INFLUENCE OF PREPREG AGING AND TACK ON LAY-UP EFFECTS/DEFECTS IN THERMOSET AUTOMATED FIBER PLACEMENT

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Abstract
Large structural parts for state-of-the-art airliners are made of carbon fiber reinforced plastics (CFRP) using automated processes. For complex lay-ups thermoset Automated Fiber Placement (TS-AFP) is commonly used. Here, preimpregnated (prepreg) fiber slit-tapes are laid up subsequently. Quality and speed of the lay-up strongly depend on the interaction between material and process. Since material properties change as the material ages, it is crucial to know how these changes affect the interaction. Several studies have investigated the material changes. However, their influence on the occurrence of lay-up defects remains unclear. To investigate the effects of material aging at room temperature on its lay-up behavior, the authors conducted experiments on steering (lay-up along a non-geodesic path) and bridging using a robot based AFP machine. In steering the material's lay-up behavior worsens significantly after fourteen days of aging. Furthermore, the defects change from in-plane fiber waviness to out-of-plane buckling to even no adherence as a function of the material's out life. However, we did not observe these results in bridging where the bridged length appeared unaffected from material aging. In future work we will focus the generalization of these results and the effects of changing process parameters.

1. Introduction

Thermoset Automated Fiber Placement (TS-AFP) is widely used in the aerospace industry for the automated manufacturing of large parts with complex lay-ups. In the process several prepreg slit-tapes are laid up onto a mold by a placement head which is usually attached to an industrial robot or a gantry system [1,2]. To achieve cost-efficient manufacturing and a high part quality, knowledge about process productivity and lay-up phenomena is of special interest. Both, lay-up rate and lay-up effects/defects are highly dependent on the interaction between material and process. The material properties of the uncured prepreg slit-tapes change during storage at low temperatures (usually at −18°C) and even more during storage at room temperature (RT) because of the ongoing crosslinking process of the resin [2]. The primary material property, which changes due to material aging, is the tack of the uncured prepreg tapes [3–5]. The level of tack directly affects the occurrence of lay-up phenomena such as out-of-plane buckles [6]. It thereby determines whether a part of complex geometry can be manufactured or not. Since prepreg tack is neither quantified by material manufacturers nor is there a standard test method, new test methods had to be developed. Several publications show the successful use of test benches for the measurement of peel tack [3,5,7]. However, it remains unclear to which extent the change in tack effects lay-up phenomena in TS-AFP.

To show the correlation between material aging and lay-up effects/defects and to verify lab scale tack measurements the authors conducted a series of lay-up trials with an industrial robot based Coriolis AFP machine (see Fig. 1).

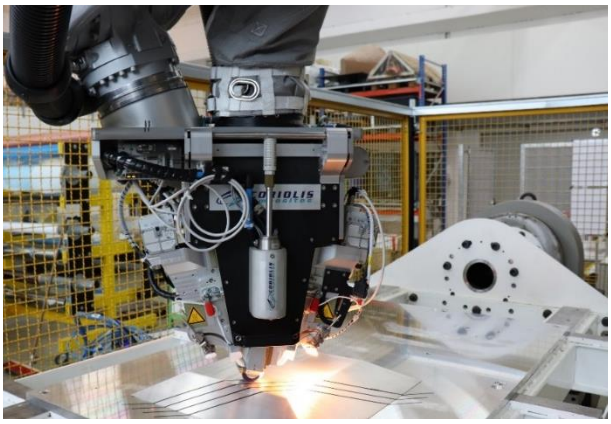

Figure 1. Coriolis AFP machine at Technical University of Munich (TUM), lay-up of single tapes on a double-ramped tool

The lay-up trials included the placement of tapes along curved paths on a flat plate (steering) with three different steering radii as well as the placement on ramp tools with two different heights and two different ramp angles. We repeated the trials at a total of three different aging conditions and then used the same material for tack and degree of cure measurements. Thus, this paper presents the occurrence of out-of-plane buckling, in-plane fiber waviness and tape pull-off during steering as well as bridging as a function of room temperature material aging for different geometric boundary conditions.

