authors have read and agreed to the published version of the manuscript.

Funding: This research originates from the project MAI CC4 CaRinA (Carbonfaser Recyclingwerkstoffe für industrielle Anwendungen) which was kindly funded by Bayerisches Staatsministerium für Wirtschaft, Landesentwicklung und Energie under grant number 2-NW-1707.

Acknowledgments: We like to thank Christina Aust and Petra Amann for their great support with all their experience in testing of composites. Furthermore we like to thank Werner Münch, Dajan Kheder, Matthias Abbt and Christoph Klement for their support in producing nonwovens and counting vast numbers of fibers. They greatly enhanced the quality of this study with all their support. Our gratitude to the company Dilo Machines GmbH, Eberbach for the generous provision of a complete nonwoven line as well as their unwavering technical support.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Sauer, M. Composite United e.V. Market Overview, 2020.
2. Pickering, S. Recycling technologies for thermoset composite materials—current status, *Composites: Part A* **2006**, A37, 1206-1215. https://doi.org/10.1016/j.compositesa.2005.05.030
3. Pickering S. J.; Liu Z.; Turner T. A.; Wong K. H. Applications for carbon fibre recovered from composites. *IOP Conf. Ser.: Mater. Sci. Eng* **2016**, 139, 12005. DOI: 10.1088/1757-899X/139/1/012005
4. Pimenta S.; Pinho S. T. The effect of recycling on the mechanical response of carbon fibres and their composites. *Composite Structures* **2012**, 94 (12), 3669–3684. https://doi.org/10.1016/j.compstruct.2012.05.024
5. Pimenta S. Toughness and strength of recycled composites and their virgin precursors. Dissertation, Imperial College London; 2013. https://doi.org/10.25560/11083
6. Park J. M.; Kwon D. J.; Wang Z. J.; Gu G. Y.; DeVries K. L. Effect of thermal treatment temperatures on the reinforcing and interfacial properties of recycled carbon fiber–phenolic composites. *Composites Part A: Applied Science and Manufacturing* **2013**, 47, 156–164. https://doi.org/10.1016/j.compositesa.2012.12.002
7. Nahil M. A.; Williams P. T. Recycling of carbon fibre reinforced polymeric waste for the production of activated carbon fibres. *Journal of Analytical and Applied Pyrolysis* **2011,** 91(1), 67–75. https://doi.org/10.1016/j.jaap.2011.01.005

