PARAMETRIC EFFECT ON INLINE WIDTH CONTROL FOR THERMOPLASTIC AUTOMATED TAPE LAYUP

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ABSTRACT

Automated tape layup (ATL) has found increasing use for composite manufacturing due to its accuracy, reliability and productivity. The process becomes even more lucrative when thermoplastics are used, for the added possibility of ‘out-of-autoclave’ manufacturing. In-situ consolidation eliminates the need for post manufacturing energy-intensive, time-consuming, and therefore expensive thermal cure treatments. In-situ consolidation is possible, but it is challenging and requires well-adjusted process parameters. Furthermore, one major limitation of the ATL process is its susceptibility to positioning defects like gaps and overlaps. An approach is identified to bridge the gap between inline monitoring and parameter control to avoid processing defects. This work details of the design of inline width tessellation (IWT) concept, a technique for inline control of consolidated tape width to eliminate and/or rectify gaps and subsequent parametric variation on the width. Continuous inline width variation is achieved by inline control of the compaction force, during the layup process. Force and width correlation models obtained for different process parameters are used for the implementation of the IWT concept.

1 INTRODUCTION

Automation is becoming increasingly important in the processing of composite materials. A very high degree of automation is already common in processes that are already used today for large-scale production. The production of components manufactured by compression molding technology in the automotive industry, for example, is fully automated on production lines where the raw materials are introduced and the final contour machined components are discharged. In the field of placement technology, automated processing is to be classified as state of the art, at least for all process variants in which the final consolidation of the material is guaranteed in a downstream processing step. In the case of automatically laid thermoset prepregs, this is the successive autoclave process required for curing. If a thermoplastic material is used in the placement process, then it is possible to achieve consolidation in-situ during the placement process [1, 2]. In-situ consolidation eliminates the need for post manufacturing energy-intensive, time-consuming, and therefore expensive thermal cure treatments. For in-situ consolidation, however, there are particularly high demands on the process control. The process optimization essentially concentrates on the consolidation of the tapes that are placed one on top of the other. Typically, the quality of the lateral consolidation between the tapes placed side by side is neglected. In any case, lateral consolidation can only be influenced indirectly. Since the tape undergoes deformation when it is laid down due to the consolidation pressure, an optimization can be carried out with precise knowledge of the geometry of the previously placed tape and the tape laid down next to it. The optimization can be carried out both via the path guidance, i.e. the distance to the adjacent tape, and via a control of the tape width change. The width change is adjusted via the applied consolidation pressure. Control can thus be carried out by means of an adjustable consolidation pressure. Such a control also enables a flexible response to the variation in the width of the supplied tape. Since the change in the tape width under the consolidation roller is associated with a corresponding influence on the thickness of the deposited tape, a detailed understanding of the relationships is required here and the limits within which the geometric changes may take place must be defined beforehand and then adhered to in the process [3–5].

Due to the process methodology, which is defined by the placement of thin, narrow tapes next to each other and in layers on top of each other, the automated tape layup is characterized by a number of resulting challenges. Fluctuations in the quality of the tapes, e.g. variation in the cross-sectional geometry, local defects in the tape, e.g. longitudinal splits, or inaccuracies in the positioning during the placement process can lead to defects in the laminate. One major limitation of the process is its susceptibility to positioning defects like gaps and overlaps which are not only detrimental to the structural integrity of the part [6], but also reduce the productivity due to time and effort intensive rectification process. The process often employs manual visual inspection, which in itself leads to undetected flaws and reduced productivity due to lack of automation and reliability. For complex shaped and doubly curved structures, these defects appear in a structured pattern in due to steering restrictions. The nature of these defects, renders them as being a design feature for such processes [7, 8].

An approach is identified to bridge the gap between inline monitoring and parameter control to eliminate processing defects. This work details of the design of inline width tessellation (IWT) concept, a technique for inline control of consolidated tape width to eliminate and/or rectify gaps and subsequent parametric variation on the width. Continuous inline width variation is achieved by inline control of the compaction force, during the layup process. A fully equipped test rig for thermoplastic ATL with monitoring capabilities [9] was used for inline width variation and thereby gaps prevention [Fig. 1].

