METHODS FOR THE POST-CONSOLIDATION OF HIGH-SPEED-WOUND THERMOPLASTIC CFRP TUBES

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Abstract

This study investigates post-consolidation methods for thermoplastic carbon fibre reinforced plastic (cfrp) tubes produced using Continuous Resistance Heating Technology (CoRe HeaT). CoRe HeaT uses the electrical resistivity of carbon fibres to heat them up intrinsically via the Joule effect, allowing for extremely fast heating rates and volumetric heat generation within the fibres. The goal is to determine suitable process chains for producing high-speed wound carbon fibre reinforced thermoplastic tubes that can be used for cost-effective cylindrical products such as tanks, piping or struts. One important step to make high-speed processing of thermoplastic tapes viable is the post-consolidation, which is mandatory to maintain/obtain good mechanical properties. The study compares three consolidation methods, using shrink tape, vacuum, and their combination, to achieve good consolidation quality at minimal costs. The use of an autoclave is avoided, reducing investment costs and improving resource and energy efficiency. To examine the consolidation quality of tube samples, optical microscopy is used. Furthermore, mechanical properties are tested using Apparent Hoop Tensile Strength tests based on ASTM D2290. The results provide a differentiated analysis of post-consolidation methods and their effects on material and mechanical properties. Moreover, they offer insights into the phenomena arising from the consolidation process.

1. Introduction

The increasing demand for high-speed production of advanced carbon fibre reinforced plastics (cfrp) has driven the development of novel manufacturing techniques. One such approach is the Continuous Resistance Heating Technology (CoRe HeaT) process, which is being developed at the Center for Lightweight-Production-Technology (ZLP®) of the German Aerospace Center (DLR) in Stade, Germany. It aims to accelerate processes like filament winding and automated fibre placement (AFP) of composite materials. CoRe HeaT uses resistance heating to heat up carbon fibre (cf) tapes. Therefore, the surface of the cfrp tapes is electrically contacted by two electrodes. The Joule effect heats up the fibres volumetrically. Especially in the field of thermoplastic cfrp materials, which require a high energy input to exceed the melting temperature of the matrix, CoRe HeaT offers the possibility to increase the production speed with high energy efficiency. Furthermore, the investment costs are comparatively low and there is no need for costly safety enclosures as in established laser assisted fibre placement processes. [1, 2]

After successfully using the technology in AFP processes [1, 2, 3], the technology was adapted to winding processes.. The present study investigates post-consolidation methods for thermoplastic cfrp tubes produced using CoRe HeaT, aiming to determine suitable process chains for producing high-speed wound tubes with optimal consolidation quality at acceptable costs in terms of time and resources.

In order to achieve optimum consolidation of the laminate with adjustable material properties of the thermoplastic matrix, especially when using semi-crystalline thermoplastics, post-consolidation is used in the process chain with CoRe HeaT. The use of heat shrink tapes can help to increase the degree of automation and ensure a resource-saving post-consolidation process. Furthermore, an out-of-autoclave process is used in favour of the low-cost approach. Various consolidation methods, such as the use of heat shrink tapes, the use of a vacuum build-up and a combination of both methods are considered. In addition, parameters such as the number of shrink tape layers and their winding tension are varied during the wrapping process.

Mechanical test methods for pipe test specimens are usually far more complex than established standard methods for testing flat laminates. For example, tests on entire tubes that are subjected to internal pressure or tested under combined tension/compression and torsional loads are very resource-intensive. Furthermore, in the context of current research, it is expected that many iterations of different parameter sets and materials will need to be tested to increase the technology readiness level of this high-speed manufacturing process. For this reason, the Apparent Hoop Strength (AHS) test according to ASTM D2290 is used. In this test, pipe segments, i.e. rings, are tested for their circumferential tensile strength in a split disc device [4]. In addition, the consolidation quality is analysed with micrographs.

