FIRST PLY TACK OF AN AUTOMATED FIBRE PLACEMENT PROCESS – INFLUENCE OF HEATABALE MOULD SURFACE, RELEASE FILMS AND PROCESS PARAMETERS

Chinh D. Nguyen[1], Dominik Delisle[2]

German Aerospace Center (DLR)
Institute of Composite Structures and Adaptive Systems
Address: Ottenbecker Damm 12, 21684 Stade, Germany
Email: [1] chinh.nguyen@dlr.de, [2] dominik.delisle@dlr.de
Web Page: www.dlr.de/fa

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ABSTRACT

In the context of an automated manufacturing process of carbon fibre reinforced plastic (CFRP) parts, material is laid up on a tool with Automated Fibre Placement (AFP) or Automated Tape Laying (ATL) technology. For this, a sufficient tack between first ply and mould surface is important, especially for a layup on a vertical positioned mould surface. With the aim of providing the highest possible tack, the influence of a heatable mould surface with variated layup surfaces and process parameters was investigated. These tests provide important insights for the development of a reliable method for a layup process on a mould in vertical position. The selection of the layup surface showed a significant influence on the tack. Furthermore, an increase of tack could be determined, if the mould surface was heated.

1. INTRODUCTION

In the last decade layup technologies like ATL and AFP got more popular and affordable for part manufacturing in commercial aircraft business [1]. To meet the demand for higher production rates at same part quality new machine concepts are necessary. Since 2010 the German Aerospace Center (DLR) is developing an innovative production plant called GroFi®. Compared to state of the art facilities, main benefit of the GroFi® plant is the simultaneous work of up to four robots on a vertical positioned mould.

During a layup process the first ply usually needs to provide sufficient tack to the mould surface to withstand forces caused by the layup of subsequent plies without any displacement or slipping of the material. In contrast to a layup process on a horizontal positioned mould, additional shear forces occur on a vertical positioned mould due to gravity. These shear forces have to be compensated additionally by the tack of the first ply. Because of that, using a vertical positioned mould, a high tack between the first ply and the mould surface is more essential than using a mould in horizontal position.

The overall objective of the project EWiMa (Efficient Wing Cover Manufacturing), funded by the German Ministry for Economic Affairs and Energy, is to develop key technologies for an efficient, industrial production of wing covers in CFRP. One focus of this project is to identify different parameters influencing the tack between first ply and mould surface. The test methods as well as the results are shown in this paper.

2. STATE OF THE ART

A brief overview of the AFP technology and the necessity for a layup on a vertical mould surface is given in this chapter. Furthermore, the prepreg tack and its behaviour in AFP processes are described here.

2.1 Automated Fibre Placement Process

Compared to hand layup, a higher productivity with increased quality can be achieved by automated manufacturing of CRFP parts [2]. Two main technologies are ATL and AFP. Industrial ATL machines usually handle only one material spool. Because of the great width of the material (usually 150 mm or 300 mm), high productive layup can be achieved. 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 low width of one tow (usually 3.17 mm to 12.7 mm), 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.

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 are able to operate simultaneously at one part. By means of this concept, a substantial increase in flexibility and efficiency of a fibre placement process can be achieved. In addition, compared to current production plants an up to ten times higher productivity is expected. At present, two ATL units for prepreg material or expanded copper mesh with a width of 150 mm, two AFP units for 16 x 6.35 mm slittape material and one Dry Fibre Placement (DFP) unit are integrated in the GroFi® plant.

According to reachability and an increased productivity by laying up material on a double sided mould, mould surfaces in the GroFi® plant are mostly positioned vertically. In this case, a sufficient tack between layup surface and the first ply has to be guaranteed.

Figure 1: Left: Overview of the GroFi® plant. Right: production of a fuselage skin with AFP-Technology and vertical positioned mould surface.

2.2 Prepreg tack

According to Crossley [3], in fibre composite technology, tack is the adhesion between two surfaces during a layup process, before the part is cured. It can be differentiated in tack between ply and ply, and tack between mould surface and first ply, which was investigated here. While, because of the adhesive surfaces of both plies, a sufficient tack between ply and ply can generally be secured, the tack between mould surface and first ply has to fulfil particular requirements. On the one hand, a sufficient tack has to be ensured to prevent the material from slipping on the mould surface during the entire layup of the part. On a vertical positioned mould, where gravity causes shear forces between first ply and mould surface, this requirement is even more important. On the other hand, after the curing process the tack has to be low enough to guarantee a damage-free demoulding of the part.