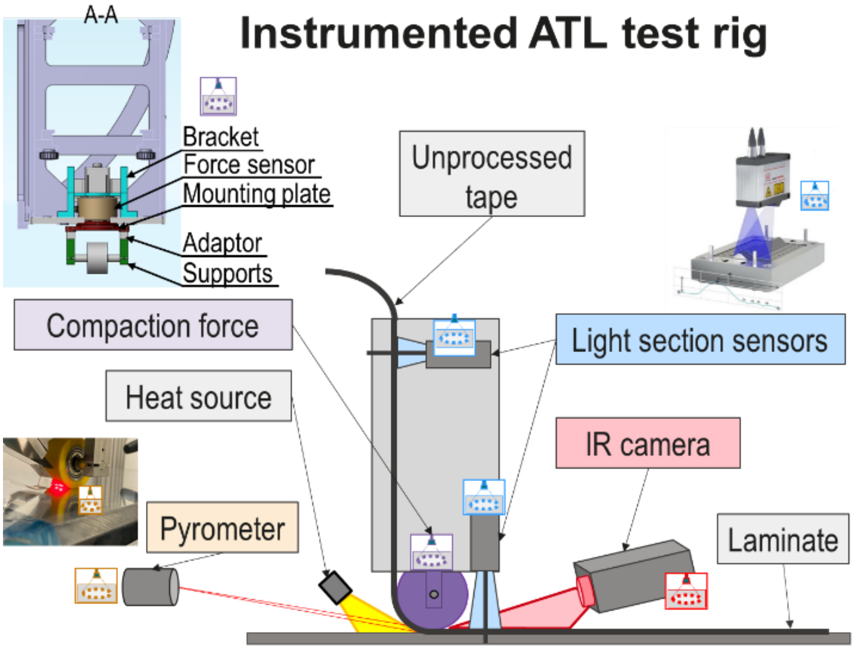

Figure 1 Instrumented ATL test-rig used

2 METHODOLOGY

Material deformation during consolidation is used as the basis of width variation concept. Compaction roller applies a force on the incoming tape, leading to a pressure field formation. A combination of heat and pressure leads to morphological changes in the thermoplastic tape. This material deformation is defined as squeeze flow and for thermoplastics it is treated as creeping motion [10].

Among the process parameters, heat input and process velocity have a stronger influence on bond strength than compaction force. An increase in compaction force leads to higher degree of intimate contact and reduced void content, having limiting effect on consolidation quality [2, 5, 11–13]. For a single process run, heat and velocity are usually kept constant to ensure homogenous consolidation quality. Compaction force can however be treated as a parameter that can be varied relatively freely during the process, within certain limits guided by the material, having minimal impact on the bond strength.

As thermoplastic tape deformation is guided by compaction force, a correlation between the two can be used to vary the tape dimensions by varying the applied force. A force/torque sensor is used to monitor the compaction force and light section sensors are used to detect the tape dimensions at two points, i.e. before and after consolidation. Width spread during consolidation is thus controlled by inline force adaptation to conform to tool geometry and restrict gaps and overlaps. The concept is especially useful for variable angle tow (VAT) or variable stiffness panel (VSP) laminates and complex shaped and doubly curved structures.

For the present test-rig set-up as shown in Figure 1, three realistic use case scenarios are considered. The first application is concentrated on gap prevention for VAT/VSP and complex shapes. In this case, a-priori knowledge of path planning is used to pre-program force variation resulting in defined width spread. The second case is real-time gap prevention accounting for raw material (as supplied by manufacturer) variability. For this, the raw material is monitored continuously and force is adjusted online to account for this variability. The last case is related to defect rectification. In this case, any remaining gaps and overlaps are identified and heat and pressure repass are used to rectify them. This research work is focused around the first case. A correlation between force and width is modeled. Parametric study is performed to analyze the effect of different parameters on width spread.

To sum up, a technique for inline control of consolidated tape width to eliminate and/or rectify gaps is identified, hereby referred to as, inline width tessellation.

