SPREADING OF HEAVY TOW CARBON FIBERS FOR THE USE IN AIRCRAFT STRUCTURES

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Abstract

In times of rising costs for mobility the years of purely performance driven materials in the aircraft industry are long gone. The need for cheaper structures forces aircraft manufacturers to open their mind from the cost-intensive materials that are used nowadays to new alternatives and ways to make flying economically more efficient.
The idea of this study is the review of heavy tows as a solution for making use of the high mechanical properties of carbon fibers while retaining lower material costs and exploiting process cost reductions. This paper describes the investigations and results of the spreading process of these materials.
An investigation was conducted on the parameters of an industrial spreading machine with its different parameters fiber tension, machine speed, fiber deflection angle and vibration frequency of the spreading bars. Several commercial carbon fibers in 12, 24 and 50K were measured in a single tow configuration and compared to assess the influence of fiber parameters like sizing content and dry fiber properties on the spreading quality and fiber width. Due to the characteristics of the carbon fibers, repeating tests had to be done to quantify the variance of the fiber width over the length of one spool as well as over different spools of one fiber batch. Finally the results shall give a first indication of the technical feasibility of using heavy tow carbon fibers for structural applications in the aerospace industry.

1. Introduction

The market for structures of commercial aircrafts is currently in a global transition. While the latest developments were targeted at the high performance long range market with a high efficiency as the first objective, current developments are aimed towards the much bigger market of short range aircrafts. And although the production numbers are a lot higher and the predictions promise a demand of 20.000 aircrafts over the next 20 years ([1],[2]) this market is rapidly changing to be cost dominated. New competitors like the Bombardier C-Series, the Sukhoi Superjet or the Comac C919 from China are entering into the market that was owned by the Airbus A320 and Boeing B737 for a long time. With the high percentages of carbon fiber parts in the long range aircrafts, it has become clear that these materials can lead to very light and efficient structures. But another question is their competitiveness regarding costs and effectivity.
The idea of this study is to investigate some of the cheaper carbon fiber materials, mostly heavy tows with a linear mass density bigger than 1600 tex. These fibers are currently used in the wind and automotive industry and exhibit slightly lower mechanical properties but also at a lower price.
Considering these boundary conditions, at several projects at Airbus Group Innovations it is being looked into the useage of heavy tows. Besides the mechanical performance one key element of the process chain is the spreading process. Since the areal weight does have to be in the same range for most of the parts, the much thicker fibers with 50.000 filaments and a linear mass density of 3000 and more have to be spread a lot wider than there siblings with a titer of 24K or less.
In this study, the investigations of the spreading process are shown and some results from the tests of four commercial heavy tows are presented. Besides the analysis of the path of the fiber through the

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spreading machine a parameter study was conducted. Furthermore, a quality investigation was accomplished on the variance of the fibers throughout one spool and for several spools of one batch. These findings shall help to find a way to make use of heavy tow carbon fibers in future applications for commercial aircrafts.

2. Theory

2.1. Literature

Heavy Tow Fibers

The market of carbon fibers is constantly growing with a current demand of about 50.000 tons per year and a forecasted demand of 100k tons in 2020 ([3]). Besides the strong aerospace market, other industries are catching up and until 2020 the market will be divided more evenly between the sectors.

Today already one third of the produced carbon fibers are heavy tows which are designated for the wind and growing automotive industry ([4], [5]). The wind industry uses the fibers to manufacture bigger wind turbines, which have more power and a higher efficiency ([6]). But the costs for carbon fibers are still a lot higher than for the established glass fibers, so that hybrid constructions of the blades are widespread. Nevertheless, several studies looked into the use of carbon for this industry and predict a constant need and stable growth ([7], [8]).

As another newcomer in the market, the car manufacturers benefit from the high mechanical properties at a very low weight to reach their goals of carbon emissions ([9]). Therefore, more and more parts are being produced using carbon fiber materials. In comparison to the wind industry, this market is even more cost driven and new material concepts have to prove themselves against strong and established competitors like steel and aluminium. This results in a demand for fast processes and low cost carbon fibers, which do not have to achieve the highest properties, but to be cheap and fulfil the requirements of mass production ([10]).

This is why there is a strong need for the development of heavy tow fibers, which is answered by several new fiber producers that are currently entering the market and intensify the competition.

In the aerospace industry, nearly no investigations were made in the direction of using heavy tow carbon fibers. Due to their poor mechanical performance, the use was a no-go for a long time and high performance fibers were used to built structural aircraft parts. Today, the demand is shifting and especially for high volume aircrafts, cost reduction is a main criteria. In a study from Cinquin et al ([11]) the possibility of using heavy tows for an aerospace use was slightly evaluated, but today, the market of heavy tow fibers has changed and new competitors with new products enter the market.