Figure 2 illustrates parameters influencing the tack. While the influence of AFP-Technology and material can be seen as given, process parameters like compaction force, layup temperature of the material and layup speed [4] can be variated to achieve the required tack. Increasing the compaction force for example leads to an increase of tack [5]. Regarding the layup speed, the higher it is the lower is the compaction time. This again results into a decrease of tack. According to Ahn [6], an increase of tack can be achieved by increasing the temperature of the material. But if it is too high, it can also lead to a decrease of tack. Furthermore, especially the first ply tack can also be influenced by the surface finish as well as surface temperature, where the material is laid on.

Currently there are no standardised methods to measure the prepreg tack reasonably [7, 5]. Dubois [5] summarised test methods to determine the adhesion between two surfaces, but they turned out to be inappropriate for the requirements, which are given here.

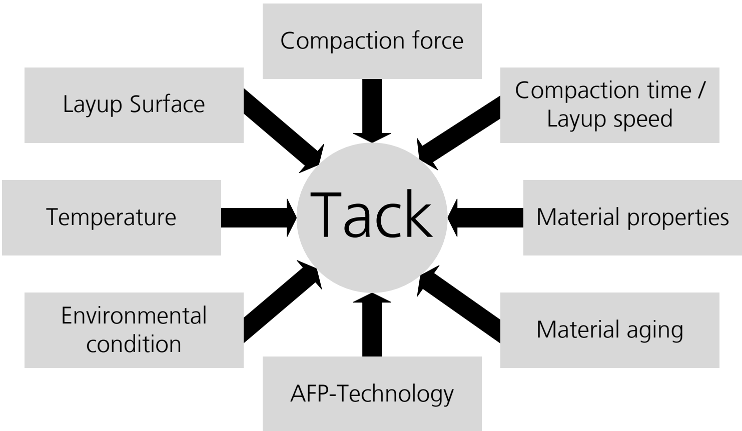


Figure 2: Tack influencing parameters

3. EXPERIMENTAL SETUP AND DESIGN

The aim of this test series is to identify the influence of different parameters to the tack between the first ply and mould surface. These results can be used to ensure that the laminate does not slip from a vertical positioned mould surface due to gravity. Tack influencing parameters, which were investigated here, are layup speed, heating of the material, different release films and mould surface temperature. First of all an appropriate test method to determine the tack behaviour had to be developed.

3.1 Experimental Setup

As mentioned above, after considering the given requirements, a standardised method is currently not available and therefore had to be developed first. The given requirements are:

- The measurement needs to be done within the plant, where the layup takes place
- The material to be tested is laid up on a vertical mould surface

- Pulling parallel to fibre direction is not possible due to geometrical constraints of the AFP-Technology

Due to these requirements a modified shear test, loosely based on ASTM D1002 [8], turned out to be appropriate. The test was carried out as follows. A robot based unit with AFP-technology lays up a single prepreg tow with a width of 6.35 mm and length of 300 mm on a vertical mould surface which is covered with a release film (Figure 3). The material, which was used here, has a fibre area weight of 134 g/m² with 34 % of epoxy resin. To influence the tack, layup speed and heating power of the infrared heater (maximum power: 1200 W) as well as release film and mould surface temperature were variated here.