3 EXPERIMENTS

Light section sensors have been shown as capable of detecting gaps and overlaps [14–17]. Two such sensors are integrated in the in-house built ATL head, as shown in Figure 1. They have a resolution of 2µm, 1280pixels/profile and measuring speed up to 300Hz. The first sensor detects the geometry of the raw material before consolidation and the second sensor detects the geometry of the tape after consolidation. Second sensor is also used to monitor gaps and overlaps occurring due to material variability and steering restrictions.

Compaction pressure is applied via a pneumatic pressure system and a maximum of 1.2kN can be applied. A 6-axis force/torque sensor, placed directly above the compaction roller measures the compaction force applied on the substrate. Force can be varied both inline and online. The resolution is 0.2N, accuracy ~4N and stabilization time ~1ms. More information about the test-rig, system characterization and performance assessment tests consisting of calibration, validation and initial results could be found in a previous study [18].

For parametric study, heat, velocity and force were varied at three levels and their effect on tape width after consolidation was monitored. Data from laser light section sensor and force/torque sensor is used to formulate an empirical model for width changes in relation to force variation for different process parameters. These models can then be used to vary the force according to the width spread requirements. Three samples, each consisting of 450 data points were collected at 100points/s. Heat was varied between 2500W, 3000W and 3500W. The velocity values were set to 50mm/s, 100mm/s and 150mm/s. Compaction force levels were 100N, 200N and 300N.

The material used for this study is thermoplastic CF-PA6 tape (SGL Carbon). The melting point of the material is 220°C, the width and thickness are 25.4±0.1mm and 0.2mm respectively. Thermoplastic tape has a fiber volume content of 42%. The layup tool is temperature controlled and for all the experiments conducted in this study, it was maintained at 30°C. A soft conformable silicon compaction roller having shore hardness 70 and width 30mm is used.

4 RESULTS AND DISCUSSION

In a first step, the force/torque sensor mounted directly above the compaction roller was calibrated and checked for standard weights. Pressure sensitive foils and pressure mapping systems were used as standard pressure sensors for benchmarking tests. A good agreement between the force/torque sensor and the benchmarks were obtained. Performance assessment tests were elaborated which demonstrate online variation of force from 50N-1000N, having a standard deviation of 10N. For online force variation of 100N, a stabilisation time of 0.3s is required.

Feasibility studies for minimum and maximum attainable width spread were performed and it was shown that for a fully consolidated CF/PA6 tape a width increase of 5% to 50% compared to initial width can be obtained using the given test rig. It was observed that compaction force level as low as 50N is enough to increase the width by 1mm, accounting for 5% width spread compared to initial width. As noted by [5], 50N is generally sufficient to have an intermediate level of degree of bond. For the present experiments, 50N compaction force corresponds to 0.6MPa pressure level. This value is sufficiently high compared to the values listed in literature, 1-4kPa [19]. The lower limit of 50N can therefore be used for width variation with no adverse effects on intimate contact and bond strength. Attention should however be paid to the overall material behavior while establishing parametric upper and lower bounds. A combination of high temperature and force leads to matrix flow/squeeze out which is the dominant mechanism for mechanical property loss for low melt viscosity matrices like PA6 [20]. For a compaction force of 350N, a width spread of 8.8% is observed. The average width increment with an increment of 50N is ~0.2mm. The upper and lower bounds for incidental gaps that occur in the course of ordinary ATL operations are 1.27mm and 0.762mm [21, 22]. A width spread of 0.2-2.25mm can be achieved using the present inline width tessellation, which is sufficient to cover incidental gaps, according to the aerospace industry standards.

For VAT/VSP laminates a maximum of 41.4% width spread can be expected to eliminate gaps in extreme cases [23]. Due to hardware restrictions, smaller width tapes were preferred to demonstrate system feasibility and capability. Experiments were conducted at 500N and 750N for an initial tape width of 6.3mm and 12mm. For an initial width of 6.3mm, an increment of 50.7% is obtained for 750N. For an initial width of 12mm, a maximum of 29.16% increase is obtained at 750N. A further increase can be expected if lower velocity and higher heat input is used.

Effect of linearly varying force on the consolidated tape width resulting in a trapezium shape was studied for several different initial tape widths, as shown in Figure *2*. Force and width correlation models were obtained for standard tape width of 1-inch (25.4mm). Detailed results and illustrations can be found in a previous study [18].

