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THE CONSOLIDATION OF RAPID LASER DECONSOLIDATED COMPOSITE TAPES

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Abstract
This work studies the effect of compaction of tapes that have been heated using a laser during automated fibre placement. The deconsolidation has been shown to have a significant effect on the surface roughness, degree of effective intimate contact and void content. This work investigates whether after compaction the as-received (i.e., before heating) properties are obtained, or whether the deconsolidation-compaction cycle has an influence on the final tape quality. First, a lab test set-up is designed and manufactured to mimic the real manufacturing conditions. Next, the set-up is used to study the influence of the placement speed and pressure on the final quality. The results show that the effects of deconsolidation are mostly reversed, but the final tape still has slightly worse qualities. This effect will have to be taken into account for accurate modelling of the laser-assisted automated fibre placement process.

1. Introduction

Automated fibre placement (AFP) is often used nowadays to manufacture large composite structures. Currently, most AFP is often done using thermoset materials, which need to be put in the autoclave afterwards. However, using thermoplastic materials, one could achieve in-situ consolidation , removing the need for any secondary processing. While this manufacturing method can potentially lead to large time and cost savings, it is not well understood what happens to the material during the heating phase.

One of the challenges of in-situ consolidation in AFP is that the material needs to be heated to the processing temperature, which for CF-PEEK is around 400°C. Three heating methods can be used for this: hot gas torch, pulsed light and a laser. While gas torch is not as controllable, both other methods are viable candidates with a lot of control on the heating. In this work, we will be using a laser to heat thermoplastic tapes, leading to laser-assisted AFP (LAFP).

Research on LAFP has shown that deconsolidation of thermoplastic composite tapes occurs during the rapid heating phase. During the increase in temperature, various mechanisms occur that change the micro- and meso-structure of the tapes. The observed deconsolidation forms are increase in thickness, surface roughness, void content and waviness. It was identified that the deconsolidation forms have a negative effect on the bond formation as intimate contact development is reduced.

Experimental studies have shown that it is possible to resolve the deconsolidation of the tapes when pressure and temperature is applied for a considerable amount of time [1]. However, during LAFP, the time for re-consolidation is limited. This time limit is expected to have a negative influence on the consolidation quality. This work aims to acquire knowledge on the consolidation of rapid laser deconsolidated thermoplastic composite tapes by developing a novel experimental set up that can achieve LAFP-like process parameters and by analysing the produced specimens using microscopy.

2. Experimental set-up

To start with, an experimental set-up had to be designed since the laser enclosure at Delft University of Technology is not large enough to fit a robot with AFP head. However, the set-up should be able to mimic the LAFP process. This means that the roller has to move, and tape has to be placed. For safety reasons, it was opted to keep the laser and roller constant, and have a platform (shown in brown in Figure 1) that can move. By having a slider with a weight on top, the pressure applied by the roller can be changed, while the roller can also be lifted easily to put a new piece of tape.

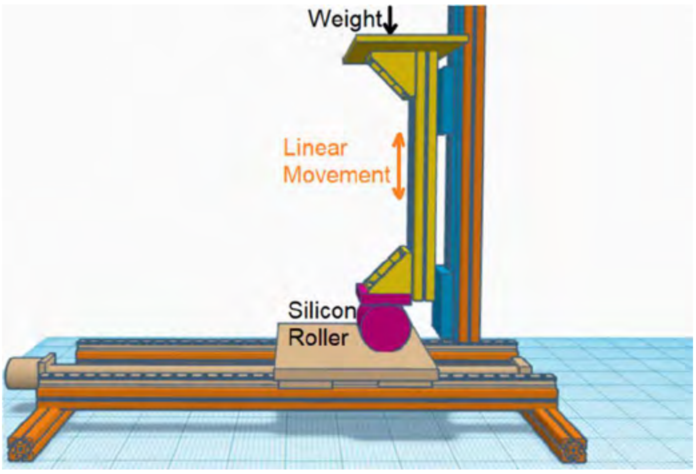

Figure 1. schematic drawing of the test set-up.