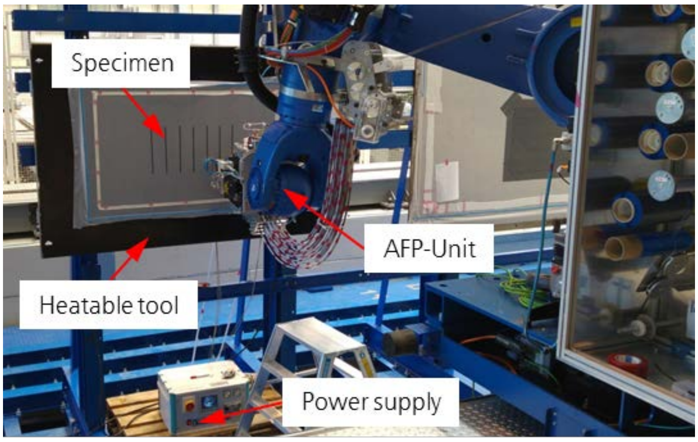
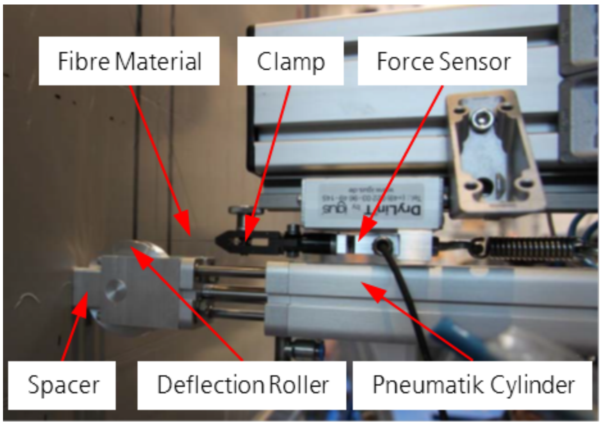


Figure 3: AFP-Unit during layup of tows on CFRP tool with heatable mould surface

Afterwards another robot unit, which is equipped with the tack measurement system (Figure 4), approaches the sample to execute the shear test. Here, a spacer on the right and left side of the deflection roller attaches on the mould surface with the deflection roller centred to the specimen (Figure 4, right). With the spacer, a defined gap of 0.2 mm between deflection roller and mould surface can be ensured. With a prepreg thickness of 0.13 mm it is secured that the material is not clamped between deflection roller and mould surface. Testing length L_{test} in this case was 30 mm, which means that in this length the prepreg material has contact to the mould surface. Then the upper part of the prepreg material was turned around the deflection roller and fixed with a clamp, which is mounted to a force sensor.



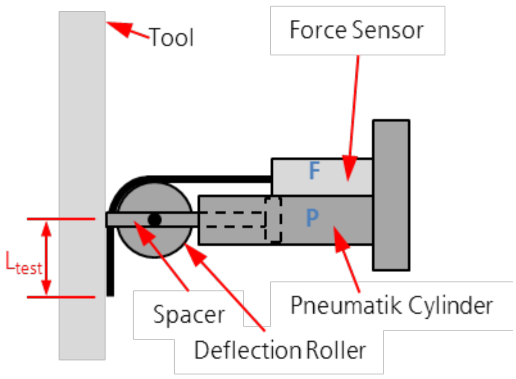


Figure 4: Tack Measurement System. Left: implementation. Right: schematic presentation

In a final step the tack measurement system removes from the mould surface with a defined speed of 10 mm/min. The pneumatic cylinder keeps the spacer with the deflection roller on the mould surface. Thus a constant angle of deflection of the fibre material during the reverse movement can be achieved. The shear force, needed to remove the fibre material from the layup surface, can be recorded with a force sensor (Figure 5).

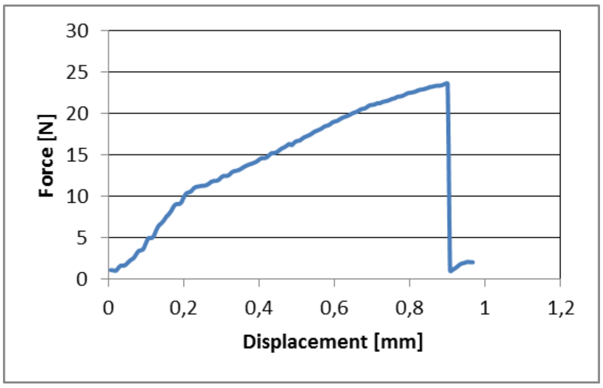


Figure 5: Force-Displacement-Diagram of a tack measurement

3.2 Experimental Design

The test series was separated in three phases (Table 1). To limit the number of experiments, the compaction force was kept constant at F=1000 N during the entire test series.

