MECHANICAL PERFORMANCE OF IN-SITU CONSOLIDATED THERMOPLASTIC FIBER REINFORCED TAPE MATERIALS

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ABSTRACT

The lecture presents investigations for the comparison of different heating systems usable for in-situ consolidation. The heating procedures flame, hot gas, and infrared are analyzed. The in-situ consolidation takes place with aid of an instrumented thermodynamic test rig for fiber reinforced tape material. Since the tapes used have a thickness of up to 1mm, the resulting in-situ consolidated specimens are not useful for tests which require thick specimens, e.g. double cantilever beam (DCB) test to characterize the energy release rate. To define optimizsed processing parameters for in-situ consolidation it is necessary to know the parameters resulting in a maximum value for energy release rate. The already known correlation between DCB propagation data and the wedge peel resistance is used to define, depending on the different process parameters, a possible process window for the tape processing.

1. INTRODUCTION

Large interest exists in different industrial ranges at the introduction and/or further spread of continuous fiber reinforced thermoplastics for complex shaped parts [1, 2]. Beside the well known autoclave technology, commonly used for producing thermoset based parts, but also applicable for manufacturing thermoplastic based parts, which is economically useful only for small-scale production or just even for prototypes, two further technologies can be used for large-scale production. The first is using fully consolidated organic sheets, to thermoform them and, if necessary, to weld them by e.g. induction welding [3]. The second possibility is to use fully impregnated continuous fiber reinforced thermoplastic tapes [4, 5]. These tapes can be used in a winding process [6] or, to create small up to large as well as complex shaped parts, in a tape placement process [7, 8]. Thermoplastic tape placement offers due to the in-situ consolidation compared to a thermoset based process the possibility to save an additional consolidation treatment. Furthermore, the thermoplastic tape material is much easier to handle and has no limited stock life. The high quality requirement of the components requires the availability of adequate production processes and a deep understanding for the parameters effecting the process [9, 10]. During the in-situ consolidation a net-shape placement of the material and at the same time welding of the substrate in one step takes place. By this, the complexity of the process is increased and there is a large need to develop and enhance the theoretical background, the physical, thermodynamic, and chemical process understanding.

Fig. 1. Thermoplastic tape placement, components of a placement head (left) and IVW placement head “Evo I” (right).

2. PROCESS DEVELOPMENT

Tape placement is known for many years and is often used for industrial processing of thermoset systems. Thermoplastic tape placement is still in the development phase. The tape and the substrate on which the tape is placed must be heated to the melting point in the joining area directly before joining. For this reason a tape placement technology with an integrated heating technology is required. Fig. 1 shows a possible construction type of a tape placement head with its main components. Besides the there illustrated flame heating, hot gas, infrared, or laser can alternatively be used as heating systems. The use of a consolidation roller is important for a satisfying tape placement result. The tape can only be placed with reduced pre-tension during the tape placement process. Otherwise separations would especially occur in concave geometries. The necessary pressing for a sufficient consolidation in the nip point can therefore, only be reached by a head integrated, vertical to the substrate surface pressing. Based on the experiences of a successive development in the head technology with the newest head generation (Fig. 1) a complete automated plant technology was made available at the Institut fuer Verbundwerkstoffe (IVW).

Besides the development of the process technology also an intensive process analysis was carried out to increase the laminate properties of tape placed specimens. The simulation tool ProSimFRT (Process Simulator for Fiber Reinforced thermoplastic Tapes) [4], developed at IVW, makes the forecast of the developing temperature field during the process in the anisotropic material possible. Beyond that, a thermo dynamic test rig was established (Fig. 2).

