INTIMATE CONTACT DEVELOPMENT IN LASER ASSISTED FIBER PLACEMENT

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Abstract
Laser Assisted Fiber Placement is a promising technique for thermoplastic composite manufacturing. The achieved consolidation quality, however, is lower than obtained with conventional manufacturing techniques, resulting in laminates with a high void content. Interlaminar voids are dominant with the availability of current high quality pre-preg tape. Intimate contact development plays a role in the consolidation process and the formation of interlaminar voids. It comprises the local deformation of the tape and substrate surfaces in order to facilitate interdiffusion of polymer chains. The consolidation quality of the tape after heating and just before consolidation is crucial for the intimate contact development. Currently, it is assumed this quality equals the input tape quality. The aim of this research is to validate this assumption and to capture the consolidation state of the tape after heating. For this purpose, tapes were placed with gradually reduced pressure. The results show that the tape deconsolidates during the heating phase, resulting in a fiber rich surface and an increase in void content. Consequently, a percolation flow of resin is required to wet the surface to bond the tape with previously laid-down plies. For the tapes investigated, the intimate contact development mechanism seems, therefore, different than currently assumed.

1. Introduction

Laser Assisted Fiber Placement (LAFP) is a production technique for thermoplastic composites with the potential for in-situ consolidation. A post consolidation step could be omitted when a sufficient consolidation quality can be achieved during the placement, resulting in a great reduction in manufacturing costs. Another advantage is the automated layup, which increases production quality while reducing manufacturing costs. LAFP also offers the freedom to manufacture laminates with a variable layup and fiber steered plies, which can be used to optimize part performance. Finally, production waste can be reduced by manufacturing near net shape parts.

A schematic picture of the process is shown in Figure 1(a). During the fiber placement process a thermoplastic composite pre-preg tape is heated above its melting temperature using a laser without applying pressure. Subsequently, pressure is applied with a compaction roller to create intimate contact and to bond the tape to the previously laid-down tapes. In this way, a part can be build up and consolidated ply-

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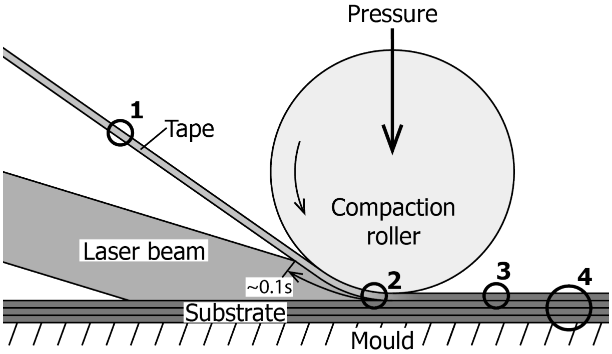
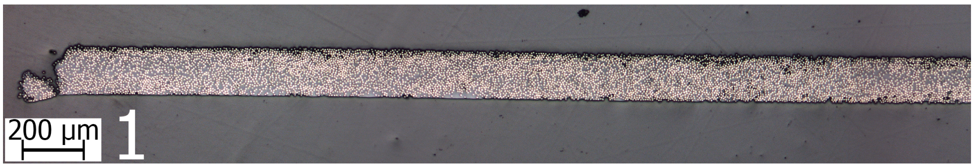
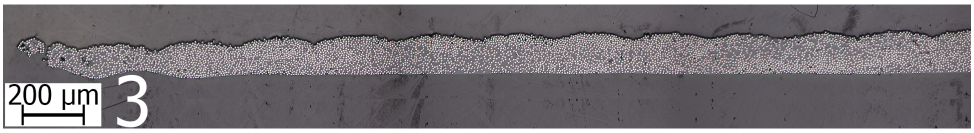
by-ply. The typical characteristics of the process are high heating and cooling rates, short consolidation times and multiple heating cycles. This differentiates the LAFP process from the conventional thermoplastic composite production technologies. The final in-situ consolidation quality, however, should be on the same level as for conventional thermoplastic composite production technologies.