In the course of the first phase the power of infrared heater and layup speed as well as two different types of release films, WL5200 from Airtech and Flex$^{PLAS®}$ from Fraunhofer IFAM [9], were varied. The mould surface was not heated at this stage. With this phase the optimal adjustments for power of infrared heater and layup speed for the tested films can be determined for further tests. Phase two is to determine the most appropriate Flex$^{PLAS®}$ film regarding best tack. For this six different films were tested. These films consist of slightly different thermoplastic elastomere (TPE) material with different plasmapolymeric coatings resulting in different adhesive properties to e.g. the prepreg matrix after curing. The Flex$^{PLAS®}$ release films No. 1, 2, and 3 have easy release while No. 4, 5, and 6 have higher adhesion.

While the layup speed was still variated, the power of the infrared heater, which was determined in the first phase, was kept constant. The mould surface was still not heated. With phases one and two the influences of layup parameter as well as release films could be determined. With this, in the third phase the influence of a heatable mould surface could be determined with a manageable number of experiments. The tests were executed with two films, Airtech WL5200 and Flex$^{PLAS®}$ No. 6, which was identified in phase two. For the layup the mould surface temperature was increased in several steps up to 75°C. In a first test series the tack measurement was executed at a heated mould surface. This simulates the case, when the mould surface is heated during the entire layup, from first to last ply of a part. In a second test series, after layup on a heated mould surface, the mould surface was cooled down to room temperature, before executing the tack measurement.

Because the entire test series lasted for several weeks and the prepreg material changes its condition at room temperature continuously, new material was used every second day.

Table 1: Test phases

Phase 1	**Influence of power of infrared heater and layup speed** • 2 release films (Airtech WL5200 / Flex$^{PLAS®}$ No.1) • Variation of power of infrared heater • Variation of layup speed (4, 7, 10 m/min) • No heating of mould surface
Phase 2	**Influence of Flex$^{PLAS®}$ release films** • Variation of Flex$^{PLAS®}$ release films • Variation of layup speed (4, 7, 10 m/min) • Constant power of infrared heater • No heating of mould surface

Phase 3	**Influence of heatable mould surface**
	• Constant power of infrared heater (phase 1)
	• Constant layup speed (phase 1 & 2)
	• 2 release films (phase 1 and 2)
	• Variation of mould surface temperature during layup
	  • Tack measurement at deactivated mould surface heating
	  • Tack measurement at activated mould surface heating

4. RESULTS AND DISCUSSION

Disregarding the tack measurements at a heated mould surface, during the entire test series, the shear forces, which were needed to separate the prepreg material from the layup surface, were on a relatively high level of at least 11 N at a contact area of 6.35 x 30 mm². In comparison to that, the shear force caused by gravity of a laminate with 300 plies and same size of contact area is just 0.115 N. This means that with all tested parameter variation the tack was always high enough to withstand shear forces caused by gravity.

The layup trials and tack measurements with unheated mould surface showed little influence of the infrared heater to the tack between prepreg and layup surface. This could be observed for both release films tested in the first phase, Airtech WL5200 and Flex$^{PLAS®}$ No.1 (Figure 6). The reason for that behaviour is the setup of the fibre placement head. Due to space limitations, the infrared heater illuminates the material, which has to be laid up, only to a little extend. It mostly illuminates the surface in front of the compaction roller. For a layup of prepreg on prepreg the already laid up material gets heated and the tack increases. In case of the first ply the infrared heater mostly illuminates the mould surface with the release film where, due to convection, the thermal energy does not last long enough at the layup point. For both release films, Airtech WL5200 and Flex$^{PLAS®}$ No. 1 the maximum force needed to separate the prepreg material from the layup surface was about 15 N, variating between 11 N and 19 N.

Figure 6 also shows no clear differences of tack between the tested layup speeds of 4, 7 and 10 m/min. The layup speed mostly influences the compaction time, of which the compaction roller presses the prepreg material on the layup surface. The higher the layup speed, the lower the compaction time. Due to a deformation of the compaction roller a compaction length of 15 mm occur. While a layup speed of 4 m/min results into a compaction time of 0.225 seconds, for 10 m/min the compaction time is 0.09 seconds. Even though the compaction time is more than two times longer at a layup speed of 4 m/min compared to 10 m/min, in both cases the absolute compaction time is very short. Therefore no influence between the tested layup speeds could be observed. A possibly clearer influence could occur at a significant higher compaction time. To achieve this within an automated layup process, the layup speed has to be decreased dramatically. Regarding the aim of high productivity this would not be a use-oriented case anymore.