2. Methods

A core motivation for using CoRe HeaT technology for winding thermoplastic cfrp pipes is to increase winding speeds, since the heating rates, which can be achieved with CoRe HeaT, can potentially exceed 100000 K/s [2]. The high-speed winding process is followed by post-consolidation in the process chain, which is needed to adjust the final component properties. Furthermore, by actively controlling the cooling rates, the crystallinity of semi-crystalline matrix systems can be adjusted to suit the application [5, 6]. What is desirable here is an efficient post-consolidation process that requires few resources, is fast and highly automated and results in good mechanical properties. In order to simplify the consolidation process, out-of-autoclave methods are being investigated.

For the present investigations, pipes are wound from thermoplastic cfrp tapes with Polyamide 12 (PA12) matrix of the Suprem™ T type with a fibre volume content of 55%, a width of 1/4" and a thickness of 0.26 mm using CoRe HeaT. On steel cylinders preheated to 80 °C with a diameter of 70 mm and a wall thickness of 5 mm, 8-layer pipe preforms of 90 mm length are produced at a winding speed of 200 mm/s at a processing temperature of 240 °C on average. The tapes are wound side-by-side with circumferential winding angles of quasi 90°.

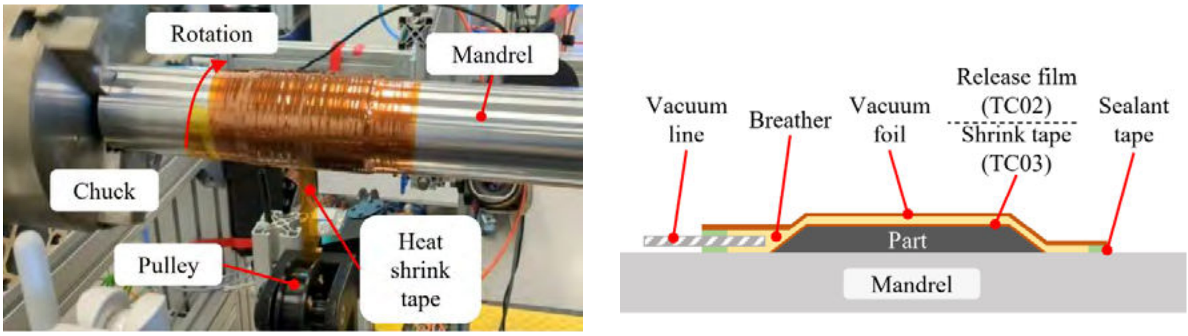

Figure 1. Shrink tape winding setup (left). Vacuum consolidation build-up (right).

A key focus of the test series is to evaluate the suitability of heat shrink tapes as an aid for the consolidation of thermoplastic pipes wound using CoRe HeaT. High temperature resistant 208X polyimide heat shrink tapes kindly provided by The Dunstone Company, Inc is used for the post-consolidation process. A picture of the shrink tape winding process is shown in Figure 1 (left). As part of the tests, several configurations and parameter variations of the post-consolidation are investigated. The first comparison involves varying the consolidation method. Pipes wrapped in shrink tape and pipes in a vacuum setup (see Figure 1 right) are compared. Furthermore, a combination of the two variations, a pipe wrapped in shrink tape which is consolidated in a vacuum build-up (see Figure 1 right), will be investigated. In addition, the influence of the tape tension when wrapping the shrink tapes, the number of shrink tape layers, the oven holding time and the overlap during wrapping are tested.

Consolidation takes place in an industrial oven at 240 °C with a heating ramp of around 4 K/min, a holding time of 40 min and slow passive cooling with a rate less than 1.5 K/min. The holding time begins as soon as the steel mandrel has reached a temperature of 230 °C. The samples are removed from the oven and demoulded at a temperature <80 °C, which is below the permanent service temperature of PA12. [7]

This results in the following configurations:

Table 1. Tested consolidation parameter sets.