2. Materials and methods

2.1. Material

For the investigations we selected an aerospace grade prepreg which is well reviewed in literature: IM7/8552 by Hexcel Corp. [8–10]. The manufacturer indicates a tack life (time at RT, during which prepreg retains enough tack for easy component lay-up) of ten days [11]. Before the start of the investigations the material had been unfrozen at around 10°C for 4.5 days. During the investigations the temperature and humidity had been recorded continuously. For lay-ups the material is cooled to 15°C inside the AFP machine to avoid a high level of tack during material feed. For a controlled aging the material was stored at 21.8°C (±0.2°C) and 33% (±4%) relative humidity in between the experiments. We conducted the first experiments two days after initial thawing of the material, being well within the material’s tack life. We repeated the experiments seven days after initial thawing, being just past tack life, as well as fourteen days after initial thawing, being well past tack life.

2.2 AFP lay-up experiments

To investigate AFP characteristic phenomena which are directly linked to the producibility of parts with complex lay-ups we decided to conduct experiments on steering and bridging. For the experiments we used TUM’s AFP machine (see Fig. 1), which processes up to eight 1/8” (3.175 mm) wide slit-tapes (min. cut length: 63 mm) and uses infrared emitters to heat up the material prior to lay-up.

The process parameters were kept constant for all experiments to enable a sound analysis solely of the effect of changing material properties due to aging. The parameters are listed in Tab. 1.

Table 1. AFP process parameters

Process parameter	Lay-up speed **v**	Compaction force **F**	Infrared emitter power $\mathbf{P_{IR}}$
Unit	[m/s]	[N]	[W]
Value	0.05	250	258

The authors laid up single slit-tapes on a flat aluminum plate with three different steering radii (see Tab. 2). Therefore it was possible to investigate the material process substrate interaction without interferences from adjacent tapes, which could alter the defects when in contact with each other.

Table 2. Parameters steering experiments

Parameter	Steering radius	Arc length	Repetitions
Unit	[mm]	[mm]	[–]
Value	400	400	5
	600	400	5
	800	400	5

To avoid fiber straightening within the arc, each track started and ended with a 70 mm straight. We adapted Hörmann's evaluation method [12] for the analysis of defects resulting from steering (out-of-plane buckling, in-plane fiber waviness, tape pull-off [1,12]). The procedure includes (see also Fig. 2):

- laying-up of tape,
- marking of buckles and tape pull-off five minutes after lay-up (average time it takes for the defects to develop [13]),
- taking photographs of each tape section with a reference length (graph paper),
- measuring buckles and tape pull-off as well as marking and counting locations with in-plane fiber waviness using the image processing software ImageJ.

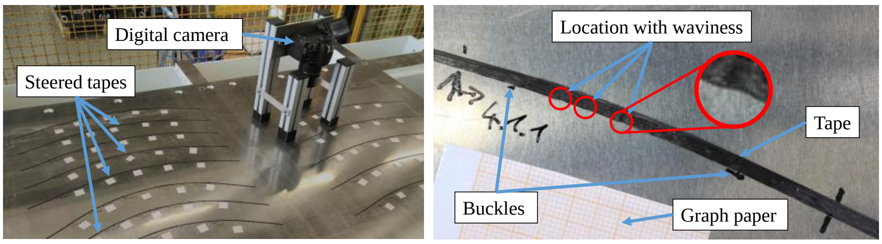

Figure 2. Steering analysis – image capturing (left), image analysis (right)

We also performed the bridging experiments with single slit-tapes to avoid interferences from adjacent tapes. The geometrical base for the experiments were two aluminum ramp tools which were attached to an aluminum plate. The one with a ramp height of 50 mm is depicted in Fig. 1. The lay-up direction was 45° referred to the ramp edge. Preliminary studies, in which the bridged length was investigated as a function of the fiber orientation, showed that 45° lay-ups lead to more pronounced bridging effects than other lay-up directions. The parameters for the bridging experiments are listed in Tab. 3.

Table 3. Parameters bridging experiments

Parameter Unit	Ramp height [mm]	Ramp angle [°]	Repetitions [–]
Value	25	25	5
	25	35	5
	50	25	5
	50	35	5

Equally to the steering experiments we marked the defects after lay-up and took photographs vertically to the surface before measuring the bridged length with ImageJ. For this we tilted the tool carrier 90° so we could take images parallel to both the flat plate and the ramps. Fig. 3 illustrates the image capturing and the image analysis. For the analysis of the bridged length we had to differentiate between the small opening angle between tape and ramp edge and the large one as the position of the compaction roller leads to different compaction behavior on these two sides.

