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Influence of prepreg material quality on carbon fiber reinforced plastic laminates processed by automated fiber placement

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Abstract

In this paper, the influence of prepreg material quality to the mechanical properties of CFRP parts is presented. During the out life of prepreg slit tape, the processability changes by aging especially when storing the material at room temperature. Therefore, investigations are done with an in-house developed AFP machine and are monitored with a thermal monitoring system to determine the influence of material aging to mechanical properties and changes in the manufacturing process. The manufactured CFRP plates are finally tested by 3-point bending test.

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Keywords: Automated fiber placement; CFRP; Material aging; Mechanical properties; Thermal monitoring

1. Introduction

The automated fiber placement (AFP) process is one of the most important manufacturing technologies when it comes to industrial composite part manufacturing. Especially the aerospace industry applies the technology for manufacturing CFRP structures like fuselage skins, wing covers and various stiffener. The AFP process is a generative manufacturing process where several small with an epoxy based matrix pre-impregnated carbon fibers (prepreg) are placed on molds. The thermoset matrix consists beside of the epoxy resin of an additional co-reactant (hardener). To prevent degradation prior use, prepregs are kept frozen until use. Once they are warmed to ambient temperature, they begin to deteriorate and lose their tack while aging [1-2].

Because of that reason, the material storage aside the manufacturing process is carried out at low temperatures, e.g. -18 °C. At these temperatures, most of the prepreg materials are storable for about one year regarding the shelf life. During manufacturing deterioration decreases the out life of the prepreg significantly [3-5].

Therefore, most of the AFP machines, like Coriolis Fiber Placement robot [6] and Fives Viper [7], use air-conditioned creels with storing temperatures at low positive temperatures e. g. 15 °C during process application [6]. A typical out life for prepreg in a non-frozen condition at 21 °C to 22 °C is about 30 to 42 days [3-5]. Nevertheless, latest machine developments and the machine used for the presented investigations (see chapter 2.1) showing concepts with an in-head material storage without any air-conditioning [8-9].

Previously carried out qualitative investigations of the placement process have shown that the processability of prepreg material decreases with the time when stored in a non-air-conditioned area. It becomes apparent that the tack of prepregs decreases and the prepreg becomes stiffer. Based on these perceptions, further investigation should be done, to analyze the influence of the material age to the processability and the resulting mechanical stiffness and stability.

With this paper, the influence of aging prepreg material to the mechanical properties is investigated. Moreover, the thermal monitoring system analyzes the influence of the material aging on the AFP process.

In the following, the production environment consisting of an AFP machine and its thermal monitoring are presented.

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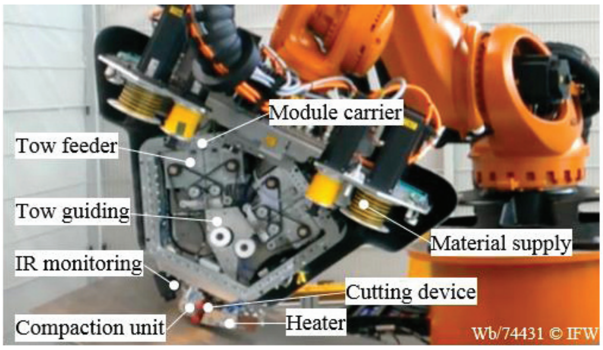

Fig. 1. In-house developed 4 tow automated fiber placement head for robotic applications.

2. Description

2.1. Automated fiber placement system

The experimental investigations are conducted on an in-house developed ¼ inch four-tow automated fiber placement machine [10], which is due to its open architecture and good accessibility mainly designed for research purposes. In Fig. 1, the machines head is displayed.

The head is subdivided into five functional modules, which are integrated into one module carrier. The material is stored in a supply unit, then fed through the feeding and guiding device with controlled speed, cut to desired length and finally placed and consolidated with defined pressure on an IR-heated tooling.

Hence, the material storage is integrated in the head, any negative influence of a complex material guidance in regard with an external creel can be avoided. However, this makes it more complicated to provide a constant climate condition for the material storage. To reduce the effect of deterioration the storage temperature can be adjusted using an integrated air-conditioning system. In Table 1 an extraction of AFP head properties is given.