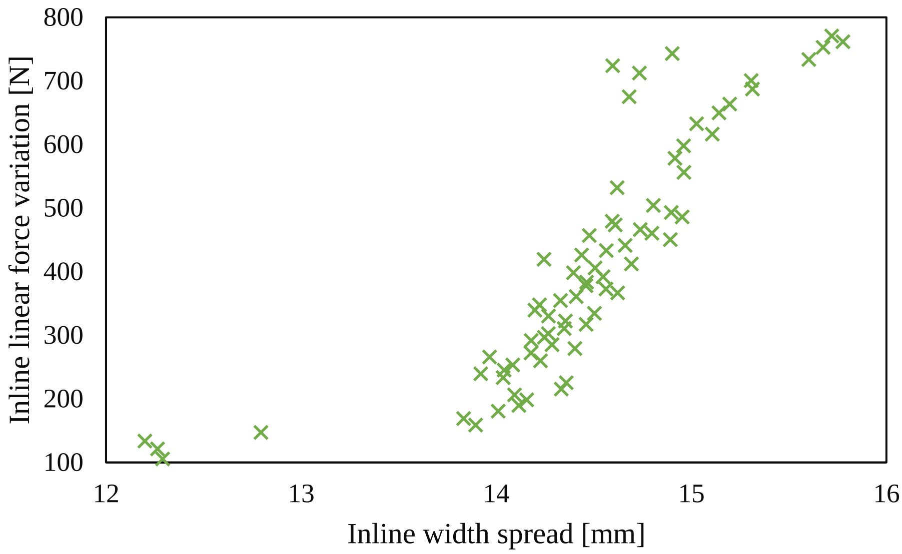

Figure 2 Inline width spread as a result of linearly varying consolidation force

The parametric effect of heat, velocity and compaction force on width spread is analyzed, as shown in Figure 3. Maximum width spread is obtained for high heat, low velocity and high force. Velocity has a very strong influence on the material behavior. At high speeds, even a very high heat and force (150mm/s, 3500W and 300N) application does not result in considerable width increase. The difference in width spread for different heat input is very small, indicating that at very high velocity (150mm/s), heat input has a minor impact on material behavior. Increasing the force at this stage again leads to only a slight increase in width. It should be noted that compaction force has a strong dependence on process velocity. The layup velocity dictates the amount of time available for polymer healing. Lower velocity results in higher temperature, leading to lower melt viscosity and consequently higher degree of intimate contact. At high velocity there is less time for polymer healing and even if compaction force is increased continuously it will not result in increased degree of bond [5]. For a low velocity, the width spread for the least heat and force (50mm/s, 2500W and 100N) is still greater than that for higher velocity at maximum heat and force (150mm/s, 3500W and 300N).

For a constant heat input, the difference in width spread between 50mm/s and 100mm/s is quite stark compared to the difference between 100mm/s and 150mm/s. The overall width spread for different heat inputs look very similar and even though the width increases as the heat increases, the increment is not considerable for higher velocities. This can again be attributed to time available for polymer healing. A substantial increase in width can be seen for increased force (100N to 300N) and heat (2500W to 3500W) for low velocity (50mm/s). The overall maximum width increase is found at 50mm/s, 3500W and 300N. The overall minimum is at 150mm/s, 2500W and 100N.

Changing the velocity at the lowest parametric set (150mm/s, 2500W and 100N to 50mm/s, 2500W and 100N) gives better result than changing force (150mm/s, 2500W and 300N) or heat (150mm/s, 3500W and 300N). Same applies for highest parametric set. If velocity is changed, the values drop significantly. Width and force follow a quadratic curve, but more data points are required to verify the correlation.