Series name	Consolidation method	Shrink tape overlap	Shrink tape layers	Total amount of layers	Shrink Tape Tension (N) (normalized to 1” shrink tape)	Holding Time (min)
TC01 (reference)	Shrink tape	1/2	4	8	15 (20)	40
TC02	Shrink tape + Vacuum	1/2	4	8	19,6	40
TC03	Vacuum	-	-	-	-	40
TC04	Shrink tape	0	8	8	15 (20)	40
TC05	Shrink tape	1/2	2	4	30 (40)	40
TC06	Shrink tape	1/2	8	16	15 (20)	40
TC07	Shrink tape	1/2	4	8	15 (20)	80
TC08	Shrink tape	1/2	2	4	15 (20)	40
TC09	Shrink tape	1/2	4	8	30 (40)	40

An easy and resource efficient test method is the Apparent Hoop Strength (AHS) test in accordance with ASTM D2290, in which the strength of pipe segments is tested in a tensile test using a split disc device [4, 8, 9]. According to studies in the literature, stress peaks occur at the indentations that are to be used in accordance with the standard [9, 10]. Since the effect of these indentations is not clear for the tubes which are being produced, they are not used. This results in more uniform stress distribution in the specimen [7], easier production and better comparability to similarly produced specimens. Pipe segments of 6 mm width are cut out of the post-consolidated pipes using a water-cooled cutting device. Afterwards they are dried in an oven and conditioned at 23 °C and 50% relative humidity before testing. The Apparent Hoop Strength is calculated as follows [4]:

$$\sigma_a = \frac{F_{max}}{A} = \frac{F_{max}}{(b_1 t_1 + b_2 t_2)} \tag{1}$$

The Apparent Hoop Strength σ_a describes the maximum test force F_{max} when the test specimen breaks, and the widths b_1 and b_2 and thicknesses t_1 and t_2 of the two lateral breaking points. The dimensions of the breaking points are measured using micrometers. A total of 5 rings per series are tested with a testing speed of 2.5 mm/min with an apparent hoop strength fixture attached to a Zwick Roell 1484 universal testing machine. After determining the AHS σ_a, the test series are examined for outliers and a best fit of the data is used for evaluation, which retains the basic tendencies and processes the data in favour of better comparability. Figure 2 depicts the AHS fixture, comprising one pair of mounting adapters, split disks, and bolts. The figure also shows the nominal thickness and width of the specimen used. Note that measurements were taken at two points directly on the horizontal plane of separation between the split disks, precisely where the specimen is expected to fail during testing.

In addition, cross-sectional and longitudinal micrographs of pipe segments are prepared for visual examination with an optical microscope in order to analyse the consolidation quality optically.