Spreading

In some earlier investigations, the spreading process was identified as a key element to using heavy tow fibers for aerospace applications ([12]). Appel et al conducted a short study on the spreading process of heavy tows and the online measurement of relevant parameters, but the goal was more to develop the measurement system itself ([13]). There are several ways to spread different kinds of fibers, which are described in various studies and patents. An overview of these techniques is given by Irfan et al ([14]). They can be divided into active or passive methods including a combination of both. For the active methods, energy is used to spread the roving, for example the use of an airflow (pressure or suction) in a small gap ([15]–[17]) or the transfer of (ultra-)sonic waves and vibrations into the filaments ([17],[18]). The passive methods do only use tension and a constant movement over different geometries like spreading bars, convex or other geometrical guiding elements ([14], [20]–[24]).

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2.2. Calculations

Prior to the tests, some calculations had to be done to investigate the geometrical differences between standard and heavy tow fibers. Since most of the test runs of parameters were done with several different fiber types, their properties had to be adjusted to be comparable. The main criteria of the spreading process is the fiber width which results in the fiber areal weight (FAW), therefore a factor for the aspect ratio of the fiber was determined. It is calculated using Formula 1, where w is the width of one fiber roving at 100 percent of coverage. t is calculated by Formula 2 and includes the material properties of the fiber as well as a theoretical dry fiber volume content of FVC = 0,7.

$$\boldsymbol{AR = \frac{w}{t}}$$ **Formula 1**

AR	*Aspect Ratio of fiber*	*[-]*
w	*Measured roving width*	*[mm]*
t	*Calculated roving thickness from* ***Formula 2***	*[mm]*

$$\boldsymbol{t = \frac{FAW}{\rho * FVC}}$$ **Formula 2**

FAW	*Fiber Areal Weight (calc. from width and titer)*	$[\frac{g}{m^2}]$
ρ	*Density of material (from material datasheet)*	$[\frac{g}{m^3}]$
FVC	*Theoretical Fiber Volume Content (= 0,7)*	*[-]*

To get a feel for these numbers, a short calculation shall be made. Looking at the common areal weight for aerospace parts with 125 gsm, one can recognize that the needed aspect ratio with a heavy tow fiber is a lot higher than using a standard tow. In this case (FAW = 125 gsm), the aspect ratio comes to 50 for a 800 tex fiber and 200 for a 3200 tex fiber. This demonstrates the importance of the detailed investigation of the spreading process to use these materials in comparable laminates.

3. Experimental Setup

This segment describes materials and methods that were used to conduct the investigation.

3.1. Materials

For this study, four heavy tow and two reference fibers were used:

- HT1 3300 tex
- HT2 3200 tex
- HT3 3700 tex
- HT4 3450 tex
- ST-12K 800 tex
- ST-24K 1450 tex

No further materials were needed since the fibers were only spread and measured and no binder fixation or processing was done.

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3.2. Process

Machine Setup

For this study, a spreading machine UD500 from the machine manufacturer LIBA (now Karl Mayer Technische Textilien GmbH, Naila) was used. It can produce UD-tapes up to 500mm width and combines coated spreading bars with the possibility of adding vibrations to spread the fibers. The machine setup is shown in Figure 1 and basically consists of 6 steps:

1. Fiber creel and guiding bars (not shown on scale in diagram – starts at pos. -9000 mm)
2. Spreading Unit 1 (9 spreading bars, 5 bars vibrating)
3. Spreading Unit 2 (7 spreading bars, 3 bars vibrating)
4. Transportation unit / drive
5. Bindering unit (not shown in the graph, including heating zone)
6. Winding unit

The parameters, that influence the spreading width, can be adjusted in the ranges shown in Table 1. The tension was adjusted in reference to the linear mass density to get a better comparison between different fiber types. The mid machine speed had to be adjusted at a low value of 3 m/min due to measurement and machine restrictions for the relatively short test runs (see *).

Table 1: Used parameters of spreading machine

Parameter	*Unit*	*Min*	*Mid*	*Max*
ten_{rel}	g/tex	0,1	0,35	0,6
Defl. Angle 1	°	0	22,5	45
Vibr. Frequ. 1	Hz	0	25	50
Defl. Angle 2	°	0	22,5	45
Vibr. Frequ. 2	Hz	0	25	50
Mach. Speed	m/min	1,5	3*	15

Measurement Setup

The main characterization parameter of the spreading study was the fiber width. Therefore, two types of sensors were used. The first and main sensor was a high speed laser micrometer from Micro-Epsilon (optoControl 2500). It can measure at a resolution of 1µm and a very high rate and is capable of online data recording via a PC. The sensors were positioned right before the inlet into the spreading unit (position 0 mm in the diagram in Figure 1) and after the main drive of the machine (position 2900 mm in the diagram in Figure 1).