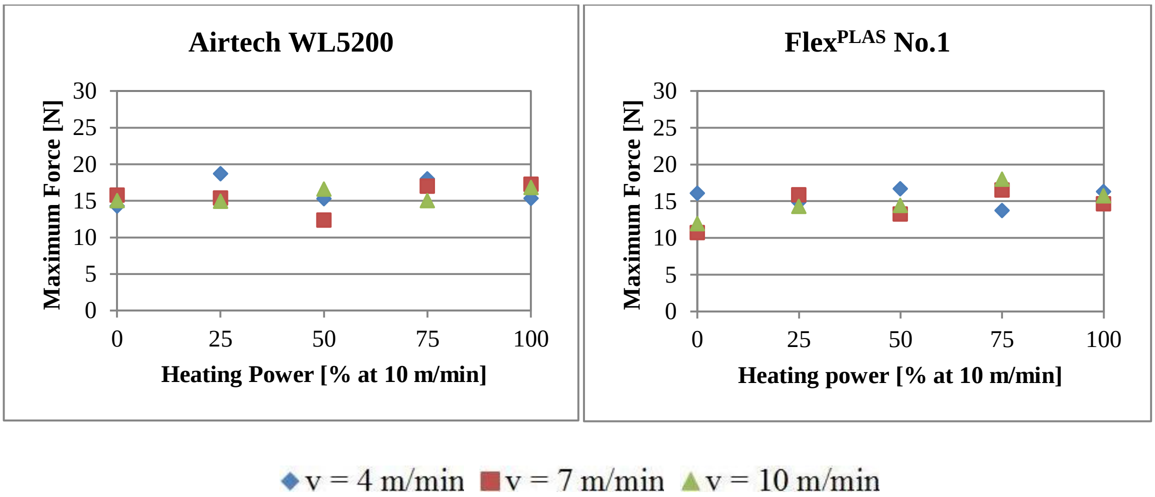


Figure 6: Tack between prepreg and release films (Airtech WL5200 / Flex$^{PLAS®}$ No.1). Variation of heating power and layup speed. Mould surface was unheated.

In phase two of the test series six different Flex$^{PLAS®}$ films were compared with each other. Process parameters were 10 m/min layup speed and 900 W (75 %) heating power at 10 m/min. As expected, the Flex$^{PLAS®}$ No. 4, 5 and 6 with a higher adhesion showed clearly better tack than Flex$^{PLAS®}$ No. 1, 2 and 3, which had easy release (Figure 2). For further tests with heated mould surface Flex$^{PLAS®}$ No. 6 was chosen to compare with Airtech WL5200 film. The reason for this selection was on one hand the appropriate tack for the Prepreg layup, on the other hand the easy release after curing as well as a better availability during the project EWiMa.

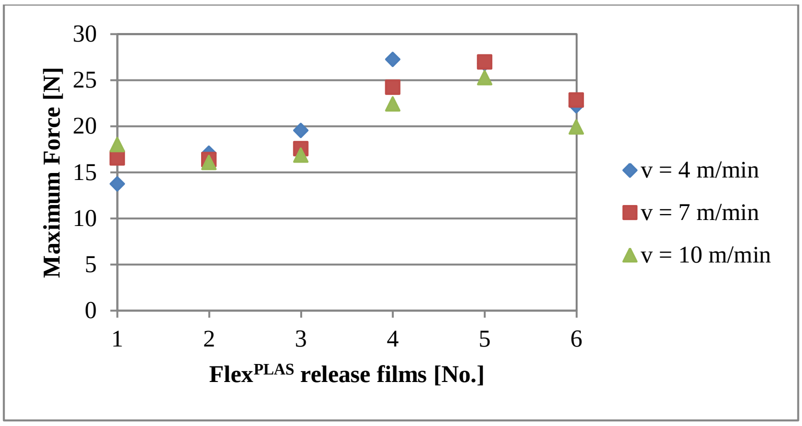


Figure 7: Comparison between different Flex$^{PLAS®}$ films. Mould surface was unheated.

