INFLUENCE OF PROCESS PARAMETERS AND MATERIAL AGING ON THE ADHESION OF PREPREG IN AFP PROCESSES

Dipl.-Ing. Chinh D. Nguyen[1], Dipl.-Ing. Christian Krombholz[1]

[1]Institute of Composite Structures and Adaptive Systems, German Aerospace Center (DLR),
Ottenbecker Damm 12, 21684 Stade, Germany
Email: chinh.nguyen@dlr.de, Web Page: http://www.dlr.de/fa/

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Abstract

In order to increase the quality of CFRP parts, the manufacturing process could be customized to the current condition of the used prepreg material. For that reason, a long term experiment was executed here, where the change of the tack due to material aging at room temperature and variation of material temperature was analyzed. With the existing requirements, among other things, to simulate a real automated fiber placement (AFP) process, a lap shear test was found to be appropriate to measure the tack between two prepreg plies. First results show, that the tack increases dramatically if the temperature of the material also increases. Regarding material aging at room temperature, without heating the material, the tack was constant for a long time and then started to decrease. If the material was heated during the automated layup, the tack did not decrease but surprisingly increased constantly for more than ten days, before it started to decrease. This unexpected behavior could result from the increasing degree of cure which leads to an increase of the viscosity of the resin.

1 Introduction

With AFP technology, the requirements of highly productive manufacturing and high quality of CFRP parts can be achieved. However, after manufacturing several large scaled parts with this technology at the Center for Lightweight-Production-Technology of the German Aerospace Center (DLR) in Stade showed, that the layup quality of the material is strongly dependent on the process parameters which were used, mainly compaction force, layup speed or temperature of the material. Effects like bridging or no adhesion between two plies can occur if wrong parameters were chosen. Furthermore, aging of the material at room temperature, which leads to a change of tack, is another effect which influences the layup. Even though the chosen process parameters are based on the condition of the material and this on the other hand changes at room temperature, aside from the first ply, the parameters are kept constant for the entire production of a part.

Through variation of the parameters depending on the current tack, the manufacturing process and part quality could be improved by customizing to the particular requirements. For example, one could be a constant tack of the plies for a best possible part quality (low porosity, no bridging effect, etc.). If, instead of that a high productivity is the focus and the part quality secondarily, the parameters can also be adjusted according to this requirement.

For that reason, the changes of the adhesion between two plies depending on the aging of the prepreg material at room temperature and depending on the heating of the material were analyzed here. With this understanding, an optimized layup due to material condition and depending on the requirements of the final part can be achieved.

2 State of the Art

Compared to hand layup, main advantages of the automated manufacturing of CFRP parts are higher productivity with increased quality [1]. Two main technologies are Automated Tape Laying (ATL) and Automated Fiber Placement (AFP). Industrial ATL machines usually handle only one material spool. Because of the wide material (usually 150 mm or 300 mm), high productive layup can be achieved on the one hand. But on the other hand, the wider the material, the lower is its ability to drape and it tends to wrinkle if the part is strongly double curved. For that reason, ATL technology is usually used for parts with flat surfaces. In contrast to ATL, AFP machines layup up to 32 separate tows next to each other within one course. Because of the lower width of the material (usually 3.17 mm to 12.7 mm) compared to ATL material, its ability to drape is a lot higher. For that reason, AFP technology is commonly used for strongly double curved parts but can also be used for flat parts. Because of the lower total width of a course, AFP machines are generally lower productive than ATL machines.

Usual plants either have AFP or ATL technology. In contrast to that, the German Aerospace Center (DLR) operates the GroFi plant (Figure 1) at the location in Stade/Germany, where several AFP and ATL units will be able to operate simultaneously at one part. With this approach, an up to ten times higher productivity compared to current plants as well as high flexibility and efficiency of the plant can be demonstrated. At the moment, there are two ATL units for 150 mm wide prepreg material or expanded copper mesh, two AFP units that layup 16 x 6.35 mm slittape and one Dry Fiber Placement (DFP) unit.

Figure 1. Left: Overview of the GroFi plant. Right: production of a fuselage skin with AFP technology.

Independently, if AFP or ATL technology is used, the manufacturing process and quality of automated manufactured composite parts are amongst others influenced by the tack of the prepreg material [2]. In fiber composite technology, tack is the adhesion between two surfaces (tool with first ply or ply with ply) during the layup process and before the part is cured [3].