The second measurement system was camera-based where 6 cameras were placed on the machine, synchronized and run by distant control. The pictures then had to be copied (offline-system) and the fibers widths were evaluated using a matlab tool and contrast-analysis. Each picture could contain several measurement values which had to be analyzed separately. Measurements with the cameras showed an accuracy of about 0,1 to 0,5 mm/Pixel, which was sufficient for this type of material.

After the adjustment of each machine parameter setup, a length of 10m of fiber was run before the measurement of 10m was conducted. This length resulted in about 200 values from each camera (1 picture per second) and 1000 measurement values from the laser sensors. The results from the camera system had to be referenced by using a master sample and then the numbers from both systems were copied into an Excel-Spreadsheet and analyzed. Measurement runs with twist or other visible defects were excluded from the results and mean values and standard deviations were calculated.

3.3. Test Matrix

For the parameter runs, several different parameters had to be tested and compared to each other. Therefore, a DoE test matrix was conducted with all of the parameters shown in Table 1. Furthermore, a simplified matrix was set up to get a better overview of the parameters. In these tests, the machine

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speed was held constant and the two spreading units were not handled separately. For the comparison of different spools the mid machine setup, which is also shown in Table 1, was used.

4. Results

The diagram in Figure 1 shows an example of the fiber width over the length of the spreading machine, beginning at the inlet and first measurement position with a laser sensor. After a small constriction in a guiding element, the first and the second spreading unit can easily be recognized in the graph of the diagram (numbers 2 and 3). Following after the second spreading unit, the drive of the machine also had an influence on the spreading width and led to an increase of about 8mm for this mid machine setup. The second laser sensor measures the width directly after the drive at the highest point of the graph. The long and nearly unguided length of the fiber up to the winding unit led to a significant reduction of the fiber width. In a production machine, this effect is partly restricted by the adjacent rovings and the application of binder material.

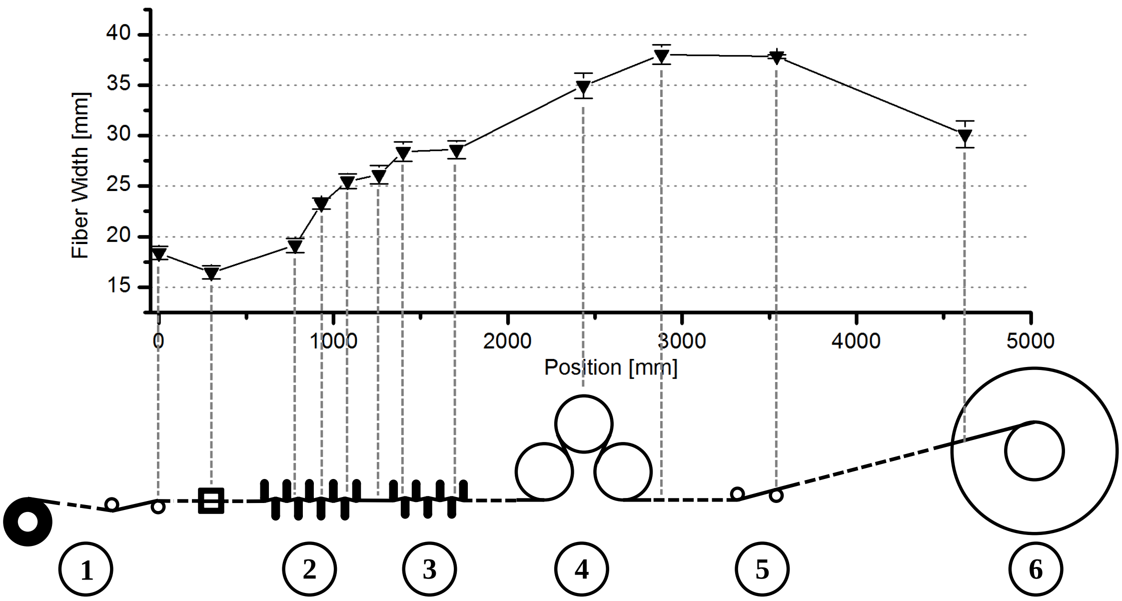

Figure 1: Fiber width course and measurement points (data for HT4 at mid machine parameters)

4.1. Machine Parameters

In this section, some parameters and results shall be explained in detail. The diagram in Figure 3 shows the aspect ratios for three relative tension values. It reveals that the carbon fibers do behave very differently and no significant trend is visible. Three of the heavy tow fibers are only slightly influenced by the fiber tension and show an enhancement of the aspect ratio of a factor of about 2 from the lowest to the highest tension. The 12K standard tow shows a slightly higher enlargement from 300 to 750 of aspect ratio. The 24K fiber is highly spreadable and shows values of 800 to more than 1300 which would mean an areal weight below 40 gsm. The heavy tow HT3 shows a negative behavior at higher tension and the aspect ratio decreases by a factor of -2.