Phase three researched the influence of a heated mould surface to the tack. To minimise the number of trials, layup speed and heating power was kept constant during these tests. Based on the tests with unheated mould surface the layup speed was 10 m/min and heating power of the infrared heater was 1200 W (100 %). Starting at room temperature (no mould surface heating), the mould surface temperature was increased to 30, 45, 60 and 70°C.

Depending on the used release films, the results show different behaviour of tack, if the mould surface is heated (Figure 8). If the layup takes place on a heated, and the tack measurement takes place on an unheated mould surface, for Airtech WL5200 film the tack was mostly constant at 16 N. For Flex$^{PLAS®}$ No.6 film, an increase of tack from 20 N to 25 N could be observed with increasing mould surface temperature. In this case the tack reaches its maximum at a mould surface temperature of 45°C. Further increase of mould surface temperature does not lead to further increase of the tack.

If both, fibre layup and tack measurement take place on a heated mould surface, a significant decrease of tack with increasing mould surface temperature could be observed. This behaviour can be explained due to the decrease of the viscosity of the resin with increasing temperature. If the heating of the mould surface was deactivated after the layup, the viscosity of the resin increases again. This leads to a higher tack. But if the heating of the mould surface is activated during the measurement, the tack remains at the low level. Due to these observations a permanent heated mould surface during the entire layup of a laminate cannot be recommended.

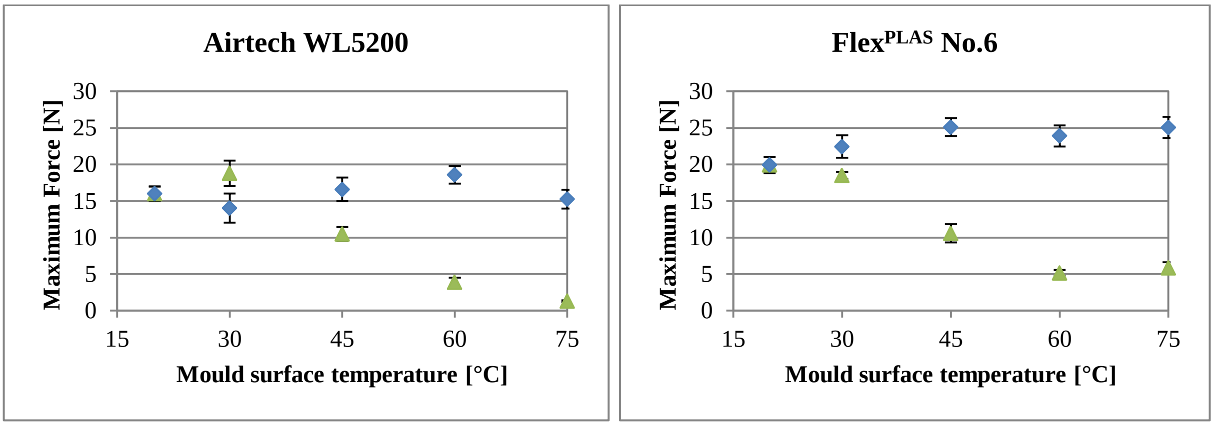


Figure 8: Tack at different mould surface temperature for Airtech WL5200 and Flex$^{PLAS®}$ No.6. Layup of prepreg at heated mould surface. Tack measurement at deactivated (◆) / activated (▲) mould surface heating.

5. Conclusion

To get a reliable layup of the first prepreg ply on a vertical positioned mould surface without slipping or displacement, the influence of a heatable mould surface was investigated with the aim of achieving a sufficient tack between first ply and mould surface. Beside the influence of a heatable mould surface, the influences of different process parameters as well as different release films were investigated. With the test series carried out here, a reliable process could be determined.

Compared to shear forces caused by the gravity of a laminate with 300 plies, a sufficient tack could be achieved with all tested configurations. Nevertheless various parameters influenced the tack differently. While a significant influence of the process parameters layup speed and heating power of the infrared heater could not be determined for the tested range, differences between several release films could be observed.

Regarding heating of the mould surface, an increase of surface temperature leads to an increase of tack for the Flex^{PLAS} film. For the Airtech film no influence could be determined. If the mould surface is heated, then it should only be heated during the layup of the first ply.

Regarding the aim of a high tack, heating during layup of the entire laminate cannot be recommended.

6. Acknowledgement

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