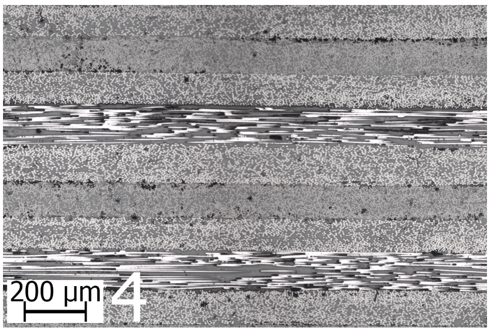
(a) Schematic view of the LAFP process



(b) Input tape



(c) Tape placed on a laminate covered with PI foil



(d) Fiber placed laminate

A low void content is crucial to obtain a good in-situ consolidation quality, especially for the aerospace industry. Recent developments in manufacturing of composite tapes have resulted in an increase in tape quality, see Figure 1(b), and hence, in-situ consolidation should be achievable with these tapes [1, 2]. As a result, placed tapes show a high consolidation quality, as can be seen in Figure 1(c). However, fiber placed laminates manufactured with the current setup still show a high void content, see Figure 1(d). Interlaminar voids are found to be dominant, since the increased tape quality has resulted in a reduced intralaminar void content. Incomplete intimate contact might be an origin of the interlaminar voids. The consolidation state and surface morphology of the tape during the process affect the intimate contact development. However, up to now only the input tape and the final product quality have been researched, assuming that the consolidation state of the tape does not change during heating, since the time available

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for deconsolidation during heating is short.

To summarize, interlaminar voids can originate from incomplete intimate contact and the intimate contact development is affected by the consolidation state and surface morphology of the tape. The input tape quality, indicated by 1 in Figure 1(a), and the final consolidation quality, indicated by 3 in Figure 1(a), have been researched extensively. The consolidation state and surface morphology of the tape after heating and just before the consolidation pressure is applied, indicated by 2 in Figure 1(a), have not been researched. The aim of this research is to analyze the change in consolidation state and surface morphology during the heating phase of LAFP.

2. Intimate contact development

Intimate contact development is the process of creating physical contact between the the surface of the tape and previously laid-down plies. It comprises the local deformation of both surfaces to bring these together. Intimate contact between the polymer on the surface of the tape and the polymer of the previously laid-down plies is indispensable for polymer chains to cross the interface and to fusion bond them together. Therefore, a certain amount of resin is required at the surface of the tape. Furthermore, interlaminar voids may originate from incomplete intimate contact. The applied consolidation pressure serves the purpose of bringing the plies together and to deform the surfaces of the plies to obtain full intimate contact [3].

At present the models describing intimate contact development are based on the work of Dara and Loos, Lee and Springer [4, 5]. The contacting surfaces are modeled by a series of rectangles, which are deformed under the applied pressure. The required pressure and time to obtain full intimate contact are based on the geometry of the rectangles and the apparent fiber-matrix viscosity of the composite. The geometry of the rectangles, however, is difficult to relate to the surface of the used material. More advanced models were developed based on fractal surfaces, which can be related to the power density spectrum of the roughness of the tape [6]. For all these models it is assumed that there is a resin layer at the surface and a percolation flow of resin is not required to obtain intimate contact.

Although experimental validation of these models is difficult, these do seem to fit reasonably well to the experimental data [6]. The geometry of the surface used in the intimate contact models are based on the surface of the input tape. However, the surface geometry, or morphology, of the tape might change during the heating phase of the process due to possible deconsolidation of the tape. The actual consolidation state of the material in the melt, just after heating and just before the consolidation pressure is applied is yet unknown. A better understanding of the change in consolidation quality and morphology of the tape during heating would allow the improvement of intimate contact modeling and hence the final part quality.