One effect, which influences the tack, is the aging of the prepreg material at room temperature [4]. At this temperature, where the layup process usually takes place, the epoxy resin starts to cure and the tack of the material is changing continuously. For example, prepreg material M21 from Hexcel has a tack life between 10 and 15 days, depending on the layup process (hand layup, ATL or AFP) [5]. Tack life is the time, during which prepreg retains enough tack for easy component layup [5]. Furthermore, the tack can be influenced by process parameters, which are mainly compaction force, layup temperature of the material and layup speed [6]. According to [4], an increase of compaction force also increases the tack. The higher the layup speed, the shorter is the compaction time and this result into a decrease of the tack. Increasing the temperature first also increases the tack, but if the temperature is too high, it can also decrease the tack [7].

Although the tack changes continuously during processing at room temperature, currently it is not considered. Instead of that, the influencing process parameters are determined previously and are valid for the whole layup process, irrespective of the current tack of the material.

Standardized methods to measure the prepreg tack are not available at the moment [8, 4] and the test methods summarized in [4] turned out to be inappropriate for the requirements here. The probe test for example, measures the tack between the probe and the material. With the peel test, the tack between two material plies can be measured but with increasing time, the stiffness of the prepreg is increasing and an evenly debonding of the plies is not able anymore [4, 9].

3 Experimental Setup and Design

As mentioned in 2.2, available test methods for measuring prepreg tack are inappropriate for the requirements here. For that reason, an appropriate test method to determine the tack between two prepreg plies needed to be found. At the end, a lap shear test was found to be most appropriate, mainly because with this method also aged material can be tested.

For the experiments, all of the specimens were produced automatically with an AFP unit from the GroFi plant. For this, the first course with one tow of 6.35 mm width was laid up on the tool surface from left to right. Then, a second tow was laid up from right to left, with 20 mm of overlapping in length and 100 % overlapping in width to the first tow (Figure 2). This is important because smallest offsets could cause big variation in the results. But with the automated layup, a repeatable quality of the specimens could be secured. Due to the AFP process, the length of the specimens after layup was 600 mm, but for the following lap shear test they were finally shortened into length of 105 mm (Figure 3). For each test configuration nine specimens were tested.

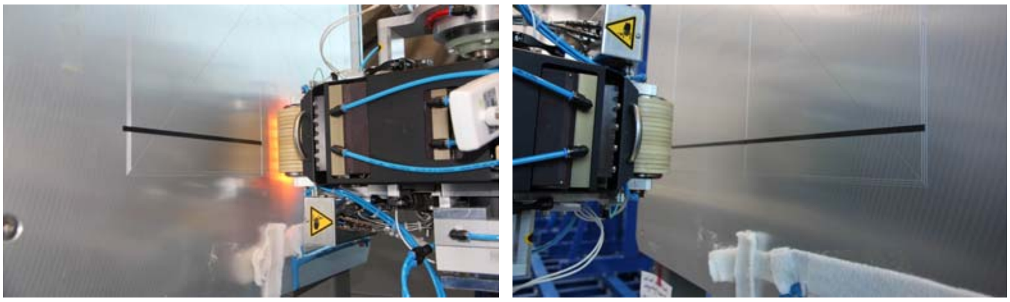

Figure 2. Left: First course with one tow. Right: Second course with 20 mm overlap to first course

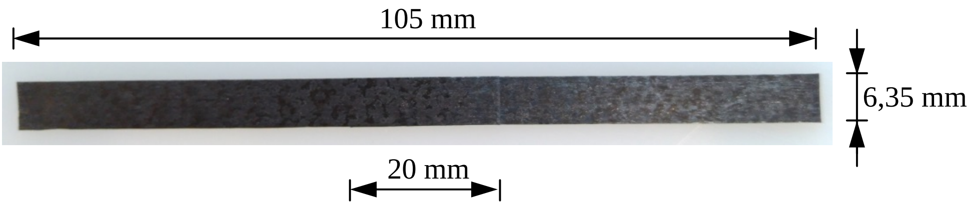

Figure 3. Specimen for lap shear test. 20 mm overlapping length.

To determine the tack between the two plies, a following lap shear test was executed (Figure 4). The specimen was fixed between two clamps and pulled apart in longitudinal direction with a speed of 0.05 mm/s. The force to separate the plies was recorded with a force sensor. To minimize external influence while handling the specimen and to get a repeatable preparation of the test, a nut for better guidance of the specimen was placed between the two clamps.

