Rapid Manufacturing of a Tailored Spar by AFP and Stamp Forming

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Abstract:
Stamp forming is a manufacturing technology used to shape flat thermoplastic composite blanks into three-dimensional components. Further cost and weight optimization can be achieved by combining stamp forming with blank manufacturing by rapid AFP. The use of AFP allows for optimized lay-ups, which improve the performance/weight ratio of the stamp formed part, and near net shape blank contours, which reduce production scrap. Subsequent stamp forming provides the final shape and consolidation quality of the part. The current work aims to demonstrate the process route of rapid AFP followed by stamp forming on a realistic component. A section of a small spar from a wingbox is designed and manufactured. The spar includes features such as local reinforcements by tailored lay-ups in either the web, flanges or both, and joggles in order to taper the height of the spar. Good consolidation of the spar is achieved, although the process is sensitive to blank thickness.

Keywords: Consolidation, Advanced Fiber Placement (AFP), Stamp forming, Tailored blanks

Introduction

The development of automated lay-up technologies, such as advanced fiber placement (AFP), offers new opportunities for the automated manufacturing of thermoplastic composite components with a high degree of lay-up freedom. This enables tailored lay-ups with local reinforcements, which can be optimized for structural performance, allowing for more efficient material use and weight reduction compared to traditional lay-ups. The current research and development efforts for AFP mainly focus on material and process optimization to allow in-situ consolidation, where no expensive post-consolidation step is required after lay-up. Potentially, this is a very attractive manufacturing route; especially for larger, relatively simple, aerostructures, such as fuselage or wing sections. As an alternative, AFP could also be attractive for smaller and more complex parts. Here, however, the authors propose to focus on a two-step approach, rather than aiming for in-situ consolidation. AFP provides partial consolidation at high lay-up rates. A subsequent, preferably quick and inexpensive, consolidation step has to be applied to achieve the final consolidation quality.

Stamp forming could serve as this subsequent step. The process uses the formability of thermoplastic composites at elevated temperatures to manufacture three-dimensional components from flat laminates, so-called blanks. Cycle times are short due to fast heating, forming and cooling, while allowing more time and pressure for consolidation than AFP. The current industrial practice is to use woven fabric reinforced blanks with uniform lay-up and uniform thickness for the production of secondary components. Although the process already is competitive compared to metal solutions, further cost and weight optimization can be achieved. Using AFP to manufacture blanks enables this by the use of unidirectional tape, optimized locally reinforced lay-ups and reduced scrap from trimming operations by near net shape lay-up. Therefore, the combination of rapid AFP and stamp forming, as illustrated in Fig. 1, is proposed as a process route for manufacturing load carrying components.

Despite its potential, the introduction of tailored blanks to stamp forming technology is not straightforward and brings up a whole new range of challenges in terms of consolidation and forming. However, previous work has demonstrated that high quality laminates can be obtained after stamping blanks manufactured by AFP [1,2]. Both consolidation quality (void content, interlaminar bonding) and flexural performance were similar to that of conventional press-consolidated blanks after stamping. The consolidation of tapering regions with ply-drops was also demonstrated [2]. The current work aims to take the previous work a step further and demonstrate the proposed process route for the consolidation of a (semi-)realistic component.

Component design

The component was designed in cooperation with Fokker Technologies and represents a spar from a wingbox. Such a spar is a thin-walled component, which makes it suitable for stamp forming. The decreasing load from fuselage to wing tip makes it