The final test set-up can be seen in figure 2. In this figure, some parts are highlighted. Number 1 indicates the position of the stepper motor and gearing necessary to achieve the desired placement speeds. This stepper motor is controlled using an Arduino. Number 2 indicates the VCSEL (Vertical Cavity Surface Emitting Laser) used in this work. It is kept static for safety reasons as mentioned earlier. The pressure application mechanism, already shown schematically in Figure 1, is indicated by number 3. Number 4 indicates the spool with the thermoplastic material on. This tape is also put under a bit of tension to mimic the real LAFP process as closely as possible. Finally, number 5 indicates the linear sliding mechanism, the only moving part of the set-up. By attaching the end of the tape on this slide, the tape is pulled forward with a given speed when the slider is moved. The roller is consisting of two parts: an aluminium core, with a silicon layer around it, which is able to deform.

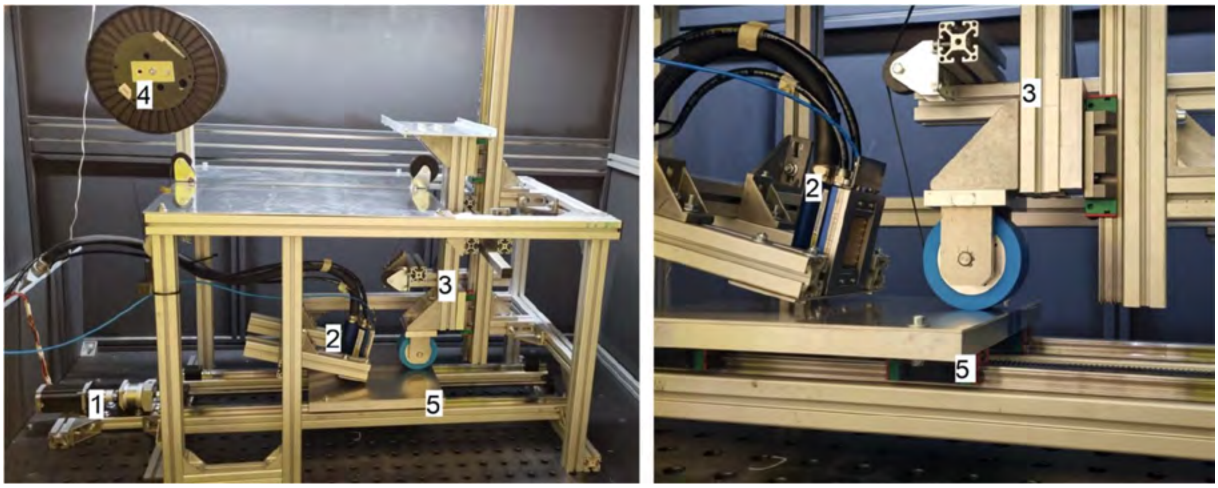

Figure 2. The novel test set-up.

3. Experimental details

The material used was quarter-inch (6.35 mm) wide TenCate Cetex TC1200 PEEK AS-4. To limit the number of experiments, without limiting the amount of understanding, it was decided to not do a full factorial design, but still select three different pressures and placement speeds, to elucidate the influence of each parameter on the final quality. The visible nip point, meaning the temperature at the point closest to the nip point that is still visible for the thermal camera, was kept constant at 385 °C. An overview of all tests done can be seen in Table 1.

Table 1. Overview of different test performed.

Visible nip point temperature [°C]	Consolidation pressure [kPa]	Placement speed [mm/sec]
385	160	40
385	160	120
385	300	120
385	600	40
385	600	120
385	600	200

During the experiment, the temperature is recorded using a FLIR A655sc High-Resolution Science Grade LWIR Camera. The roughness is measured by using a Keyence VK-X1000 Laser Scanning Confocal Microscope (LSCM). Three measurements along the length of each sample are performed, with at each location seven samplings being performed. This sampling is done to ensure that there is not an outlier identified for a certain measurement set-up. Also the degree of effective intimate contact (DEIC), essentially giving the amount of resin on the surface of the tape after placement, is determined. Finally, cross-sectional microscopy is performed to determine the void content and thickness distribution over the complete width.

4. Results and discussion

The results will be briefly discussed, always showing the same type of graphs, with on the left the actual measurements (including an error bar showing the extreme measurements), and on the right the trendlines. These trendlines are sometimes interpolated results, sometimes extrapolated results (where the same trend is assumed). This difference is highlighted by a different line style. Only the graphs showing the most clearly visible effect are shown and discussed.