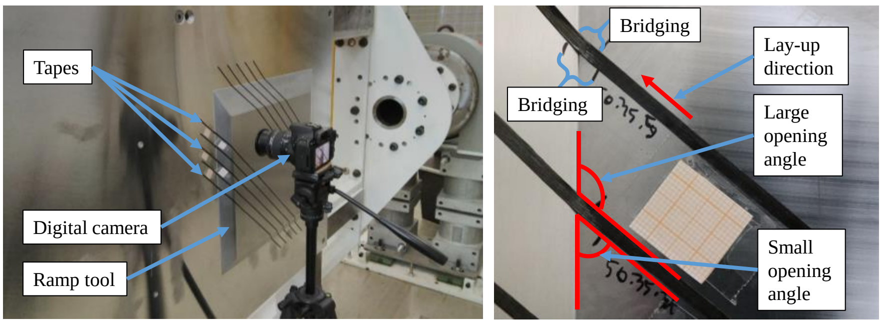

Figure 3. Bridging analysis – image capturing (left), image analysis (right)

2.3 Tack measurements

TUM's tack test bench has first been published by Stelzl et al. [7]. The functional principle had been adapted from Crossley et al. [3]. It is shown in Fig. 4 alongside a picture of the test bench and a result from former material investigations describing the measuring principle.

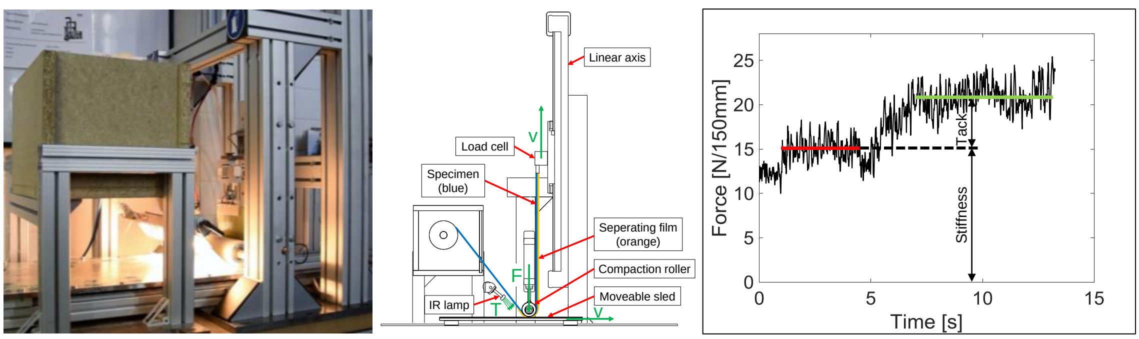

Figure 4. Tack test bench – photograph (left), functional principle (middle), typical result (right)

Since specimens have to have a width of around 150 mm to obtain clear results we laid up 47 tapes for each specimen onto vacuum film with the AFP machine without using the infrared emitter. Therefore we were able to assure that the exact same material was tested than the one in the AFP lay-up experiments without affecting it by the input of thermal energy. We repeated the tack measurements five times using the same process parameters as in the AFP lay-up experiments except for P_{IR} which we had to adapt to 1540 W because of the width of the material and the design of the emitter to achieve the same heat input.

2.4 DSC measurements

To monitor the degree of cure (DoC) during material aging we measured the glass transition temperature (T_g) by differential scanning calorimetry (DSC) using a TA Instruments DSC Q200. The material was heated from –30°C to 300°C with a 10K/min heat-up rate. We did one measurement per material age and used the point of inflection method to determine T_g.

3. Results and discussion

3.1 AFP lay-up experiments

The results of the steering experiments are summarized in Fig. 5.