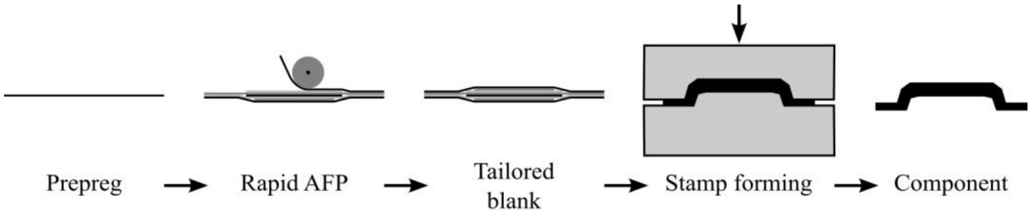

Fig. 1: *Process route.*

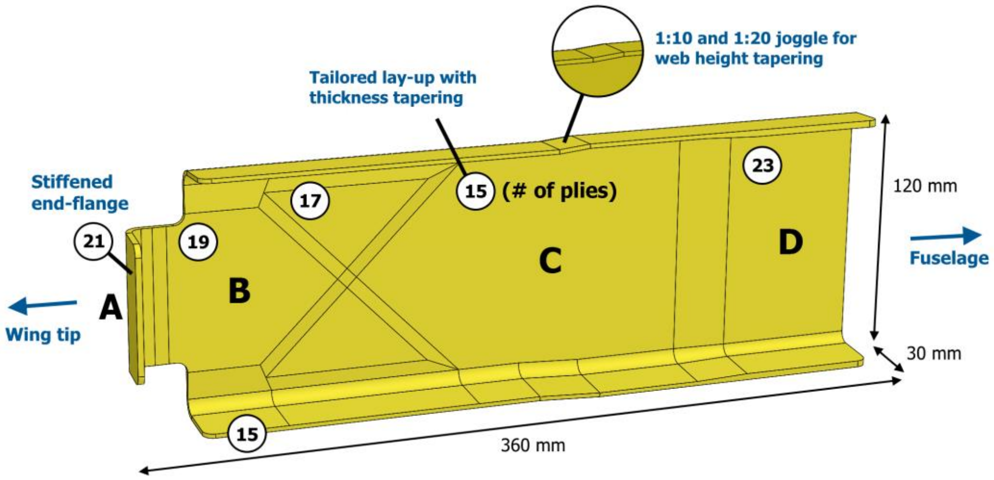

Fig. 2: *Spar design*

an excellent example of a component that benefits from a tailored lay-up. Only a small section of the spar is produced due to size restrictions by the forming press at TPRC. The designed spar is shown in Fig. 2. The spar includes a tailored lay-up with local reinforcements. Two joggles are present to reduce the height of the spar towards the wing tip.

Material

Cytec APC-2 C/PEEK unidirectional prepreg tape was used to lay-up the blanks. This prepreg has a fiber volume fraction of 59 % and a melt temperature of 343 °C. A cross-section is shown in Fig. 3. The matrix rich surface of the prepreg facilitates bonding both during AFP and stamping. Some intralaminar voids are present.

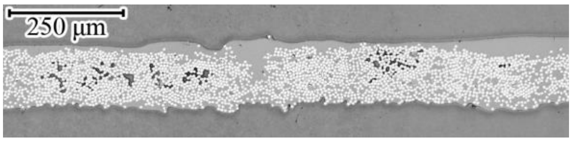

Fig. 3: *Cross-section of the Cytec APC-2 prepreg*

Lay-up

Four lay-up zones (A-D) are present, as shown in Fig. 4. Zone C is a quasi-isotropic base lay-up. Zones A, B and D include local reinforcements of either the web (B), the end-flange (A) or both the web and flanges (D). The thickness of the lay-up varies between 15 and 23 plies (2-3 mm). Although the main benefit of using tailored lay-ups is the possibility of structural optimization, this work focusses on the consolidation of a component with tailored lay-up. Therefore, no structural optimization was performed and the lay-up was chosen in cooperation with Fokker Technologies.

All transition zones are designed with a tapering ratio of 1:24 (3.2 mm between each dropped ply) and with the dropped plies interleaved between continuous plies. Dropped plies extend 1.6 mm into the tapering region to guarantee pressure on the tapering region, which is required for the material to flow into the ply-drop pockets. This also makes the blank more robust against blank-tooling misalignments, as these could lead to poor consolidation of the tapering region [2]. Since the AFP machine used in this work cuts tapes perpendicular to the fiber direction, ±45° plies create a saw tooth ply-drop edge with large ply-drop pockets. This makes consolidation of these ply-drops challenging [2].

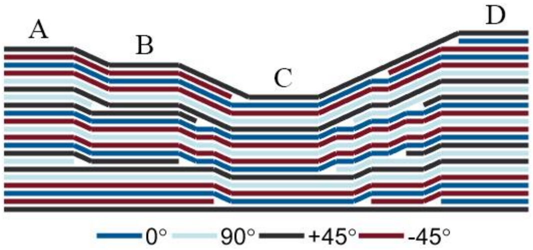

Fig. 4: *Lay-up. 0° orientation parallel to longest edge of the spar.*

Blank design

The blank contour was designed such that scrap from trimming operations both before and after forming was minimized. For first trials a post-forming trimming edge of 1 cm was assumed to guarantee good consolidation close to the edges. This could be reduced further. The Coriolis Composites AFP machine used in this work has a minimum fiber length of 100 mm. This makes near net shape blank lay-up challenging in tight corners. Hence, some pre-forming trimming scrap could not be avoided for certain ply orientations. Figure 5 shows the pre-forming trimming scrap, post-forming trimming scrap and final spar contour. Four gripper tabs were included for gripping during forming.