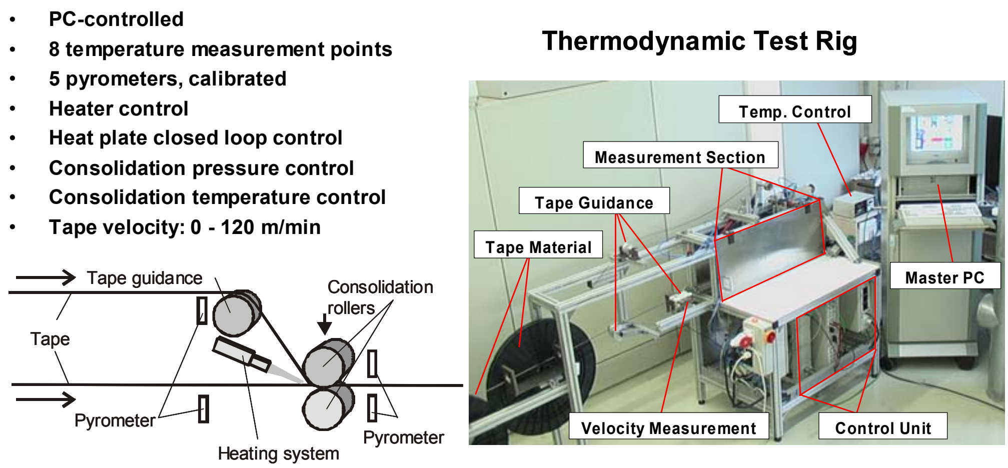

Fig. 2. IVW's thermodynamic test rig (right), its instrumentation and a sketch of the "Double Tape" configuration for in-situ consolidation investigation (left).

The motivation of the development and the major tasks of the test rig can be described shortly as follows:

- Determination of temperature flow of thermoplastic tapes during a thermal joining procedure in the style of tape placement/winding.
- Variation of the heat-up parameters (kind of pre-heating and feed angle).
- Variation of consolidating parameters temperature, pressure, and speed.
- Determination of simple discharge verification data for two dimensional process models by simplified and reproducible geometric boundary conditions compared to tape placement/winding.
- Determination of empirical partial models for complex partial processes (e.g. flame heating).
- Determination of boundary condition data for thermodynamic simulation.
- Investigation of deformation behavior of tapes during the consolidation.
- Processing of peel strength samples.

3. MATERIAL AND TESTING

The thermoplastic tape placement process is particularly used for the production of very large components with very high mechanical load bearing. Therefore, the targets of application are in the aviation area. Here matrix materials as engineering thermoplastics like PEEK or PPS and the carbon fibers as fiber materials are used. The investigations of the presented work were accomplished with full impregnated CF/PEEK tapes. Apart from the qualified APC2/AS4 quality (Cytec Fiberite), also the new developed modified TIF APC (PEEK) AS4 (Cytec Fiberite), and the SUPreM Tape CF/PEEK (Gurit Suprem) were examined.

Target of the work was the characterization of the process parameter influence on the laminate quality during the tape placement process. In order to understand the direct correlation it is important to examine the directly reached laminate properties achieved by the in-situ consolidation step. Usually the laminate quality is evaluated by the characterization of the crack propagation resistance. Double cantilever beam (DCB) tests for mode I impact, end load split (ELS) tests for mode II impact, or three point being tests are typical tests carried out. Test specimens of several millimeter thickness are required for all methods. The tapes usually used for the tape placement process have, depending on the type, only a thickness of 100 – 200 µm. Several layers are to be placed on top of each other in order to manufacture test specimens which meet the geometry demands specified above. This means not only an increased material consumption but also multiple influence of the in-situ consolidated zone by the repeated override with the tape placement unit. A simple and fast test method, which allows the evaluation of two in-situ consolidated tapes should be used. In this case a wedge peel test is chosen (Fig. 3). Hulcher et al [11] showed, that the principle curve of the DCB propagation data corresponds with the wedge peel resistance as function of the consolidation parameter.

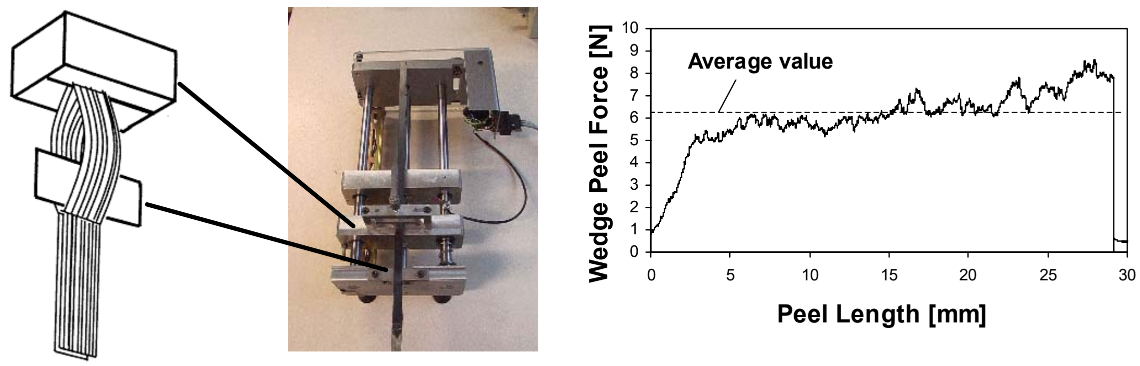

Fig. 3. Wedge peel resistance test, test configuration (left [11]), test rig (middle) and resulting data plot of wedge peel force vs. peel length (right).