When observing the surface roughness, it was found that the placement speed had the largest effect. The pressure also had a positive effect (i.e., the higher the pressure, the lower the surface roughness), but less pronounced than the placement speed, which is shown in Figure 3. Based on previous research [1], the value after deconsolidation is expected to be in the range of 6 to 10 µm. As can be seen, the surface roughness is clearly lower than after deconsolidation, but it does not go down to the value of the as-received tape. The reason for this behaviour is expected to be the cooling down of the tape between the visible nip point (where the temperature is measured) and the actual nip point (where the tape is compressed by the roller). Due to the higher speed, the temperature at the actual nip point is higher, leading to the resin being more viscous and easier to smoothen by the roller.

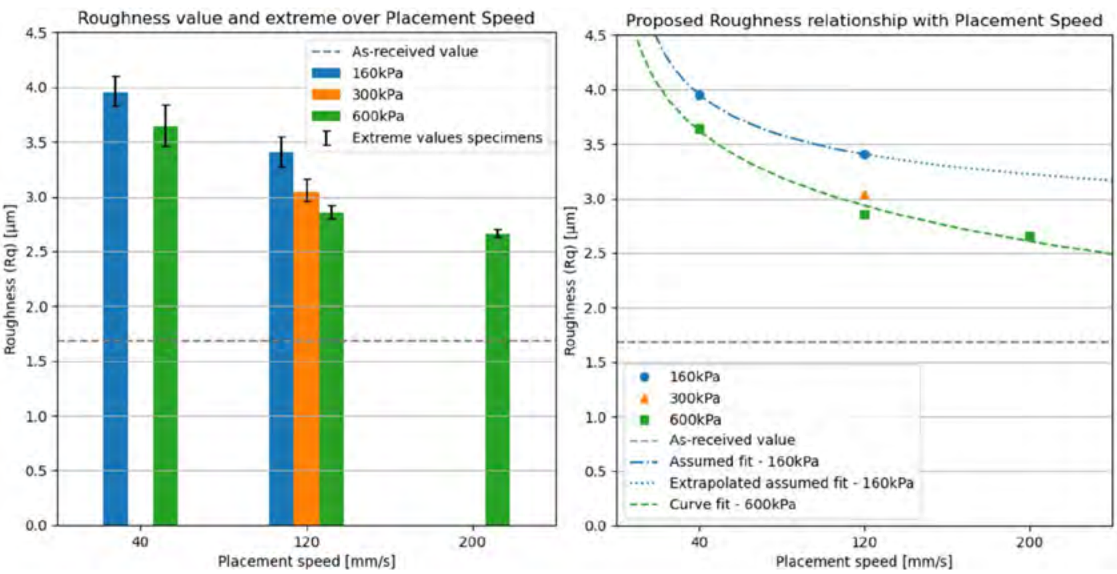

Figure 3. The effect of placement speed on the roughness.

Shifting the focus to the DEIC, it was observed that the placement speed had the largest effect. The pressure also had a positive effect (i.e., the higher the pressure, the higher the DEIC), but less pronounced than the placement speed, which is shown in Figure 4. Based on previous research [1], the value after deconsolidation is expected to be close to zero (0-1%). As can be seen, the DEIC is clearly increasing after compaction again. And even though we do not reach the as-received value, we do recover a significant part of the DEIC that was lost during deconsolidation. The increasing trend can again be linked to the temperature at the actual nip point, which is expected to be higher for higher placement speeds, allowing more fibres to be 'pushed into' the resin during compaction.