3. Method

A method is proposed to investigate the consolidation quality and morphology of the tape after heating with the laser, just before being pressed and cooled by the compaction roller. The standard LAFP process is used, but consolidation underneath the compaction roller as well as further deconsolidation after the heating phase had to be prevented. To accommodate for this, brass shims were used to reduce the pressure of the compaction roller on the tape, as shown in Figure 1. Furthermore, a steel mould was used as a heat sink to promote cooling of the tape and prevent deconsolidation after the heating phase.

The thickness of the shims was varied. Increasing the shim thickness reduces the pressure on the tape and limits the consolidation underneath the compaction roller. However, sufficient pressure is required

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to assure contact with the steel mould in order to promote fast cooling of the tape.

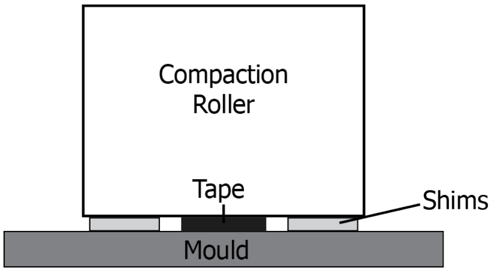

Figure 1. Setup of the deconsolidation experiment

A Coriolis Composites LAFP robot was used to place TenCate Carbon PEEK tapes. A well defined applied thickness was achieved by using a stiff Teflon roller, which prevents the effects of deformation of the roller. A pattern was imprinted on the roller and this pattern could be used to analyze if pressure was applied onto the tape. The laser power settings were based on previous research to achieve a nippoint temperature between 450 and 500 °C, at a placement speed of 50 to 200 mm/s and a compaction pressure of 100 N was used [7]. After placing the tapes, these were embedded, polished and analyzed with the use of an optical microscope. As a comparison, tapes were also placed on a laminate covered with Polyimide (PI) foil without the use of shims. This configuration is similar to the normal processing conditions during manufacturing of a laminate with similar thermal and optical properties of the substrate.

4. Results

A typical micrograph of the TenCate Carbon PEEK input tape, before placement, is shown in Figure 1(b). The cross section of the tape has a uniform thickness and a uniform fiber distribution. The tape has a low void content with most of the voids at the surface of the tape.

As a reference, tapes were placed with the Teflon roller at 100 mm/s and a compaction pressure of 100 N on a laminate and steel mould. The resulting cross sections are shown in Figure 1(c) and 2(a) respectively. The regular pattern left by the roller can be clearly identified on the top surface of both the tapes. From this it can be assumed that the tapes were melted through the thickness and sufficient pressure was applied to deform the tapes. Both tapes have a uniform fiber distribution after placement, similar to the input tape. The bottom surface, however, seems to be slightly more fiber rich and rough for the tape placed on the steel mould, since the surface contacting a steel mould cools faster than the tape surface in contact with the laminate. Therefore, the time available to squeeze out resin is reduced, resulting in a more fiber rich surface.

Figure 2(b) to 2(d) show cross sections of tapes placed with an increased shim thickness and therefore a reduced consolidation pressure. With 150 µm shims, Figure 2(b), the regular pattern left by the roller can still be identified, suggesting that the tape has experienced some consolidation pressure and therefore contact with the steel mould can be assumed. Moreover, a reduction in consolidation quality can be observed, with an increased void content and a rough bottom surface with fiber rich areas. Increasing the shim thickness to 175 µm, Figure 2(c), further reduced the pressure on the tape and the pattern of the roller is not clearly visible anymore. The consolidation quality is further reduced, since an increased void content and fiber rich areas with loose fibers at the surface can be observed in the cross section. However, further increasing the shim thickness to 200 µm, Figure 2(d), does not result in a large decrease in consolidation quality as in the previous step. This suggests that these tapes probably did not cool quick enough to prevent deconsolidation after the roller. Similar results were obtained for other placement