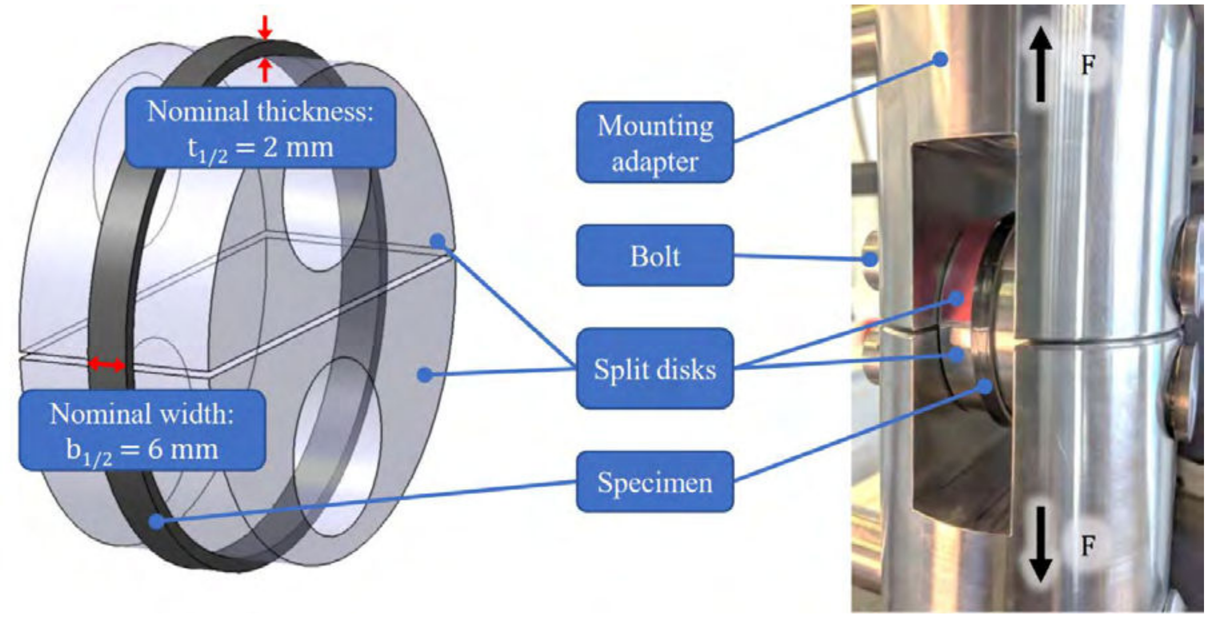

Figure 2. Apparent Hoop Strength fixture and specimen dimensions.

3. Results

3.1. Apparent Hoop Strength Tests

Apparent Hoop Strengths of the three consolidation methods are shown in Figure 3. The shrink tape samples with an AHS of 1425 N/mm² perform best, ahead of the two vacuum assisted variants. Interestingly, a combination of shrink tape and vacuum performs worst. Besides, Figure 3 shows the AHS results when doubling the holding time. Only a slight increase in the AHS is visible, although the fluctuations are somewhat greater.

Figure 4 shows the influence of the number of shrink tape layers, of the shrink tape winding tension and the variation of overlap on the AHS properties. Considering varying numbers of shrink tape layers, it appears that TC08 with the lowest number of layers has with 1669 N/mm² the highest AHS values comparing it to the reference sample TC01 and TC06, which are almost on the same level. The variation of the overlap shows no significant influence on the resulting AHS values (TC01 vs TC04).

Moreover, Figure 4 shows the results of the tests with a higher shrink tape winding tension. When comparing TC05 to TC08, there is a clear tendency towards lower AHS values when the tape tension is doubled, using a low number of 4 layers. However, it should be noted for TC05 tape tension that only 3 test specimens were included in the calculation due to an irregularity in the testing process and that a relatively low average thickness of the test specimens of 1.86 mm was recorded. With a larger number of 8 layers on the other hand (TC09 vs TC01), there appear to be slightly better AHS values when the tape tension is increased. These tendencies are counter-intuitive to the behaviour with a low number of layers.