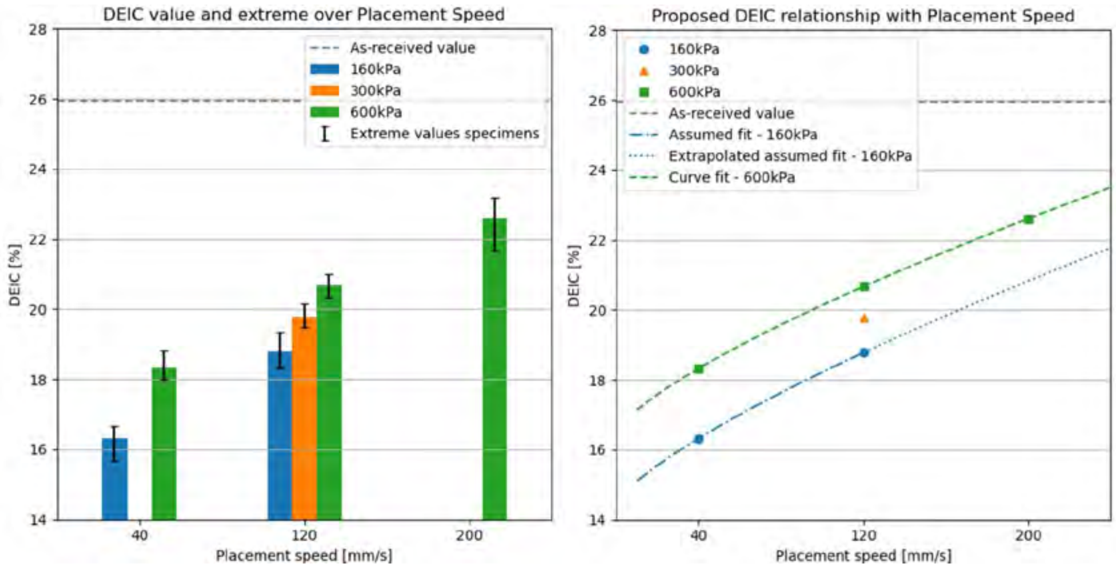

Figure 4. The effect of placement speed on the degree of effective intimate contact.

The void content is harder to interpret. For reference, the expected value after deconsolidation is between 3.3 and 4.3%. As a function of pressure, the trend (not shown) is clear: the higher the pressure, the lower the void content. As a function of the temperature, the trend is not as clear. As shown in Figure 5, there are two possible trendlines that fit the measurements relatively accurate. Either there can be a parabolic relationship, indicating an optimal speed for low void content; or a power relationship can be used, indicating that the higher the speed is, the lower the void content. It is plausible that from a certain speed, the material is still above its glass transition temperature, leading to voids re-appearing after the compaction, which is a reason to prefer the parabolic distribution. However, whether this already happens at the speeds obtained during this set of experiments is unsure. Since the tape temperature after compaction was not measured, it cannot be confirmed what the temperature after compaction was. Hence, both trends are presented as equally plausible.