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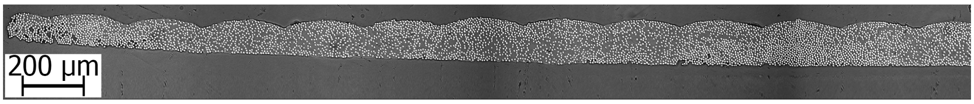
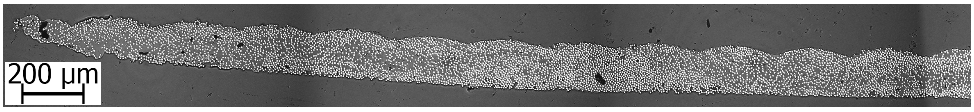
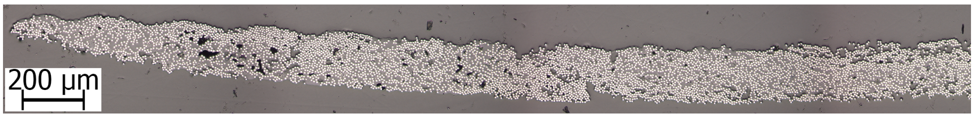
velocities.



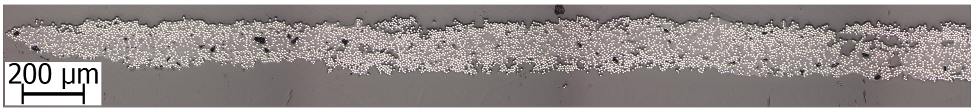
(a) Tape placed on a steel mould



(b) Tape placed on a steel mould with 150 µm shim



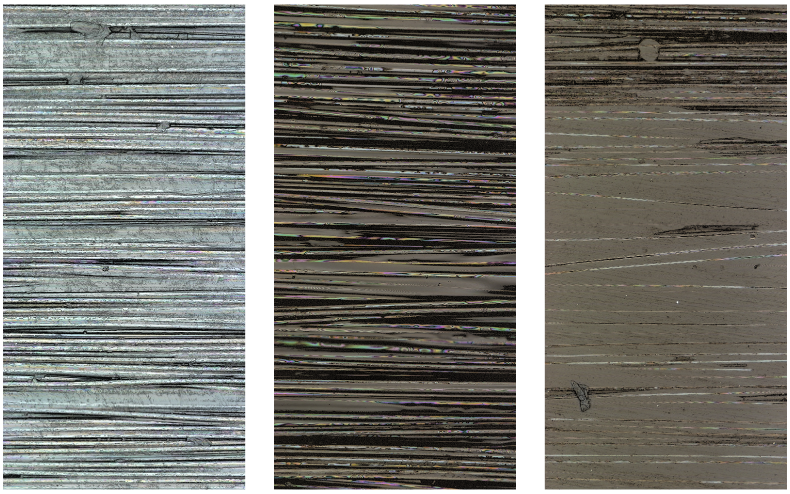
(c) Tape placed on a steel mould with 175 µm shim



(d) Tape placed on a steel mould with 200 µm shim

Figure 2. Micrographs of tapes placed at 100 mm/s, 450 to 500 °C, with varying shim thickness

Surface scans made with a confocal microscope of the surface contacting the mould of some of the placed tapes are shown in Figure 3. The input tape, Figure 3(a), shows a layer of polymer on the fibers along with some dry fibers. The scan of the tape placed on a steel mould with 175 µm shims, Figure 3(b), shows mostly dry fibers and some resin pockets. The tape placed with the full consolidation pressure, without shims, on a laminate covered with PI foil, shown in Figure 3(c), has a resin rich surface, suggesting a flow of resin out of the tape.