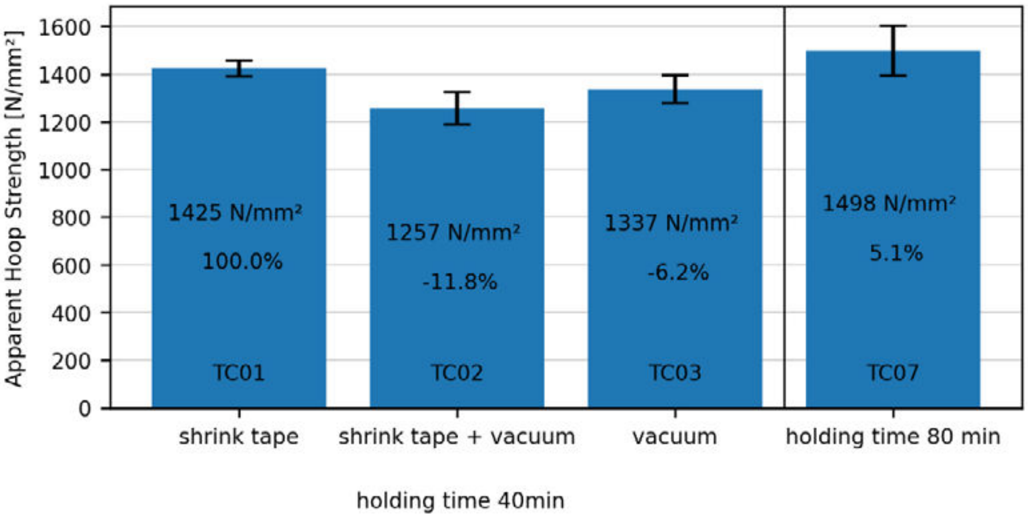

Figure 3. Comparison of the AHS for different consolidation methods and holding times. Error bars describe the standard deviation. Number of samples: n=4.

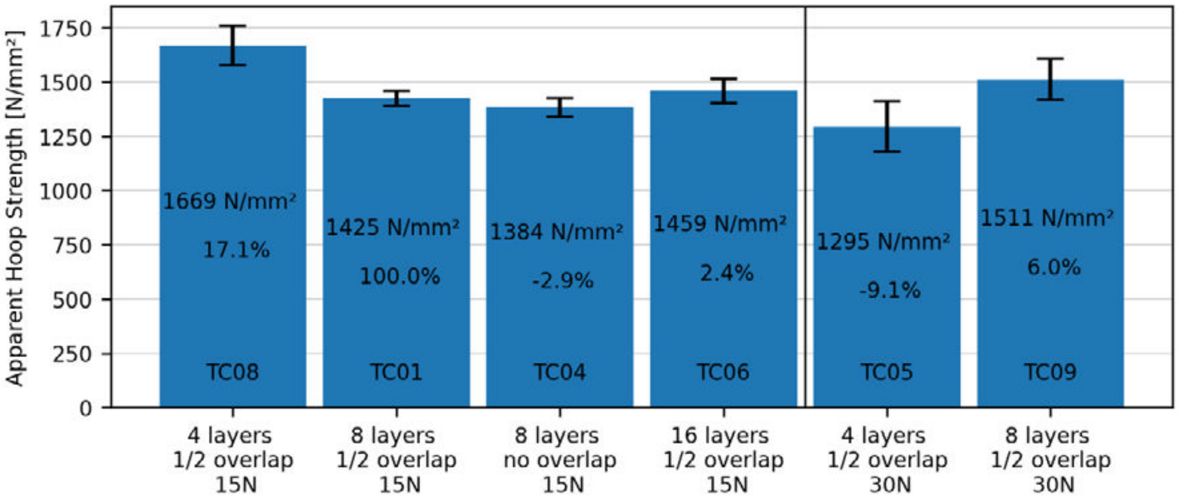

Figure 4. Comparison of the AHS for different number of shrink tape layers and overlap. Error bars describe the standard deviation. Number of samples: n=4 (except TC05: n=3).

3.2. Microscopy

The microscopic images revealed a noticeable phenomenon in all cross-sections of the samples: crumbling of the individual layers, which indicates a wave-like to wrinkle-like fusion of the wound layers. This crumbling is shown in Figure 5 (top right), whereas Figure 5 (top left) shows how the micrographs are taken from the cfrp tubes. The tapes were wound side by side using 1/4" cfrp tapes on 70 mm cores, which corresponds to circumferential windings with a winding angle of 88.35°. The small angular deviation of only 3.3° between the wound layers suggests that the observed crumbling could be prevented by crossing individual layers at more obtuse angles. In the bottom right corner of the image a staircase-like structure of the outer surface of the ring specimens can be seen due to the overlapping shrink tape.