Table 1. Extraction of technical specifications of AFP head.

Machine properties	Value
Material storage in-head	
Fiber path length	≈ 945 mm
Optional air-conditioning	
Segmented, adjustable compaction roller	4 mm stroke
Individual cutting of tows	
Maximum material length per tow	150 m
Maximum compaction pressure	7 bar
Minimum placement length	≈ 82 mm
Maximum heating power	2000 W

2.2. Process monitoring by thermal imaging

The automated fiber placement system also includes a thermal monitoring device to localize the placed tows and detect defects [11].

Fig. 2. Thermal process image within the ROI.

Fig. 2 shows a thermal image during the lay-up process including the different Regions of Interest (ROI) of the monitoring system. The temperature difference between the cold stored tows and the IR-heated surface can be used to determine the outer course edges as well as occurring gaps and overlaps within the ROI's. The edge detection is made right behind the compaction roller and therefore close to the nip point where the temperature contrast is high. In addition, there is a surface inspection for each tow and also for the previous course and the subsurface where the next course will be placed.

The temperature distribution of the tows depends on certain process and material parameter. Foreign bodies or connection faults influence the heat transfer from the subsurface to the tows surface. Hence, the surface inspection detects these deviations of the temperature distribution within the ROI.

3. Experimental setup

3.1. Material

The studied material is a carbon fiber/epoxy resin prepreg, which is cut into slit tapes with a width of ¼ inch (6.35 mm) especially for AFP application. The high tensile strength (HTS) 12k filament based tape amounts a fiber volume content of 35 % with a fiber grammage of 145 g/m². For analyzing the influence of the prepreg age to the strength and stiffness of cured laminates three test series with different coils of slit tape out of one production batch are used for manufacturing the CFRP plates for the specimen. The reason for this purpose was to consider deviations in the production process of the slit tape and the storage of the material. Furthermore, the AFP machine is in a non-air-conditioned area of test field, so the ambient temperature (17.7 to 20.8 °C) and humidity (22 to 43 % RH) varied for each placement process.

3.2. Experimental procedure

As mentioned in chapter 3.1, three different coils (further called batch #1 to #3) are used for the investigations. Table 2 shows the design of experiments. For each batch a different number of test series (v1, v2, etc.) is carried out: for batch #1 five test series, for #2 seven test series and for #3 eight test series.

Table 2. Design of experiments.

Day	#1	Aging (days)	#2	Aging (days)	#3	Aging (days)	T (°C)	RH (%)
3	v1	2					20.4	22
6	v2	5	v1	2			19.7	31
9	v3	8	v2	5	v1	2	20.8	30
12	v4	11	v3	8	v2	5	19.4	35
15	v5	14	v4	11	v3	8	19	30
20			v5	16	v4	13	17.7	24
24			v6	20	v5	17	19.5	36
27			v7	23	v6	20	19.6	39
31					v7	24	18	34
34					v8	27	18	43

The prepreg coils are frozen until two days before the first test series. The day of placement, the coils are rewind to smaller spools for AFP head application (see 2.1). After each placement process, the spools are stored in a climate cabinet and aged under constant climate conditions with a temperature of 20 °C and humidity of 35 % RH.

The CFRP plates are placed consisting of eight unidirectional plies with four courses of 25.8 mm width. The thickness of the material is about 160 µm. For the placement process the compaction pressure of the compaction roller is 1.34 MPa. The target value for the temperature of the placing surface is set to 40 °C. For each test series, the climate conditions are recorded. Then the plates were cured. In contrast to the conventional autoclave curing, the plates are cured without external pressure. In this case under vacuum in a heating chamber at 180 °C for three hours with linear heating up and cooling down rate.

For analyzing the influence of the prepreg aging to the mechanical stiffness and strength, the flexural modulus and flexural rupture strength were investigated by 3-point bending test (DIN EN ISO 14125). The specimens are tested with a ZwickRoell universal testing machine with a ZwickRoell 3-point bending test measurement equipment. The plates are cut into specimens of (l × w × t) 100 × 15 × 1.28 mm and with 0° and 90° fiber direction. It should be noted, that the resulting thickness of the specimen is thinner as specified in the norm. Nevertheless, all specimens have got the same thickness and are therefore comparable.