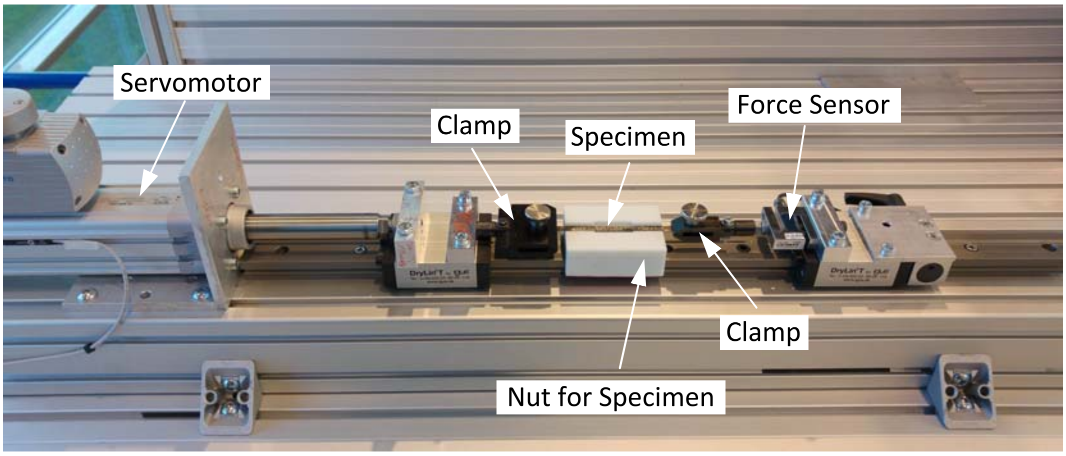

Figure 4. Lap shear test stand

The material, which was used for the experiments, was 6.35 mm wide and 0.127 mm thick (cured condition) slittape prepreg from Hexcel. It is preimpregnated with epoxy resin and has a tack life of 15 days.

As mentioned in 2.2, the three main tack influencing parameters besides aging at room temperature are compaction force, layup temperature of the material and layup speed. Because of the large number of experiments, it would not be possible to determine the influence of all three parameters at one time. In a preliminary executed experiment [9], the temperature of the material showed to be the most influencing parameter concerning tack. For that reason, besides aging at room temperature, only the influence of temperature was analyzed for now.

Because of the AFP unit in GroFi, heating of the material is not specified in °C but in regulated power of the infrared heater in relation to layup speed. The temperature of the material was not determined in this case. During the whole test run, the layup speed was 10 m/min and the compaction force was 50 N/6.35mm. The heating power was increased stepwise from 0 % (no extra heating of the material) to 25 %, 50 %, 75 % and 100 %. A twin quartz tube infrared heater from Heraeus with 130 mm length and a maximum power of 1200 W was used.

To determine the influence of the material aging, the experiments were repeated every second day, for 16 days. To make sure, that the tested specimen within one day had the same condition, the two outer plies on the material spool were unwound, before producing the specimen.

4 Results and Discussion

As expected, heating the material increases the tack between two prepreg plies clearly. Figure 5, left for example, shows the force needed to separate two plies as a function of heating power applied to the prepreg material at day seven. For the other days, until day 16, the behavior was the same. Heating the material with 100 % heating power at 10 m/min layup speed led to an increase between 38 % at day one up to 111 % at day 11 compared to a layup without heating. For the other days the increase due to heating the material was in between. Furthermore an increase of displacement at maximum force (F_{max}) with increasing heating power was also determined (Figure 5, right).

This behavior can be explained with the change of viscosity, if the material was heated. With increasing temperature, the viscosity of the epoxy resin decreases. If two plies are press on each other with the same force and the same time (equivalent to constant layup speed), the surfaces of the plies with low viscosity are more able to adapt on each other than surfaces with high viscosity. A higher contact area and as a result of this, a higher tack between the plies is the consequence. During the experiments, maximum heating power of the infrared lamp at a layup speed of 10 m/min always led to maximum tack. According to [7], it can be assumed, that if the heating power would be higher, at one point the tack reaches its maximum. But due to the test configuration, this point could not be determined for now.