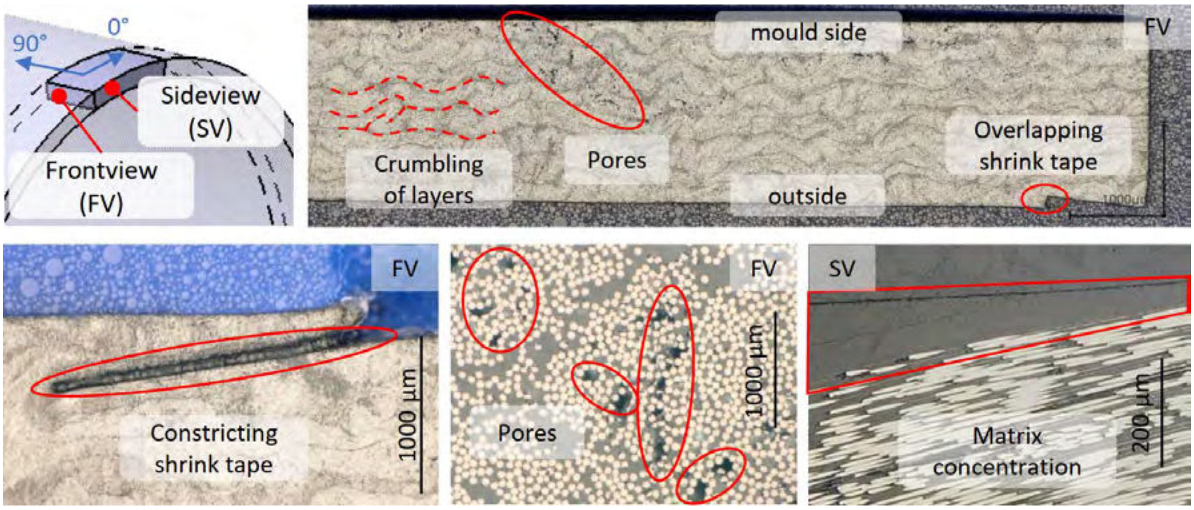

Figure 5. Micrographs with several phenomena: Description of viewing angles (top left); Crumbling of Layers (top right); Overlaps of material on shrink tape (bottom left); Pores especially at inner layers (bottom middle); Matrix concentration (bottom right).

Figure 5 (bottom left) clearly shows that overlaps caused by constricting shrink tapes occurred in the samples of type TC09 and, to a lesser extent, also in TC06 and TC07. These overlaps occur when the edge of the inner layer of the shrink tape pushes into the laminate or when fibres and matrix both flow around the edge of the shrink tape in the molten state. Both TC06 and TC09 are the parameter sets with the highest number of layers at the respective tape tension. The regular staircase-like structure of the specimen surface caused by the overlapping shrink tape is marked in Figure 5 (top right) at the right side of the image.

In Figure 5 (top right and bottom middle), pores can be recognised as they occur sporadically in the micrographs of all sample types. The pores are found in particular in the inner laminate layers towards the mould side. There are almost no pores in the outer layers. Optical analysis of the micrographs also shows that particularly few pores can be recognised in TC09, i.e. the specimen type on which the overlaps are also found. This is an indication that with a suitable shrink tape configuration, a sufficiently high consolidation pressure can be achieved to minimise the pore content. In the samples consolidated exclusively under vacuum, matrix accumulations were partially visible on the outer surface under the microscope. This is caused by folds in the release film along the cylinder axis, which was integrated in the vacuum build-up being used. Figure 5 (bottom right) shows the described matrix concentration in the microsection. Matrix concentrations are as well visible to a lesser extent in other specimens inside the laminate.

4. Discussion

The rings exhibited a staircase-like structure in the overlapping areas (see Fig 5 top right – overlapping shrink tape), which caused measurement errors when measuring the cross-sections of the test specimens. Due to the surface topography at the outer radius, it was not possible to avoid small air gaps between the measuring surface and the sample surface, which led to a slightly overestimated laminate thickness of the rings. This leads to an underestimation of the AHS calculated from the measured values.

The comparison of the three different consolidation methods clearly shows that dispensing with a vacuum build-up does not necessarily lead to poorer AHS values. The same applies to the apparently slightly positive influence of a long holding time.