First of all it was examined if the process dependant laminate properties can be evaluated by the wedge peel test. Therefore, the bending strength was compared to the wedge peel resistance. UD-laminates (20 tape layers) were produced with the IVW tape placement robot (Fig. 1) to measure the bending strength in a three point bending test. Various process conditions were achieved by use of a hot gas gun with different gas volume flow rates. Under the same process conditions peel test specimens were manufactured with the tape placement robot and tested afterwards.

For the evaluation of different heating methods for the in-situ consolidation specimens were manufactured on the IVW thermodynamic test rig in a double tape configuration (Fig. 2). Here H_2/O_2 flame, hot gas, and infrared heater were used.

4. TEST RESULTS AND DISCUSSION

The bending strength passes the gas flow rate at a maximum, which is for the used process requirements in the range of 8 – 10 nl/min (Fig. 4). The examination of the wedge peel resistance also results in a maximum and is also in the range of 8 – 10 nl/min. As already showed by Hulcher et al. [11] the wedge peel test can also be used for the process optimization due to the fact that the maximum properties are identical for both tests in regard to the process parameters.

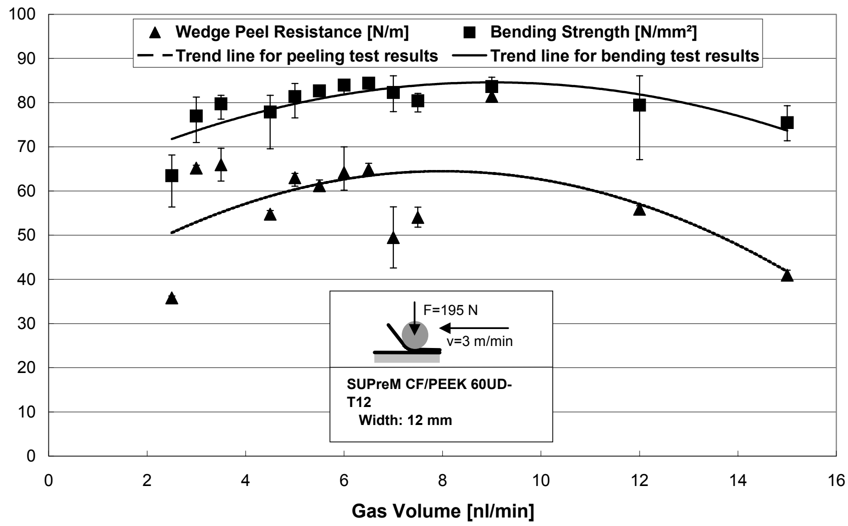

Fig. 4. Wedge peel resistance and bending strength data vs. gas volume rate used for hot gas heating.

Beside the heating energy, the parameters consolidation pressure and speed are available for the tape placement process as adjustable parameters. During the evaluation of the different heating methods a clear influence of the acting consolidation force (Fig. 5) can be observed during a constant tape placement speed of 3 m/min. For all three heating methods an increase of the wedge peel resistance with increasing consolidation force can be observed in the examined area. However, the influence of the consolidation force for the different heating methods is differently pronounced. The flame heating presents itself as the method to be the hardest influenced. With low consolidation pressure wedge peel resistance values of approx. 1 kN/m can be achieved, and which can only be increased slightly above the consolidation pressure. Clearly obvious is the influence of the consolidation pressure of the hot gas pipe. Indeed the wedge peel resistance is here on a clearly higher level with values of approx. 1.5 kN/m. Extremely noticeable is the influence of the consolidation pressure when infrared spot heaters are used. The same wedge peel resistance level as with a flame is reached but only at higher consolidation pressure.

The advantage of the hot gas gun compared to the flame and in particular to the infrared spot heater (Fig. 6) can be observed if the speed influence at constant consolidation pressure is investigated. In general, for all heating methods a decreased wedge peel resistance can be recognized by increasing the process speed.