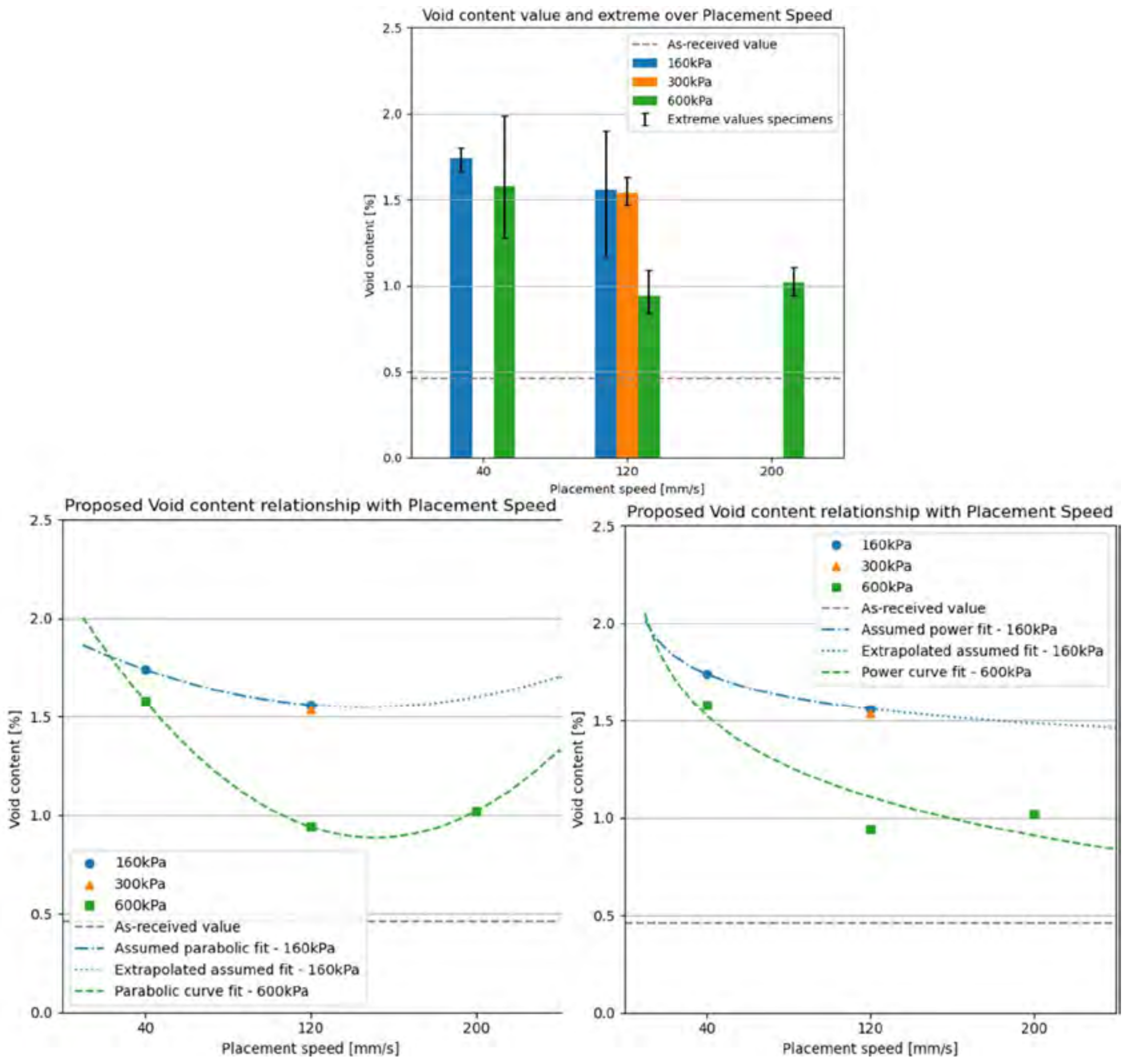

Figure 5. The effect of placement speed on the void content.

Finally, the thickness was shown to only be slightly influenced by the placement speed but still a higher speed leading to a lower thickness. For the pressure, the effect is more clear, as shown in Figure 6. It can be seen that the higher the pressure, the lower the thickness becomes. This can be partly be explained by the previous results as well: the lower void content means the total volume is slightly lower; on the other hand, the pressure is also flattening the tape, and making it wider.

This flattening is shown in more detail in Figure 7. Here it can clearly be seen that the thickness along the width of the tape is not constant: towards the side, the thickness suddenly decreases. It is believed that in this region the resin is squeezed out to the side, effectively making the tape wider, and thus less thick. Furthermore, it can be observed that it is not just resin but that fibres are also present all throughout the width, showing that the sides have at least similar fibre volume fraction as the remainder of the tape.

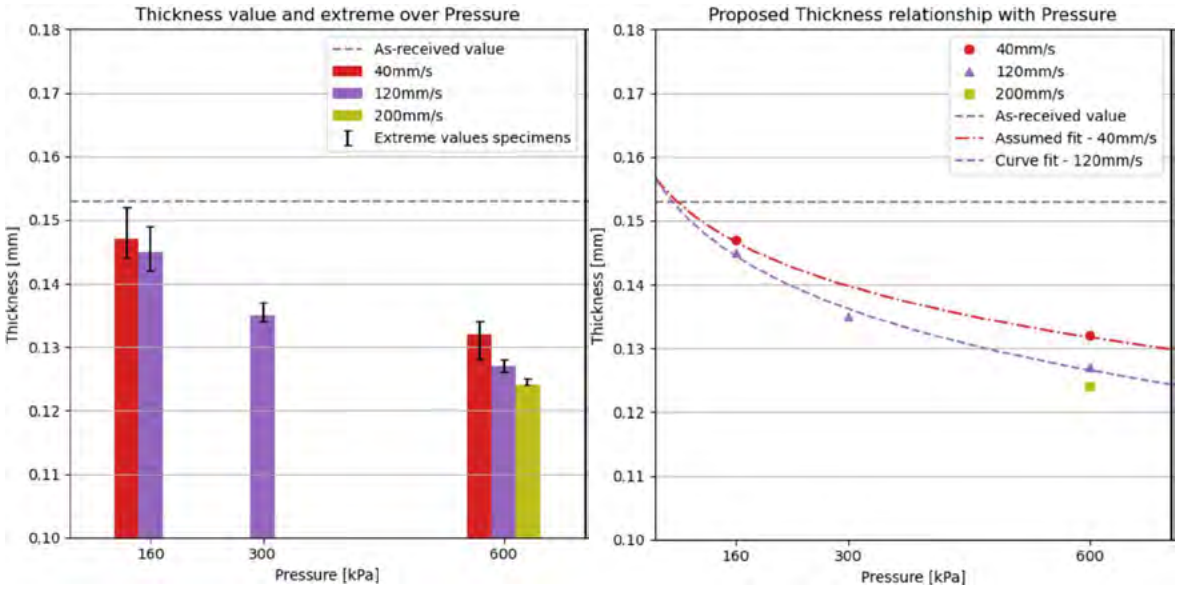

Figure 6. The effect of pressure on the thickness.