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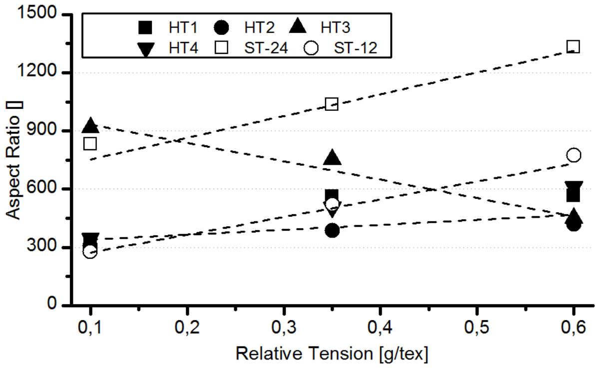

Figure 3: AR vs Relative Tension

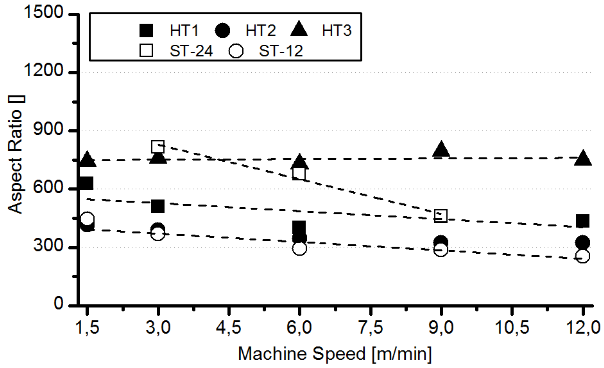

Figure 4: AR vs Machine Speed

The diagram in figure 4 shows the influence of the machine speed on the aspect ratio for some of the fiber materials. Since the simplified test matrix did not include the variation of the machine speed, results were taken from the DoE measurements and plotted in one diagram. In this case, the trend is slightly negative for all of the tested fibers which means that a higher machine speed results in slightly less spreading width per fiber.

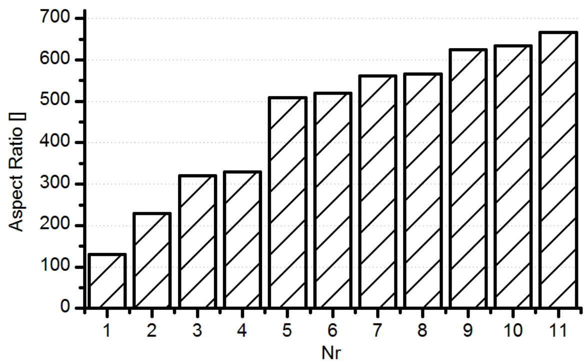

Figure 5: Aspect ratio for several test runs of HT1

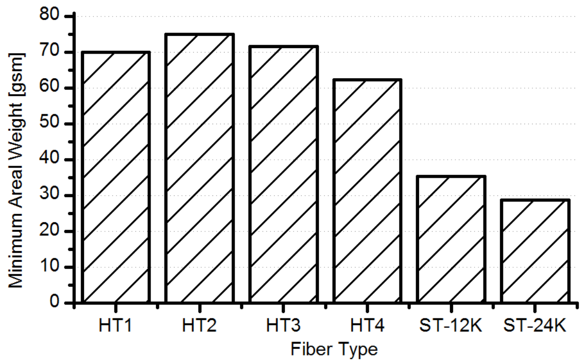

Figure 6: Minimal fiber areal weight for all fibers

Figure 5 shows a chart of aspect ratios for the material HT1 with one bar for every test run, sorted by their value. Independent of the adjusted machine parameters, all of the tested fiber materials showed a threshold of aspect ratio or fiber width. In this case, the threshold is at a value of 600-650 which results in a minimum areal weight of 70 to 75 gsm, shown in figure 6. Above this threshold, fibers could not be spread over a longer period of time or got significantly damaged.