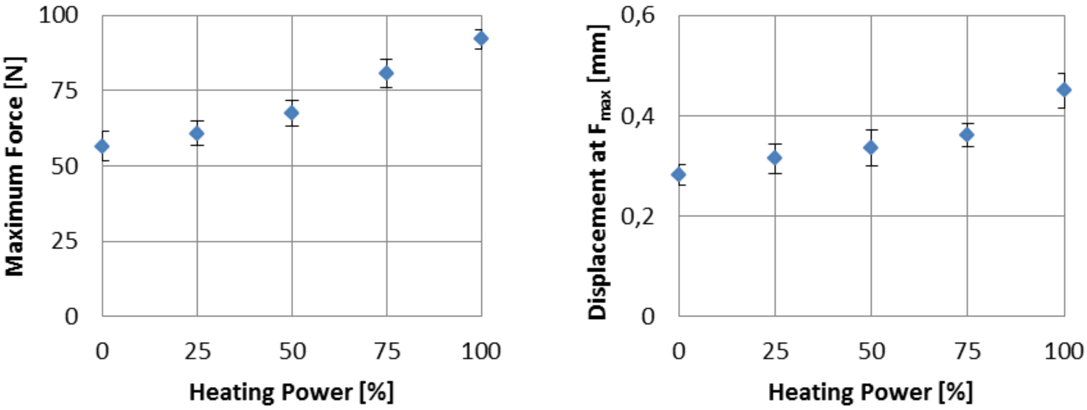

Figure 5. Maximum force F_{max}(left) and displacement at F_{max} (right) as a function of heating power at day 7

Figure 6 shows the influence of material aging at room temperature for different heating power. Without heating, neither an increase nor a decrease of the force is recognizable. For the whole duration of experiment, the force was in the range of 50 N. The results of the experiments with heated material were surprising. Until day 11 at room temperature, the maximum force was increasing and not decreasing, as expected. Also the more the material was heated, the larger was the difference of the force between day one and day 11. While there was only a small increase from 63 N at day one to 70 N at day 11 for 25 % heating power, for 100 % the force increased from 80 N at day one to 110 N at day 11. The increases of the other heating steps were in between. After day 11, for all steps of heating power instead of the one without heating, the force started to decrease.

The reason for this behavior was not clearly determined for now but one explanation could be the change of viscosity of the resin again. At room temperature, the resin starts to cure slowly and the viscosity increases. After layup the two plies are bonded through a resin film. The lap shear test then separates the plies within the resin film and the higher the viscosity, the more force is needed to separate the plies. This could lead to an increase of the tack. But at the same time, because of the slowly increasing viscosity, the contact area also slowly decreases and this leads to a decrease of tack. So due to material aging at room temperature, two effects could influence the tack counteractively. In this case, until day 11 the increase of separation force due to increased viscosity seems to have a bigger effect than the decrease of contact area and after day 11 it is the other way round. As this explanation is an assumption at the moment, it needs to be confirmed with additional analysis.

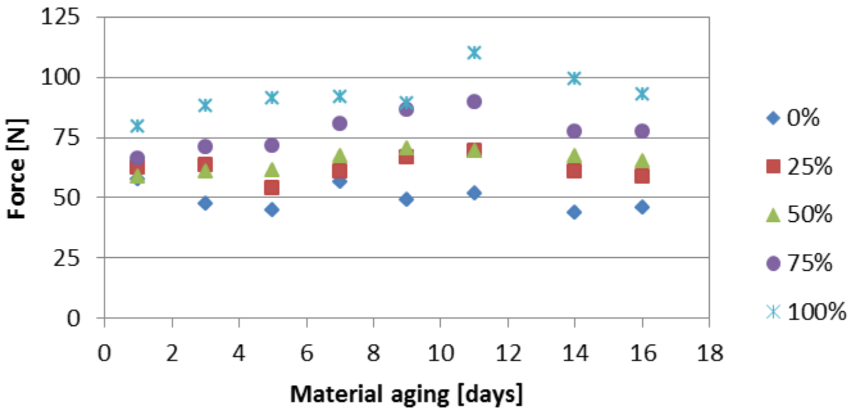

Figure 6. Force as a function of material aging for different heating power

While the maximum force increases the more the material aged at room temperature, figure 7 shows a decrease of the displacement at maximum force until day 11. This behavior can be recognized for all heating steps and also without heating. After day 11, the displacements seem to keep the constant low level. Furthermore, the higher the heating power was, the higher was the displacement at maximum force and the higher was the decrease with increased material aging.