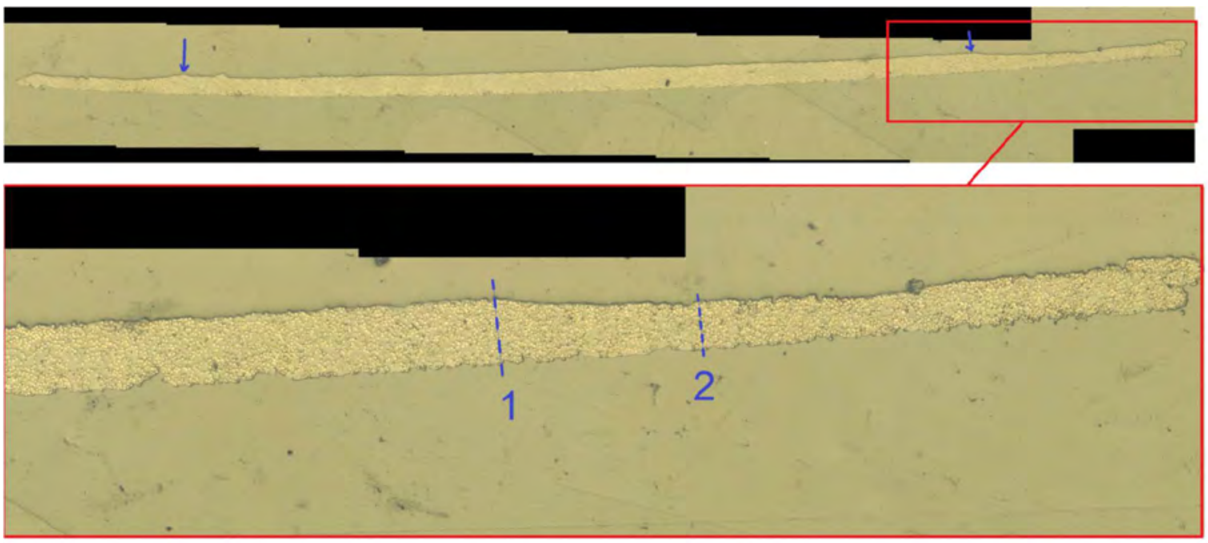

Figure 7. the thickness variation over the width.

To conclude the results, and overview of the as-received values, the values expected after deconsolidation and the values with the lowest setting (i.e., lowest speed and pressure tested) and the highest setting (i.e., highest speed and pressure tested) is given in Table 2. From this table it becomes clear that the vast majority of deconsolidation is removed during compaction. For the low setting 47 up to 73 % of the measured parameters are recovered, for the high setting 77 to 88% of the measured parameters is recovered. This highlights the importance of the compaction phase in the overall LAFP process.

Table 2. Overview of the different results.

Deconsolidation form	Reference value	Refence value	Low setting	Low setting (40mm/sec, 160 kPa)	High setting	High setting (200mm/sec, 600 kPa)
	As received	Deconsolidated [1,2]	Value	Deconsolidation resolved [%]	Value	Deconsolidation resolved [%]
Roughness [µm]	1.69	6-10	3.954	47.5-72.8	2.659	77.5-88.3
DEIC [%]	25.9	0.2	16.33	62.8	22.61	87.2
Void content [%]	0.46	3.3-4.3	1.74	54.9-66.7	1.02	80.3-85.4
Thickness [mm]	0.153	0.175-0.3	0.147	NA	0.124	NA

5. Conclusions

The current work presented a novel test set-up to mimic LAFP conditions in a small lab-scale environment. Using this set-up, the influence of placement speed and applied pressure on the tape quality after compaction. It was shown that a higher speed and higher pressure have a positive effect on the roughness (i.e., roughness decreases) and on the DEIC (i.e., DEIC increases). This positive effect can be attributed to the temperature at the actual nip point, due to the smaller time between the visible and actual nip point, and thus less time for the tape to cool down. In terms of void content, a higher pressure was found to be better; in terms of the speed, the results were inconclusive. Finally, it was found that the average thickness of the tape was decreasing with increasing pressure, and to a lesser extent with increasing speed, due to the tape getting wider. Overall, this work shows that the deconsolidation that occurs during heating can be reversed for up to 85%, but not fully going back to the initial state, which has to be taken into account when modelling the LAFP process.

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