The diagram in figure 6 shows the minimum areal weights for all of the tested fibers. It can be seen that all three of the heavy tows are on a similar level of about 70 to 80gsm and the material HT4 is slightly better at 60gsm. As already seen in the diagram in figure 3, the 24K fiber is very spreadable and reaches values even below the tested 12K fiber at around 30gsm areal weight.

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4.2. Material Quality

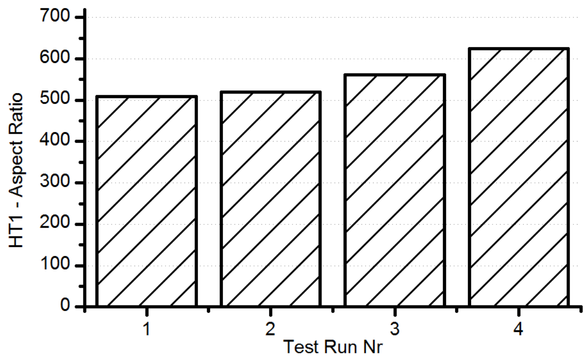

Figure 7: AR for 1 spool at mid machine setup

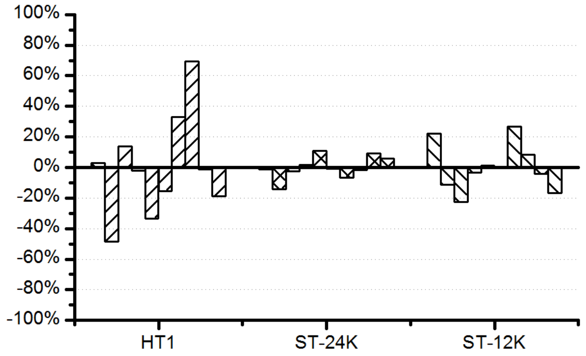

Figure 8: Deviation from mean value for 10 spools

Figure 7 shows the results of repeated measurements using the same machine parameters for the fiber HT1 over the length of the full test program of one spool. The values vary from the aspect ratio of 500 to more than 600 at run 4, which would mean a difference in width of 5mm on one single roving. Figure 8 shows the deviation of 10 spools at mid machine parameters versus their averaged value for the aspect ratio. The HT1 does not only differ over the length of one spool, but also the variation between several spools of one batch is quite big and this means a high risk of gaps when using this fiber at lower areal weights. In comparison, figure 8 also shows these values for the material ST-24K and ST-12K, which are much lower. Especially the 24K fiber ranges between minus and plus 15 percent and therefore on a very low level. The 12K deviations are a little higher, but one has to keep in mind that these values are compared in reference to their aspect ratio and the relevant widths in mm are a lot smaller for the standard than for the heavy tows.

5. Discussion

The development of the methods to measure the width of carbon fibers in a spreading machine were successfully developed in the beginning of this study. The measurements of the path of the fiber throughout the spreading machine help a lot to understand the mechanisms of spreading. Especially the fact, that the transportation unit has a big influence on the spreading width is quite interesting. The constriction up to the winding unit has to be investigated in detail in a further study since it would mean a loss of fiber width in the final product.
The parameter study is interesting and shows a different behavior for all of the tested fibers, depending on the selected parameter. Only the parameter machine speed showed the same trend for all materials, which could be explained by the exposure time of the fiber segments in the spreading units. Therefore, the speed has to be kept in mind when spreading at high degrees and low areal weights.
The results of the threshold diagram do also show, that the fibers could not be spread to a lower areal weight for example in a longer spreading unit. It seems that every material has a maximum value, up to which it can be spread using this technique of vibrating spreading bars. Above this value, the fibers get more and more damaged and the risk of a cut off gets very high. The given minimum areal weight values shall therefore be quite realistic for this type of spreading, but could not be compared to other spreading techniques and machines.
Finally some material quality findings were made. The results were very different for the tested materials. The shown diagrams of HT1 do only demonstrate the worst of the four fibers and only at the mid machine setup. Of course, at higher areal weights these effects do not play such an important role. This is also why the reference fibers at lower titers seem to have a better variance between different spools. It is an effect that has to be considered when using heavy tow fibers, but will be investigated and finally be assessed in a future publication.

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6. Conclusion

The results of the investigations demonstrate that the spreadability of heavy tow carbon fibers has to be a lot higher than with standard carbon fiber tows. But it also shows that areal weights below 100 gsm are achievable with these materials so that the integration in established processes and parts of the aerospace industry is possible. The fiber quality plays a decisive role, especially in the aerospace industry with its high requirements, and therefore some further investigations have to be made to assess the influence of the variations on the preform and the quality of the laminates.

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