The tests showed that the wedge peel test is a fast and significant test method for the characterization of the achieved quality during the in-situ consolidation process. Compared to other test methods like DCB, ILS, or three point bending tests, the wedge peel test offers the possibility to examine directly through the adjusted process parameter the adjustable quality. The sample manufacturing for the other test methods requires a repeated tape placement on top of each other. Through this a thermal activation can be observed in the already placed tape plies combined with an active consolidation force. Simulations showed that this effect can influence several of these plies (Fig. 7) [12]. More likely a worst case estimation of the reached quality of the in-situ consolidation is possible with the wedge peel test.

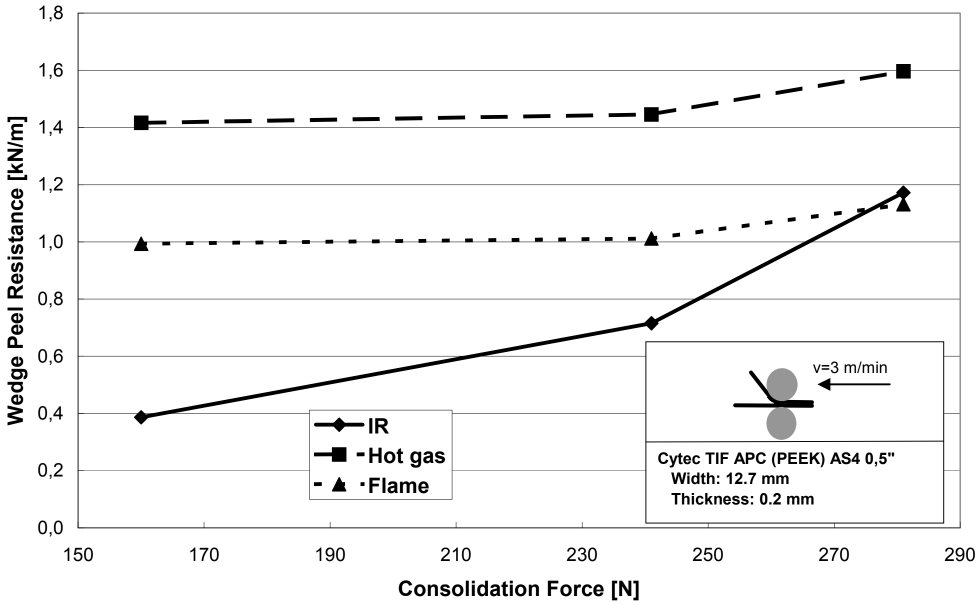

Fig. 5. Wedge peel resistance vs. consolidation force for different heating sources.

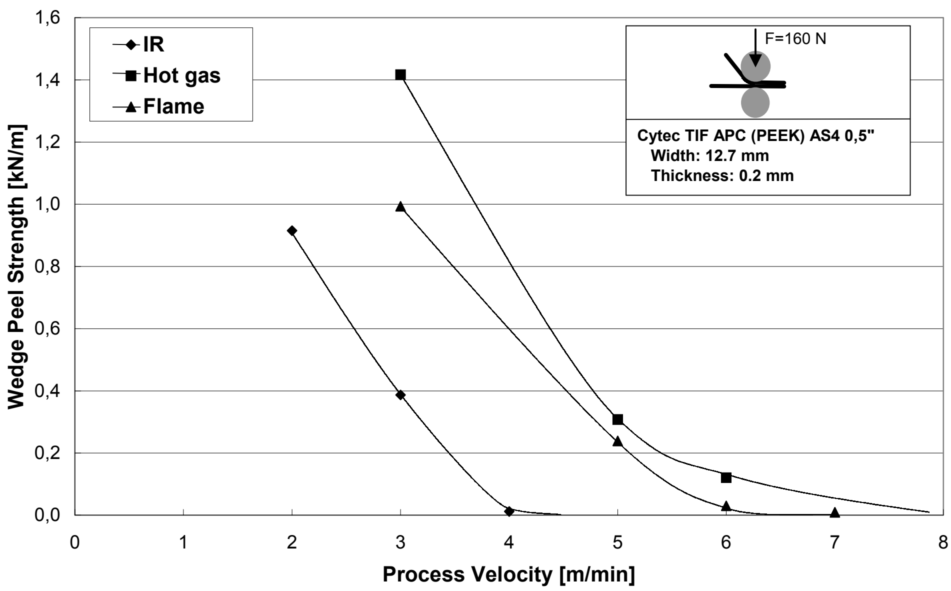

Fig. 6. Wedge peel resistance vs. process velocity for different heating sources.