8. López F. A.; Rodríguez O.; Alguacil F. J.; García-Díaz I.; Centeno T. A.; García-Fierro J. L. Recovery of carbon fibres by the thermolysis and gasification of waste prepreg. *Journal of Analytical and Applied Pyrolysis* **2013**, 104, 675–683. https://doi.org/10.1016/j.jaap.2013.04.012
9. Greco A.; Maffezzoli A.; Buccoliero G.; Caretto F.; Cornacchia G. Thermal and chemical treatments of recycled carbon fibres for improved adhesion to polymeric matrix. *Journal of Composite Materials* **2013**, 47(3), 369–377. https://doi.org/10.1177/0021998312440133
10. Iwaya T.; Tokuno S.; Sasaki M.; Goto M.; Shibata K. Recycling of fiber reinforced plastics using depolymerization by solvothermal reaction with catalyst. *Journal of Materials Science* **2008**, 43(7), 2452–2456. https://doi.org/10.1007/s10853-007-2017-8
11. Xu P.; Li J.; Ding J. Chemical recycling of carbon fibre/epoxy composites in a mixed solution of peroxide hydrogen and N,N-dimethylformamide. *Composites Science and Technology* **2013**, 82, 54–59. https://doi.org/10.1016/j.compscitech.2013.04.002
12. Morin C.; Loppinet-Serani A.; Cansell F.; Aymonier C. Near- and supercritical solvolysis of carbon fibre reinforced polymers (CFRPs) for recycling carbon fibers as a valuable resource: State of the art. *The Journal of Supercritical Fluid*s **2012**, 66, 232–240. https://doi.org/10.1016/j.supflu.2012.02.001
13. From laboratory to industrial scale. Available online: https://www.phyre-recycling.com/project (accessed on 27.01.2021).
14. The Future In Carbon Fibre Recycling. Available online: http://catack-h.com/technology-2/?lang=en accessed on 27.01.2021).
15. Hofmann M.; Nestler A. CarboLace - from Recycled Carbon Fibres to Spunlace Nonwovens. Proceedings of Aachen-Dresden-Denkendorf International Textile Conference 2017. DOI: 10.13140/RG.2.2.27610.85449
16. Manis F.; Schmieg M.; Sauer M.; Drechsler K. Properties of Second Life Carbon Fibre Reinforced Polymers. Key Engineering Materials **2017**, 742, 562–567. DOI: 10.4028/www.scientific.net/KEM.742.562
17. Shah D.U.; Schubel P.J. On recycled carbon fibre composites manufactured through a liquid composite moulding process. *Journal of Reinforced Plastics and Composites* **2015**, 35(7), 533–540. https://doi.org/10.1177%2F0731684415623652
18. Viale S. Recycled carbon fibers for high added-value product, CU e.V. Themenwoche Nachhaltigkeit, 06.05.2020. https://www.youtube.com/watch?v=Ze6bO82J3J0
19. CaRinA | Carbon fiber recycled materials for industrial applications. Available online: https://www.igcv.fraunhofer.de/en/about_us/fraunhofer_igcv/composites/reference_projects/CaRinA.html (accessed on 27.01.2021).
20. Stegschuster G.; Schlichter S.. Perspectives of web based composites from RCF material. *IOP Conf. Ser.: Materials Science and Engineering* **2018**, 406, doi:10.1088/1757-899X/406/1/012022
21. Thomas, G. Thermoplastische Formmassen. In *Handbuch Faserverbundkunststoffe/Composites : Grundlagen, Verarbeitung, Anwendungen*, 4th ed.; AVK - Industrievereinigung Verstärkter Kunststoffe e.V.; Springer Vieweg: Wiesbaden, Germany, 2014, pp. 278-290. https://doi.org/10.1007/978-3-658-02755-1
22. Harbers, T. Beitrag zum Materialverständnis kohlenstofffaserbasierter Nassvliese. Dissertation., Technische Universität München, München, 2016. http://mediatum.ub.tum.de/?id=1319156
23. Brydon, A. G.; Pourmohammadi, A. Card Clothing. In *Handbook of Nonwovens*, Russell, S. J.; Woodhead Publishing Limited and CRC Press LLC: Abington Hall, Abington, Cambridge, England, 2007, pp. 44-53.
24. Dilo, J. P. Vernadelungsverfahren. In *Vliesstoffe : Rohstoffe, Herstellung, Anwendung, Eigenschaften, Prüfung*, 2nd ed.; Fuchs, H., Albrecht, W.; Wiley-VCH: Weinheim, Germany, 2012, pp. 255-311.
25. Dauner, M.; Baz, S.; Geier, M.; Gresser, G. T. Rahmenbedingungen zur Verarbeitung von Carbonfasern durch Krempeltechnik. 31. Hofer Vliesstofftage, Hof, Germany, 9.-10. November, 2016; Bildungswerk der Bayerischen Wirtschaft (bbw) gemeinnützige GmbH Hof: Hof, Germany, 2016. URL: https://www.hofer-vliesstofftage.de/vortraege/2016/2016-05-d.pdf.
26. Schlichter, S.; Stegschuster, G.: Web Based Composites - Potenziale vliesbasierter Verbundbauteile. 31. Hofer Vliesstofftage, Hof, Germany, 9.-10. November, 2016; Bildungswerk der Bayerischen Wirtschaft (bbw) gemeinnützige GmbH Hof: Hof, Germany, 2016. URL: https://www.hofer-vliesstofftage.de/vortraege/2016/2016-06-d.pdf.
27. Schlichter, S.; Stegschuster, G. Web Based Composites : Potenziale vliesbasierter Verbundbauteile. *Technische Textilien 60*, **2017**, H. 4, S. 271-272.
28. Albrecht F.; Rosenberg P., Heilos K., Hoffmann M., Henning F. vliesRTM – Reuse of carbon fiber waste in composite structures. *SAMPE Europe Conference* **2019** Nantes 2019.

29. Pierret GmbH: Schneidemaschinen. URL: https://www.pierret.com/de/nos-produits/coupeuses/, (access on 29th January 2021).
30. Lohninger, H. Welch-Test DIN 53808-1 Prüfung von Textilien – Längenbestimmung an Spinnfasern – Einzelfaser-Messverfahren. Beuth: Berlin, Germany, 2003.
31. Voigt, W. Ueber die Beziehung zwischen den beiden Elasticitätsconstanten isotroper Körper. *Annalen der Physik* **1889**. 274, 573–587. https://doi.org/10.1002/andp.18892741206
32. Reuss, A. Berechnung der Fließgrenze von Mischkristallen auf Grund der Plastizitätsbedingung für Einkristalle. *Zeitschrift für Angewandte Mathematik und Mechanik* **1929**. https://doi.org/10.1002/zamm.19290090104
33. *Retz: Epina Softwareentwicklungs- und Vertriebs-GmbH,* **2008**. URL: http://www.statistics4u.info/fundstat_germ/ee_welch_test.html, (access on 11th December 2020).
34. Stegschuster, G.: Analyse des Kardierverfahrens zur Herstellung von Carbonfaservliesstoff als Verstärkungstextil für Faserverbundwerkstoffe. Dissertation, Universität Augsburg; 2021. ISBN 978-3-8440-7999-9