The specimens are placed on two supporting pins with a set distance apart of 80 mm and loaded at a constant rate of 5 mm/min. The results of the mechanical testing are reported in accordance with the DIN EN ISO 14125. Therefore, the measured force and deflection are recorded and the flexural rupture strength and flexural modulus are calculated. Both results are normalized to the arithmetic average of the test values of test series v1 of batches #1 to #3 to give a relative proposition of the mechanical properties development with reference to the ones of initial aging.

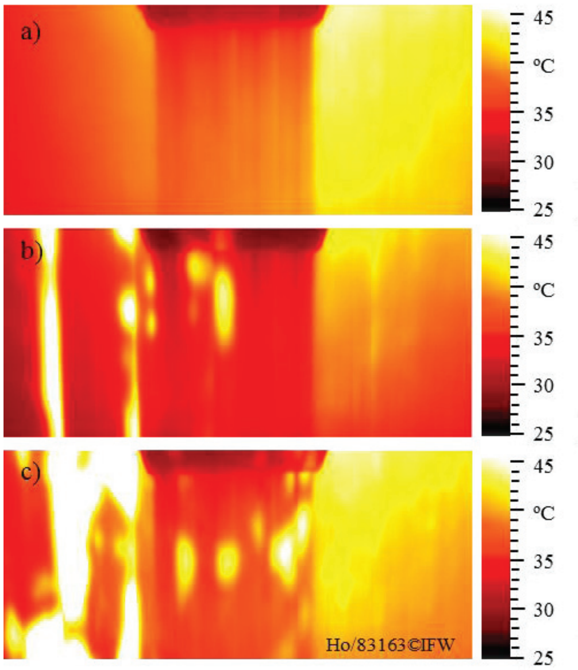

Fig. 3. Thermal images during the lay-up of the third course in the second ply: #3v1 (a), #3v4 (b) and #3v7 (c).

4. Results

4.1. Thermal Monitoring

The ageing of the material affects the processability of the slit-tape. The material becomes stiffer and therefore less flexible for the guidance inside the fiber placement head to the compaction roller. In addition, the deteriorated tapes have less tack so they stick with increasing out life worse to the tooling surface. While the mechanical bonding gets worse the thermal connectivity between subsurface and tape deteriorates as well. This leads to an inconsistent heat transfer.

The analysis of the thermal images reveals the influence of the material ageing on the laminate quality. Fig. 3 illustrates thermal images during the lay-up process of the third course in the second ply for the experiments #3v1 (a), #3v4 (b) and #3v7 (c). All images show the compaction roller and the placed tows in the middle, the previous placed course on the right hand side and the subsurface (first ply) on the left hand side. The just defrosted material shows a good tack of the first and second ply (a). Therefore, an even temperature distribution during the process can be used for a reliable detection with small tolerances. When the material becomes older connection faults especially in the first ply (b) and later on also in the following plies (c) occur. The bad tack and thus resulting air pockets lead to uneven temperature distribution and hot spots, which are detectable by the surface inspection of the monitoring system.

The mean temperature distribution of the tows can be used for a reliable monitoring. Therefore, an analytical approach to forecast the temperature distribution represents a double e-function of the temperature due to the superposition of the heat-up behavior during the lay-up process and the interaction of the laminate to the environment.

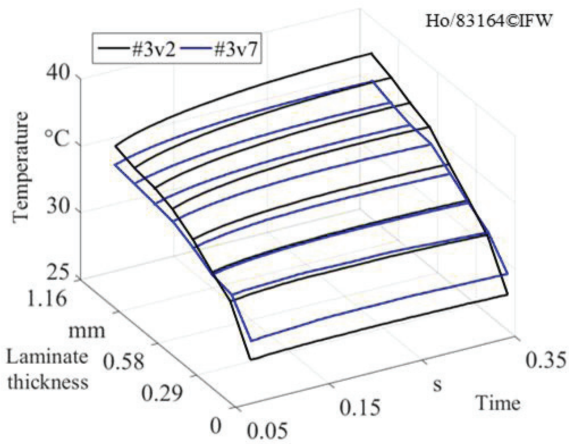

Fig. 4. Comparison of the mean temperature distribution of tow 3 for all plies of experiment #3v2 and #3v7.