(a) Input tape (b) Tape placed on a steel mould with 175 µm shims (c) Tape placed on a laminate

Figure 3. Confocal images of the surface of different tapes

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5. Discussion

The LAFP process was used to place tapes with a reduced consolidation pressure to analyze the change in consolidation quality and morphology of the tape during the heating phase. The cross sections of both the input tape and the tapes placed without shims show a high consolidation quality. Furthermore, the surface scan of the input tape made with the confocal microscope shows a surface covered with a layer of polymer. This layer of polymer is required for the fusion bonding during consolidation underneath the roller. The tapes placed with shims, however, show a change in morphology.

The consolidation quality reduced and the morphology changed of the tapes placed with shims compared to the input tape. An increase in fiber rich areas, voids and thickness can be observed. The change in morphology seems to stabilize for a shim thickness above 175 µm. Furthermore, the regular pattern left by the roller, as can be seen for a shim thickness below 150 µm, can not be observed for a shim thickness above 175 µm. This suggests that contact with the steel mould was not sufficient for a shim thickness above 175 µm, resulting in reduced cooling and probably further deconsolidation after the heating phase. For a shim thickness of 150 µm the regular pattern left by the roller can be observed, thus some consolidation pressure was applied to deform the surface in contact with the roller. This suggests both that the tape was partially consolidated underneath the compaction roller and that the bottom surface of the tape had sufficient contact with the mould to assure fast cooling of the tape. Based on the above, the consolidation quality and morphology of the tape after the heating phase seem to be between the consolidation quality and morphology of the tapes placed with a shim thickness of 150 µm and 175 µm. Hence, the surface of the tape after heating seems to have a higher surface roughness, more fiber rich surface and a higher void content compared to the input tape.

At present intimate contact models assume that the morphology and consolidation quality of the input tape do not change during the heating phase of LAFP. Furthermore, it is assumed that sufficient polymer is present at the surface of the tape. Therefore, intimate contact development between the polymer of the tape and the polymer of previously laid-down plies could be modeled as the local deformation of both surfaces. The polymer at the surface of the tape is indispensable for the fusion bonding of the tape and previously laid-down plies. The results presented, however, suggest that morphology of the tape changes during the heating phase. This change in morphology should be taken into account to model intimate contact development physically correct.

A percolation flow of resin towards the surface should be incorporated in the intimate contact development, since the tape seems to have a fiber rich surface after the heating phase. This Darcy type of flow of resin is required to wet the tape surface to promote fusion bonding of the tape with previously laid-down plies. This flow of resin can be observed in Figure 3(c) for a tape placed with similar conditions to normal LAFP process conditions. Further research is required to model this new view on intimate contact development.

It should be noted that this research was done on one type of material. Tape manufactured by other suppliers will be researched in the future, since tape manufacturing process could have an effect on the change in morphology during the heating phase. Further research is required to validate the shown results and to increase the understanding of the change in consolidation quality and morphology of the tape during the LAFP process. These should include experiments with smaller steps in shim thickness and with a setup with a stationary laser source.

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6. Conclusions and recommendations

The change in consolidation quality and morphology change during the heating phase of LAFP has been neglected up to now. A method was proposed to analyze this change for the LAFP process. Brass shims and a steel mould were used to systematically reduce the consolidation pressure and to promote fast cooling of the tape. The results suggest that a reduction in consolidation quality and a change in morphology of the tape occurs during the heating phase. The surface of the Carbon PEEK pre-preg tape undergoes a change in morphology resulting in a rough and fiber rich surface. This change should be taken into account to be able to correctly model the intimate contact development.

The intimate contact development in thermoplastic composite processing is modeled as the local deformation of the tape surface under an applied consolidation pressure. For the chosen material and the LAFP process the mechanism behind intimate contact contact development seems to differ. The material seems to have a fiber rich surface after the heating phase and a Darcy type of flow is required to wet the surface to promote fusion bonding with the previously laid-down plies. This flow of resin was observed in placed tapes and this resin flow should be incorporated in intimate contact modeling. Further research is required to get a better understanding of the change in consolidation quality and morphology of the tape during the LAFP process to improve current intimate contact models.

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