The parameter variation of the number of layers and the tape tension has some unexpected and contradictory tendencies. While a low number of layers results in better AHS values when using low tape tension, the opposite is true for high tape tension. The microscopy examinations provided further indications of possible influences on these contradictory trends. The influences of the observed phenomena on the mechanical characteristics cannot be clearly distinguished from each other. The crumbling of the layers and the matrix accumulations raise questions about process optimisation and the avoidance of such defects. Since crumbling is caused by a displacement of the fibres, it can be assumed that such deviations from an ideal, straight arrangement of the fibres can lead to an impairment of mechanical parameters such as laminate stiffness and strength. The crumbling of the layers could be due to a sub-optimal winding configuration and could potentially be avoided by using more obtuse angles. However, due to the presence of crumbling in all samples, no clear conclusions can be drawn about its effects on the AHS. The accumulation of matrix in vacuum samples may indicate a gradient of fibre volume content in the thickness direction, which may also have an influence on mechanical properties.

Even if the specimen configurations with high numbers of layers of shrink tape in the AHS tests do not necessarily exhibit lower characteristic values, shrink tapes constricting into the laminate are not desirable. One factor that favours this effect is the small angular difference between the outer fibre layer and the first shrink tape layer. This angular difference of max. 4.1° apparently favours such a constricting effect at high consolidation pressures. It is assumed that the comparatively high pressure ratios resulting from a high number of shrink tape layers in the molten state lead to this phenomenon of constriction.

Porosity, which occurs in all sample types to a limited extent, can also have a negative effect on the mechanical properties. One explanation for the predominant occurrence of porosity in the inner, mould-side laminate layers lies in the long diffusion paths to the outside. None of the consolidation processes was able to produce an absolutely pore-free laminate. Apparently, the use of many shrink tape layers and high shrink tape tension, which results in higher consolidation forces, produces slightly lower porosity. It is conceivable that the introduction of other winding angles (for both semi-finished fibre products and shrink tape), which favour probably a more even pressure distribution in the laminate, can help to reduce the pore content.

5. Conclusion and Outlook

In this study, consolidation methods for wound thermoplastic cfrp parts produced with CoRe HeaT were investigated. CF/PA12 pipe-preforms were consolidated in an oven using various strategies. Consolidation using heat shrink tape was compared with vacuum consolidation and a combination of the two strategies. A focus is set on shrink tape wrapping parameters, such as the number of layers and the tape tension as well as the holding time at consolidation temperature. AHS tests showed no significant differences when comparing the different consolidation methods. The absence of vacuum does not result in poorer AHS characteristics. Nevertheless, it was not possible to clarify which shrink tape tension and number of layers lead to better results. Using microscopy, it was confirmed that high consolidation forces, achieved by increasing tape tension and layers, lead to less porosity within the laminate. However, it appears that these two effects are intertwined and a higher tape tension does not necessarily result in better AHS properties.

The AHS test proved viable to obtain information on the strength of the laminates with minimal use of resources. However, in the case of circumferentially wound test specimens, the test only depicts fibre-dominated failure mechanisms. In addition, based on the experience gained from the AHS tests, it is recommended that the test specimens be widened and the number of samples per series increased, to reduce scattering. For the future, Interlaminar shear strength (ILSS) tests and transverse tensile tests are planned in order to generate further information on laminate quality.

Open questions for further consideration include analysing the crumbling of the layers that occurs during consolidation as well as optimising shrink tape winding parameters to minimise the indentations on the tube surface. Of particular interest here is what the decisive driving forces for these effects are and what their influence on mechanical properties are. Among other things, the influences of the thermal expansion of the core, the interlaminar slippage and the resulting frictional forces between the molten, viscous matrix and the continuous fibre must be considered. In addition, a variation of the processed materials is of interest in order to understand influences on the manufacturing process more precisely.

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