This behavior also was not clearly determined for now and will be investigated in a following step. It can be assumed, that again the changing viscosity of the resin is a reason for this behavior.

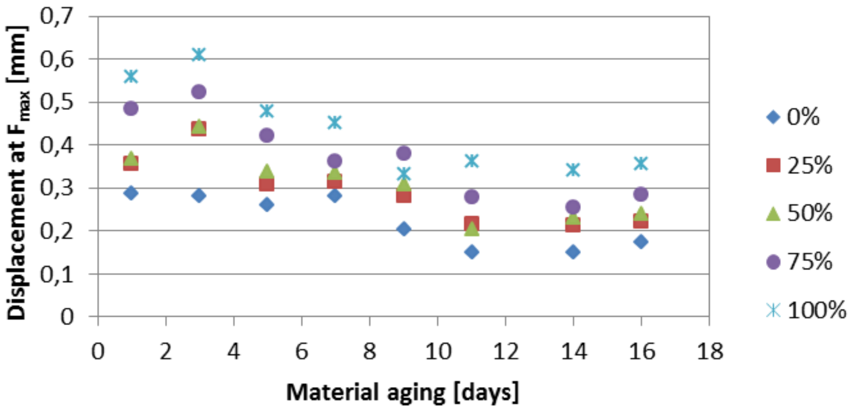

Figure 7. Displacement as a function of material aging for different heating power

Figure 8 generally summarizes the behavior described in figure 6 and 7 very well. It illustrates the increase of force and decrease of displacement at F_{max} between test day one (left) and day 11 (right), with same heating power. Furthermore, the force displacement progress after reaching F_{max} differs between day one and day 11. While the force decreased relatively slow after reaching the maximum force at day one, at day 11 the decrease mostly showed an abrupt behavior. This can be confirmed with another effect. With increased material aging, right after the force reached its maximum during the lap shear test, a little cracking sound could be noticed, which indicates immediate failure of the specimen.

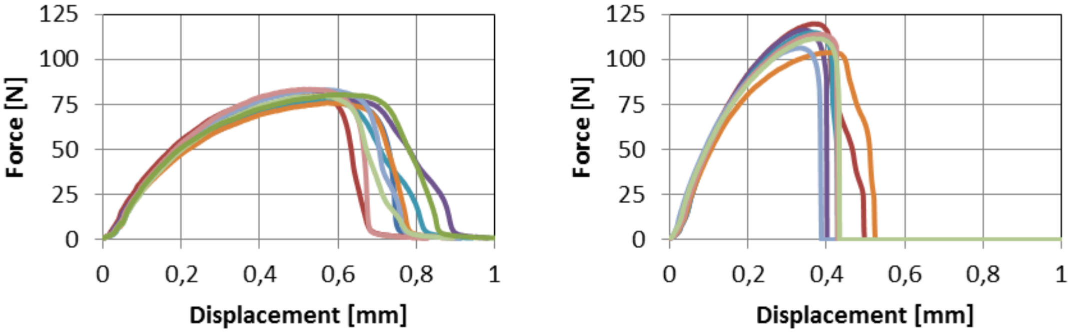

Figure 8. Left: day 1, heating power 100%. Right: day 11, heating power 100%.

5 Conclusion and Outlook

In order to optimize the quality of CFRP parts and its manufacturing process, the influence of material aging at room temperature and heating the material on the tack was determined. A lap shear test to determine the tack between two prepreg plies showed that heating the material strongly increases the tack. According the influence of material aging, against the expectations, the tack first increases and started to decrease after 11 days. A reason for this behavior, change of viscosity of the resin, could only be assumed for now and therefore should be determined in a next step. The decrease of displacement at F_{max} with increasing period of the material at room temperature could not be clearly explained for now.

The contact area, which is influenced by the layup process, may help to explain these effects and therefore will be investigated next. Also the behavior of the resin at different temperature and at different degree of cure according to mechanical behavior will be analyzed. Furthermore, the heating power could be increased to find out if the tack can be increased further and to find out the maximum tack at specific temperature. As the tack between the plies did not decrease clearly after 16 days, a longer test period will be realized to find out until what day at room temperature the material can still be laid up and how the tack at this time is. Finally, the influence of the aging material to the quality of the final part like porosity or mechanical properties will be determined.

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