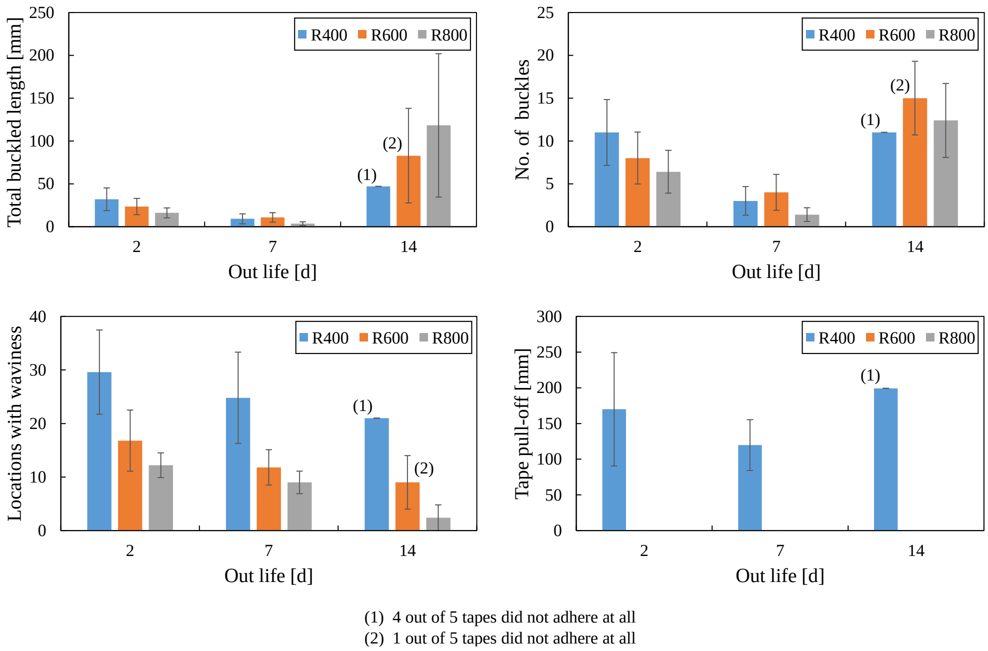

Figure 5. Results steering experiments (including standard deviation) – total buckled length (top left), no. of buckles (top right), locations with waviness (bottom left), tape pull-off (bottom right)

Fig. 5 shows, as expected, that the defects due to steering vary as a function of the steering radius and, more importantly, as a function of the material's out life. The results also show that the steering behavior can only be characterized by looking at all three defects. The highest total buckled length and the highest number of buckles occur at the highest state of ageing (fourteen days). The lowest total buckled length and number of buckles, however, occur at seven instead of two days of out life. Obviously, the material properties do not decrease monotonously. A fact that has also been observed by Endruweit and Nguyen in their respective tack measurements [5,14]. An unexpected result is the higher buckled length at fourteen days of out life with increasing steering radius instead of decreasing steering radius. We assume that the initiated curing of the resin leads to locations with a higher shear stiffness. At large radii the shear stress is not high enough to deform the material at these locations leading to buckles. At small radii the shear stress is high enough to deform the material leading to less stress in the steered tape and therefore to less buckles. However, a thorough interpretation could not be completed at this point. It will be part of future investigations. At fourteen days out life four of five tapes at R400 and one of five at R600 did not adhere at all due to the low tack (see Fig. 6) indicating that it is not possible to lay-up a steering radius of 400 mm at this material age.

Figure 6. Non-adhering tapes

The number of locations with in-plane fiber waviness decreased, as expected, as a function of the material aging. It is the initial defect due to steering. Once the compressive stress at the inner radius of the tape is too high or the tack is too low the defect converts into out-of-plane buckling [12].

Tape pull-off only occurred at R400. The decrease at seven days out life followed by the highest value at fourteen days out life demonstrates a similar trend as it is for buckling. The fact that only one value could be measured at fourteen days prevents a clear interpretation.

The results of the bridging experiments are summarized in Fig. 7.