The assessment of the tested heating methods flame, hot gas, and infrared shows the principle applicability of this technology during the in-situ consolidation. The advantages and disadvantages of the examined systems are shown in Table 1 [13]. The disadvantages during the material heating during the filament winding process can partially be adjusted by a pre-heated distance unit. In this case, also relative large heating systems can easily be integrated. The demand for the tape placement process focuses on a relatively compact placement unit. Here an as small as possible heating system is preferred. The integration of the pre-heating distance in the placement unit is to be avoided due to place and weight reasons. Due to engineering reasons the heating systems flame and hot gas are the preferred processes.

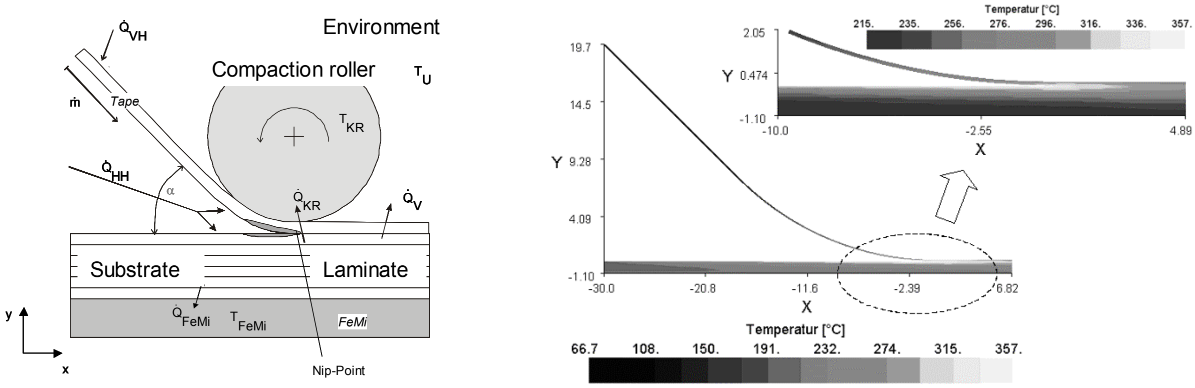

Fig. 7. Process model for thermoplastic tape placement (left) and calculated nip point temperature filed (right) for CF/PEEK, flame heating, heated compaction roller, heated metal tool, already placed 14 ply substrate and a placement velocity of 6 m/min.

Table 1. Advantages and disadvantages of different heating technologies.

Heating source	Advantages	Disadvantages
Flame	• Low investment costs • Small heating unit • Easy to integrate • Very good knowledge available • No material specific characteristic • High heat flow density • Highly robust technology	• Energy transfer mainly by heat conduction • Degradation by means of oxidation is possible • Hardly to adjust/control • Large affected area
Hot gas	• Low investment costs • Small heating unit • Easy to handle • Easy to integrate • Very good knowledge available • No material specific characteristic • Well focused energy transfer	• Medium heat flow density (depending on system) • Energy transfer mainly by heat conduction • Slowly reacting system
Infrared	• Low investment costs • Highly efficient • Good knowledge available • Contact less energy transfer	• Low heat flow density • Material depending absorption • Big sized heating unit • Hard to integrate

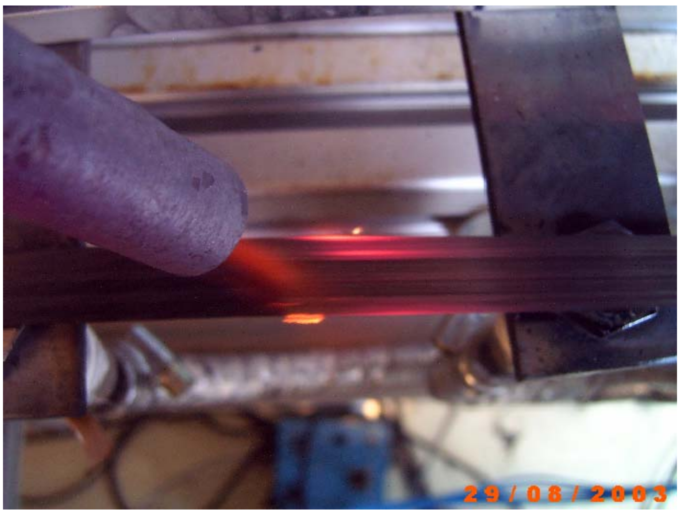

Fig. 8. Heating of thermoplastic tape material using hot gas.