The parameter of this approach depend on certain process parameter, such as tooling temperature or compaction pressure. This experiment shows that also material parameter as the age of the material influence the mean temperature distribution as shown in Fig. 4. Despite similar environmental condition (ambient temperature, humidity) during the experiments #3v2 and #3v7, the mean temperature profiles of tow 3 differ. The profiles of the second and the third ply do not show any deviations between the two experiments. But the thicker the laminate the higher the difference between the mean temperature profiles. The maximum temperature of the older material is lower during the fact that less tack leads to a lower heat transfer. Nevertheless, further investigations are necessary to better understand the detailed influence of the material ageing on single parameter of the double e-function that represents the temperature distribution during the process.

4.2. Mechanical Properties

The evaluation of the bending test shows one essential result. The aging of prepreg material has an influence on the strength of CFRP parts, which can be seen already within the out life when storing at room temperature. But this behavior is only visible when testing 90° specimens. Taking a closer look to 0° specimens of batch #3, the normalized flexural rupture strength and the normalized flexural modulus keep nearly constant on prepreg aging. This mechanical behavior is displayed in Fig. 5 and Fig. 6.

This fact conducts different when testing the 90° specimens. In Fig. 7, the measured data for flexural rupture strength for batch #3 are displayed as a function of the prepreg age. In the diagram, a clear decreasing tendency for the flexural rupture strength can be observed.

The same tendency is visible for batch #1 and #2 (see Fig. 8). The trend lines have also negative gradients in which the batch #1 trend line is stronger because of less data points for different ages of prepreg material. For a better evaluation, more measurement data of batch #1 are required but the trend lines of batch #2 and #3 have similar gradients.

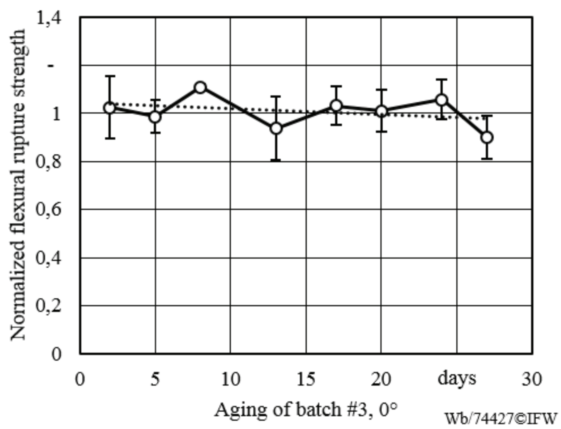

Fig. 5. Normalized flexural rupture strength for batch #3 with 0° fiber direction.

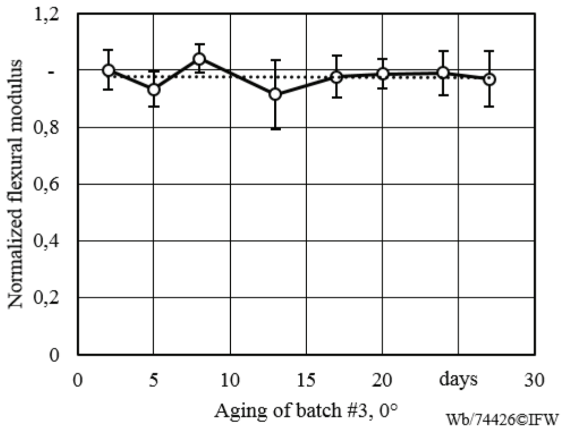

Fig. 6. Normalized flexural modulus for batch #3 with 0° fiber direction.