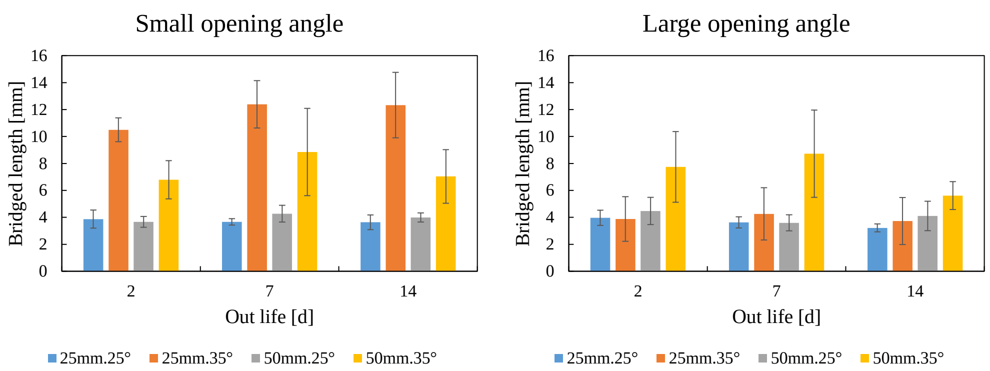

Figure 7. Results bridging experiments (including standard deviation) – small opening angle (left), large opening angle (right)

In Fig. 7 no obvious dependence of the bridged length on the material's out life is apparent. The results vary as a function of the ramp height and even more as a function of the ramp angle. At the small opening angle the ramp angle of 35° leads to a larger bridged length at both ramp heights. At the large opening angle this trend is only visible at a ramp height of 50 mm. During lay-up in 45° the placement head has to be inclined leading to an uneven contact of the compaction roller with the tool surface. This contact is less on the side of the small opening angle resulting in the larger bridged length at that side.

It is assumed that the missing dependence on material aging is due to the fact that there is only an off-axis load on the tape at a very short part of the track – the edge of the ramp. On a straight or geodesic track the tapes adhere to the surface even with a low level of tack. Since the Coriolis AFP machine allows for a lay-up with very low fiber tension there is only a local stress input at the edge of the ramp compared to steering where there is in-plane bending during the whole track.

3.2 Tack measurements

Unfortunately, the tack measurements did not lead to any useful results because the obtained values were even lower than the signal noise. The tack of the specimens was noticeably low and therefore we could not measure a significant difference between the stiffness and the stiffness+tack plateaus. A cause for a possible loss of tack might be the fact that could not do the measurements directly after lay-up since the AFP machine and the test bench are not located at the same site. We had to put the specimens into sealed bags and store them at –18°C between lay-up and tack measurement. The material handling and the material's contact to vacuum film, release film etc. probably caused a loss of tack, too. Further investigations will be done to improve tack measurements and specimen preparation.

3.3 DSC measurements

We used the T_g measurements to calculate the DoC using the material of the first experiments as the reference. The results are summarized in Fig. 8.

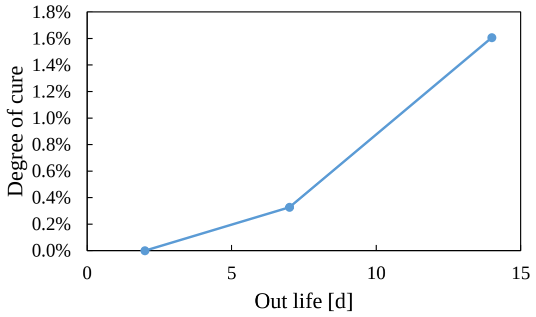

Figure 8. Results degree of cure

Fig. 8 indicates a sharper increase of DoC between seven and fourteen days than before that corresponding to the significantly increasing steering defects of the fourteen days aged material.

4. Conclusions

In thermoset AFP defects caused by steering vary as a function of the material's out life and therefore as a function of the material's tack. The initial defect in-plane fiber waviness converts into out-of-plane tape buckling as the material's tack decreases. The overall lay-up behavior worsens once the material clearly exceeds its tack life leading even to the fact that tapes do not adhere at all at R400 after fourteen days out life. Our results demonstrate that all defects due to steering have to be analyzed altogether to characterize the lay-up behavior. The dependence on material aging does not apply for bridging in the investigated case due to the fact that there is only a short part of the track where load is introduced into the tape.

The presented findings help to determine whether a certain material can be used for a part of complex geometry depending on the material's out life. Future work will be done to generalize these findings and to improve tack measurements so that the direct correlation between lay-up behavior and tack can be demonstrated. Additionally, we will investigate the influence of changing process parameters on the occurrence of defects and the effects of laying up several parallel tapes simultaneously.

Acknowledgments

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