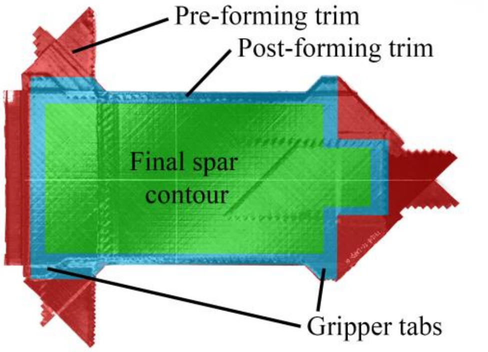

Fig. 5: *Contour of the blank.*

Tooling design

Matched metal aluminium tooling was designed to form the part. The tooling cavity was based on an average ply thickness of 0.135 mm, which was determined based on the final thickness of $[0/90]_{4s}$ AFP blanks after stamping with flat tooling. Engravings in the tooling allowed for checking the alignment of the blank after stamping.

Forming simulations

Forming simulations were performed using AniForm. The simulations enable the prediction the forming behavior and the occurrence of potential defects. The forming simulations did not show critical issues during forming. The forming simulations also aided the design of the tooling and gripper system, as well as designing a near-net shape blank contour.

Spar production

The blanks were laid up on flat aluminium tooling with a single 1/4” tow Coriolis Composites AFP machine at a rate of 200 mm/s. Laser heating was used to heat the tape up to a nip-point temperature of 450°C. The lay-up rate was limited by both the output power of the laser (1 kW) and the accuracy of starting and stopping tapes, which is especially important for ply-drops.

After a pre-forming trimming step, the blanks were dried in a convection oven for 3 hours at 250°C. This prevents void formation and delamination by moisture expansion during stamp forming.

The blanks were stamp formed on a 200 tonnes forming press. First, the blanks were aligned in the transfer frame using laser guiding and suspended by springs. Then, the blanks were heated in an IR-oven to a core temperature of 390°C in 180 s. Subsequently, the blank was automatically transferred to the forming station without considerable temperature loss and the press was closed, forming the spar. The spar was held under a pressure of 100 bar (414 kN) for an additional 60 s while cooling in the isothermal tooling at 250°C.

After forming, a second trimming step was performed to obtain the final shape of the spar.

Consolidation quality

Initial forming trials showed promising results. A series of five spars was produced. The consolidation quality of the spars was checked by visual inspection, C-scan (web), A-scan (flanges) and microscopy. The blanks showed consistent C-scans with no defects, as shown in Fig. 6 (top). Cross-sections of the spar showed good consolidation of all zones, including ply-drop regions. An example is shown in Fig. 6 (bottom). Rough surface areas were observed in the center of the web, as well as on the outer radii near the joggles. However, cross-sections confirmed no consolidation issues in these regions. A low quantity (<< 1%) of intralaminar micro-voids was still observed, as the intralaminar voids that were present in the used prepreg were not completely eliminated. However, previous work has shown that these voids do not affect flexural performance [2].

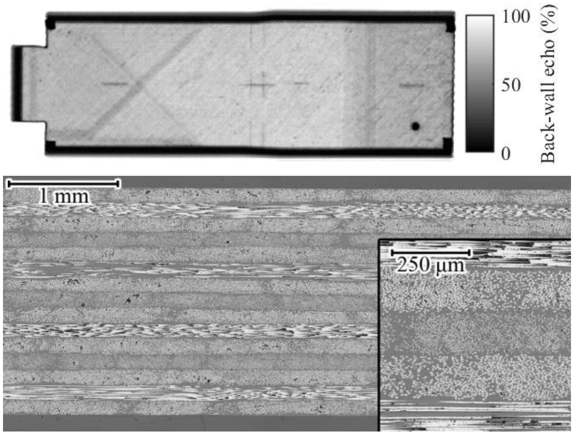

Fig. 6: *Top: C-scan of the web of the spar. Bottom: Cross-section of zone C.*

Defects

Although the five spars showed good consolidation quality, some defects were present. Firstly, warpage was observed (Fig. 7 (top)). This is caused by local fiber reorientation in the bottom plies during forming. In some cases, ply splits on the bottom side of the web (Fig. 7 (middle)) and/or a rough surface in the center of the web were present.

The origin of these defects is related to the initial thickness of the blank and the designed cavity in the tooling. A small amount of compaction, typically less than 5-10 %, takes place during stamping. This means the initial blank thickness is larger than the designed tooling cavity. Moreover, tow-to-tow or batch-to-batch prepreg thickness variations can also lead to an increased blank thickness. As a result of the increased blank thickness, the flanges of the spar are compacted before the web is during tool closure, as shown in Fig. 7 (bottom). This creates a high traction on the surface of the flanges and high tension in the bottom plies. Due to the various lay-up zones in the spar, this traction is not uniform throughout the part and causes local reorientation of fibers, leading to warpage. In extreme cases, the transverse stresses can become too large and ply splitting occurs (Fig. 7 (middle)). These defects were not observed during the forming simulations, as these were performed with a matching blank thickness and tooling cavity. Furthermore, the compaction load is primarily carried by the flanges, while the web may experience less pressure, which leads to the observed rough surface in the center of the web. This shows the sensitivity of the process to input material, especially thickness, and the importance of having a matching blank thickness and tooling cavity.