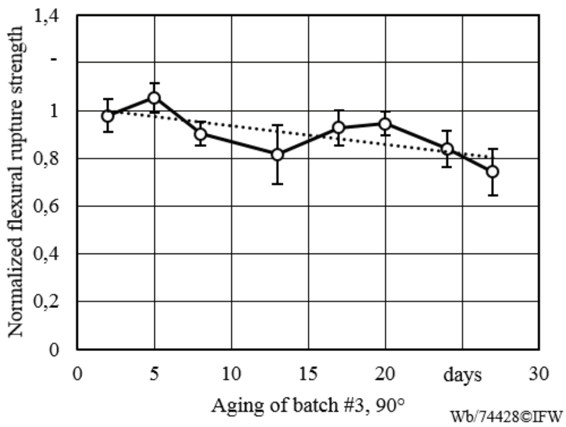

Fig. 7. Normalized flexural rupture strength for batch #3 with 90° fiber direction.

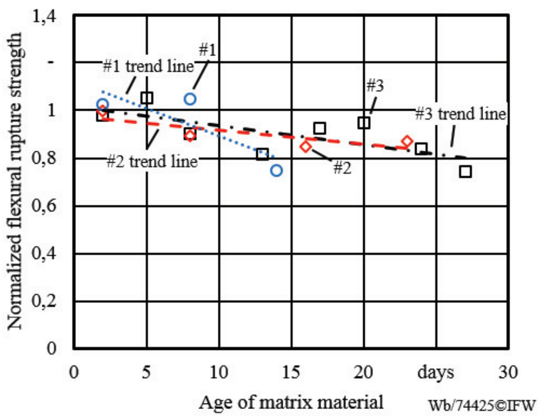

Fig. 8. Normalized flexural rupture strength as a function of aging for test series batches #1 to #3 with 90° fiber direction.

The trend of Fig. 8 becomes more explicit without differentiating into batches. Based on the trend line of Fig. 9, the decrease of flexural rupture strength can be calculated. The CFRP plates lost about 20 % of their initial strength after 25 days aging. When supposing a linear relation between material aging and stiffness represented by flexural rupture strength, the equation (1) reflects this supposition.

$$f(x) = -0{,}0083x + 1{,}0134 \tag{1}$$

The results show clearly a decrement of maximum flexural rupture strength by matrix material aging. One reason for this behavior is the rising moisture in matrix material. This effect was investigated in [12] as well. By now, it is not possible to give a quantitative statement to the moisture in prepreg material for this experimental investigation.

During the experimental investigations, the climate conditions are recorded. In Fig. 10, the ambient temperatures of all test series are displayed with the corresponding measured data of flexural rupture strength as normalized values.

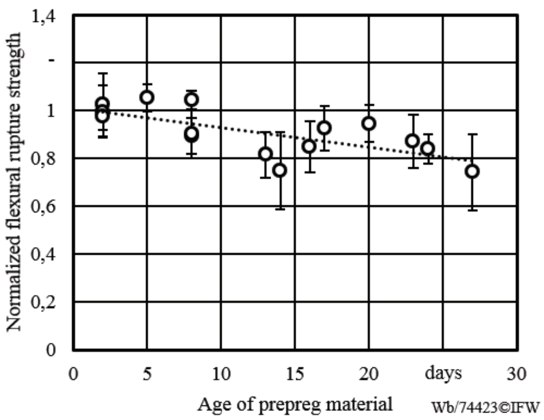

Fig. 9. Normalized flexural rupture strength for 90° specimen as a function of material aging.

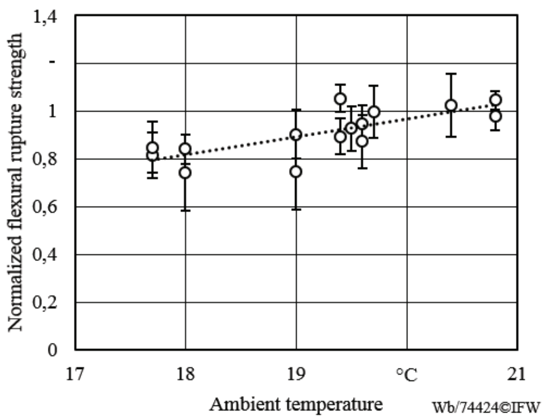

Fig. 10. Normalized flexural rupture strength for 90°fiber direction as a function of ambient-temperature.