The achieved mechanical results are clearly influenced by the processing parameters. Under economic aspects the use of the hot gas heating proves to be the most efficient process. The very effective direct acting hot gas heating is a very homogenous heating (Fig. 8). Thus, enough energy is brought into the material so that a very good consolidation is possible even at higher tape placement speed.

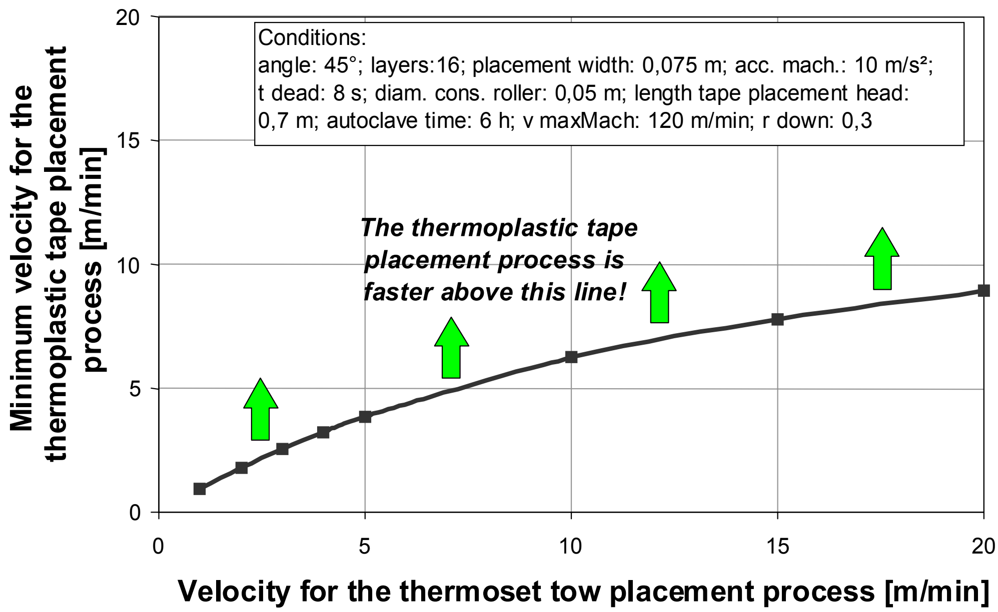

Fig. 9. Comparison between thermoplastic tape placement and thermoset tow placement for a given complex shaped part of the V-22 composite aft fuselage.

5. CONCLUSIONS

Different heating systems for processing of unidirectional fiber reinforced thermoplastic tapes were examined using in-situ consolidation. These materials are used for manufacturing of load optimized components. A typical application field for these components is in the aviation area, which uses today's primarily thermoset materials as composites, due to system experience for many years, the accordingly fully developed processing technology, and the relative low material price. Thermoplastic materials consist of some advantages compared to thermoset materials, like improved mechanical properties, e.g. clearly better impact resistance or unproblematic shelf-life. Unfavorable are, however, the relatively high material costs and the processing technology which is still not completely developed. Although the tape placement technology for thermoset and thermoplastic systems is known for many years, only the processing of thermoset systems has been established in an industrial scale. Current work deals generally with the process development and is a new challenge on the in-situ consolidation. The new process requires a placement head with integrated heating and consolidating system. The advantages of the thermoplastic system can only be utilized, if the process enables a sufficient consolidation with accordingly good mechanical properties. By the process modeling [5] the range can be estimated for which an advantage for the thermoplastic system can be achieved. Fig. 9 shows that these advantages arise already at lower process speed if compared with thermoset tow placement process.

Another challenge apart from the process development is the process optimization. The presented work showed the influence of different heating systems on the attainable mechanical properties for a component manufactured with tape placement technology.

ACKNOWLEDGEMENTS

Parts of the work presented have been supported by the AIRBUS Deutschland GmbH. Additionally the author want to acknowledge the grant of the Bundesministerium für Bildung und Forschung (BMBF) for the project „Tow placement mit neuen thermoplastischen Halbzeugen für große Strukturen – GroTherm“ (Förderkennzeichen 03N3120D) and the grant of the Deutsche Forschungsgemeinschaft (DFG) for the project “Prozessbasierte Modellierung der Fertigungszeit und –kosten für das Thermoplast-Tapelegeverfahren” (Mi 647/7-1).

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