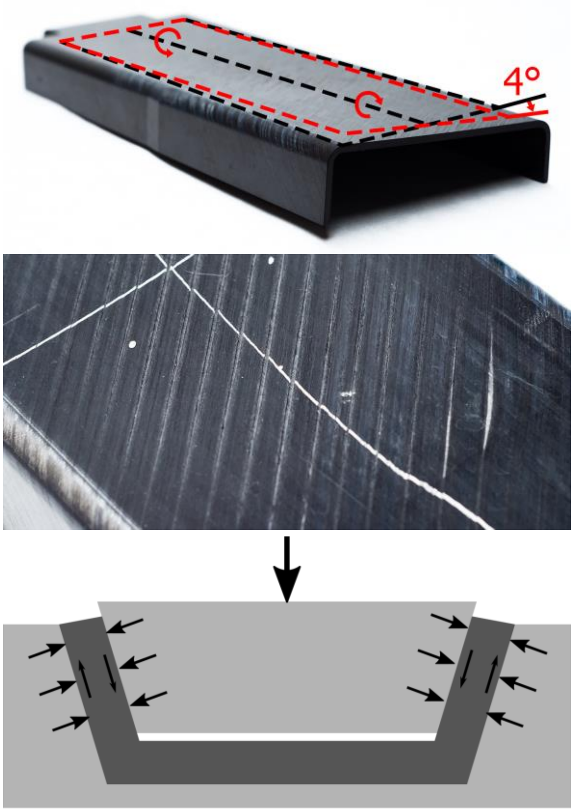

Fig. 7: *Top: warpage of the web. Middle: ply splitting at the bottom of web. Bottom: compaction and traction due to increased blank thickness.*

Cycle time and weight savings

During this work lay-up was performed using a single 1/4" tow AFP machine limited to 200 mm/s by the laser power and placement accuracy. The lay-up time with the used set-up is, according to Coriolis CADFiber lay-up simulation software, 108 minutes. However, AFP machines in industrial applications typically have 8 tows or more. More recent AFP machines are able to lay-up at a rate of 500 mm/s with good placement accuracy. With a modern machine with 8 tows and a rate of 500 mm/s, lay-up of the blank is reduced to 9 minutes. Combined with the stamp forming cycle of 4 minutes this provides a good basis for a manufacturing route for large series. A main benefit of the processing route is the use of AFP for blank production, which allows for tailored and near net shape lay-up. Figure 8 shows a comparison of the material usage for a conventional uniform thickness blank (400x230 mm^2 with 23 plies), uniform near net shape blank and tailored near net shape blank. Applying near net shape lay-up reduced the total material usage by 12 % by reducing scrap. Applying tailoring reduced the spar weight by 25 % and the total material usage by 30 %. Although the tailored lay-up was not based on structural optimization and the performance of the conventional uniform thickness spar and tailored AFP spar cannot be compared, the numbers indicate the potential of AFP blank lay-up.

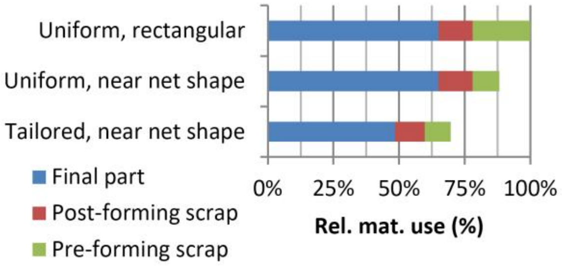

Fig. 8: *Material usage per spar. 100 % = 461 g.*

Conclusion

The current work has shown promising results on the manufacturing of a realistic component of thermoplastic composite by the combination of rapid AFP and stamp forming. This route extends the applicability of conventional stamp forming towards series production of load carrying lightweight components by omitting an additional preconsolidation step, reducing production scrap and increasing the performance/weight ratio. Spars with a high consolidation quality could be produced. However, the importance of a matching blank thickness and tooling cavity was highlighted, as thickness deviations can lead to poor consolidation and forming defects, such as warpage, and ply splitting.

References

[1] T. Zenker et al., SAMPE Europe 2017 (2017)
[2] T.K. Slange et al., ESAFORM 2018 (2018)