As shown in the diagram, the normalized flexural rupture strength increases with the ambient temperature of the test series. One reason for this behavior is that the tack of prepreg material depends on temperature. Hence, this behavior has an effect to the tackiness between the plies of the laminate. This could be decreased by using an autoclave where the temperature and pressure compact the laminate. For validation, further investigations are planned. In the appendix two diagrams show the correlation between the flexural modulus for 90° fiber direction of all tested test series as a function of material aging and ambient temperature. As expected, due to the results presented bevor, there is no significant change over the temperature and age.

5. Conclusion and outlook

In this paper, results of experimental investigations are presented respectively the influence of prepreg material aging to the stiffness and strength of CFRP parts. Furthermore the tack of the material during the AFP process is affected. Due to an inconsistent heat transfer from the tooling surface the aging can be seen within the thermal pictures of the monitoring system. Therefore, the mechanical properties are represented by the flexural rupture strength and the flexural modulus. By analyzing 90° specimens in detail, a closer look to the matrix aging is given.

Bending tests of specimens with 0° fiber direction have shown that there is no dependence of mechanical properties to the material aging. This result is expected because the load is absorbed by the fiber and the load capacity of carbon fibers is constant on material aging. When now changing the fiber direction to 90° a dependence is clearly visible for flexural rupture strength in contrast to the flexural modulus, which has no significant dependence. A reason for decreasing flexural rupture strength is the increase of moisture during the storing process when aging the prepreg. Regarding the development of flexural rupture strength to the ambient temperature, the investigations has shown that the higher the ambient temperature the higher maximum flexural rupture strength. Further investigations with an autoclave instead of curing in a heated chamber must be done, to validate if the autoclave process compensates this effect. Furthermore, the compaction pressure and the placement temperature in the placement process can be increased in order to get a better tack.

In further works, it will be discussed if it is expedient to improve the climate conditions in the laying head or, moreover, if the manufacturing of prepreg material during the process contributes neglecting material aging.

Acknowledgements

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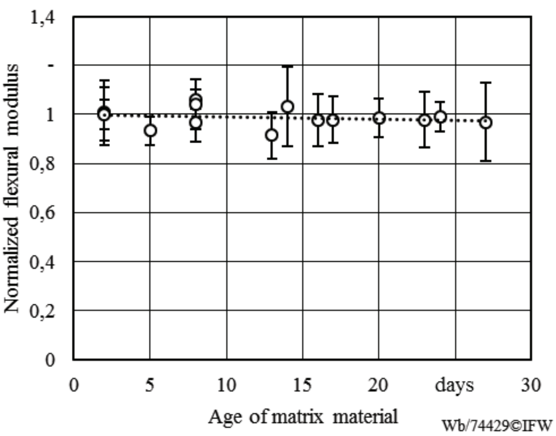
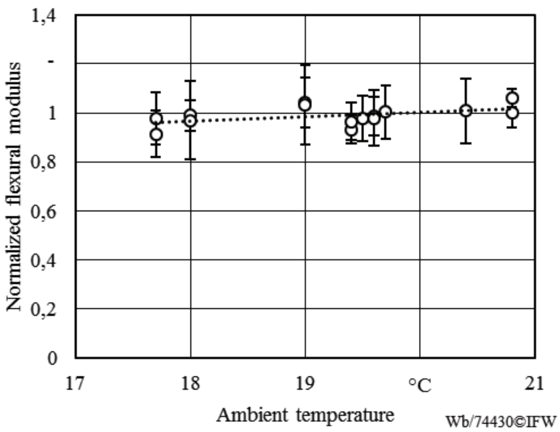
Appendix A. Results of flexural modulus for 90° fiber direction

A.1. Normalized flexural modulus of 90° fiber direction of all test series as function of matrix material aging



A.2. Normalized flexural modulus of 90° fiber direction of all test series as function of ambient temperature



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