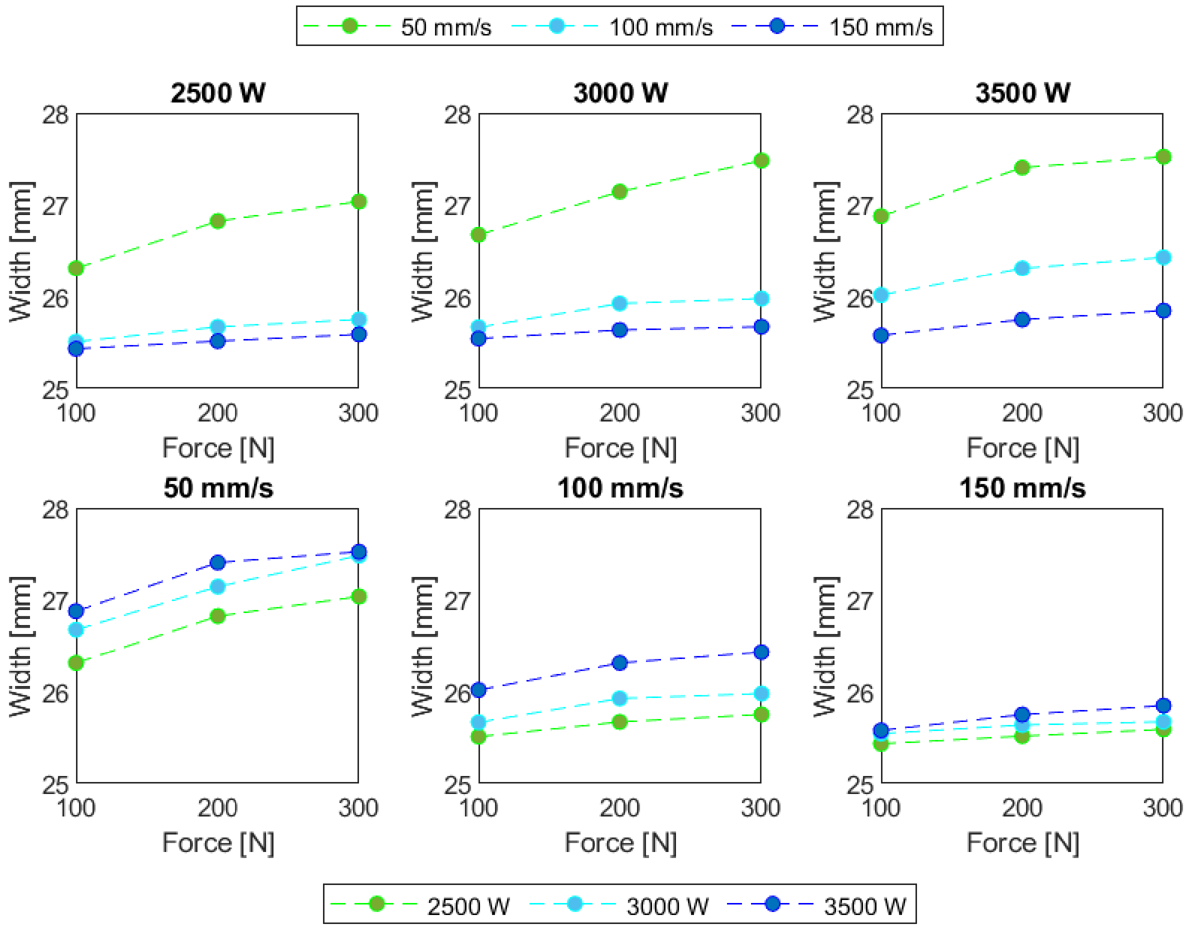

Figure 3 Parametric influence on width spread

3D surface map of all the data points is shown in Figure 4. Process velocity can easily be recognized as the major factor influencing the width increase. It can be argued if the heat input levels are sufficient to bring about a morphological change and fall within the temperature limits guided by the meting point and degradation point of the thermoplastic. From previous experiments these limits were well established and the width change at least heat input ascertains the lower limit of heat for initiating melt behavior. The maximum heat input was selected based on how the material reacts at lowest velocity. Beyond this point, the material starts degrading. Even with strict boundary conditions and limitations, a good data base is formulated. Depending on the velocity and heat, a range of width values can be found. The force can be adjusted using this relation to accommodate the width changes as per requirements. Largest range of width values are available for maximum heat input. Even if choosing just one velocity value (single surface from 3D surface map), maximum slope is encountered giving us a good range of width values to choose from. Attention should be paid that the upper limit of force values can be extended very easily without having to worry about degradation or bond strength. The more the range of width variation, the better the gap coverage possibilities. As discussed previously, the initial width of the material plays a crucial role in the maximum achievable final width.

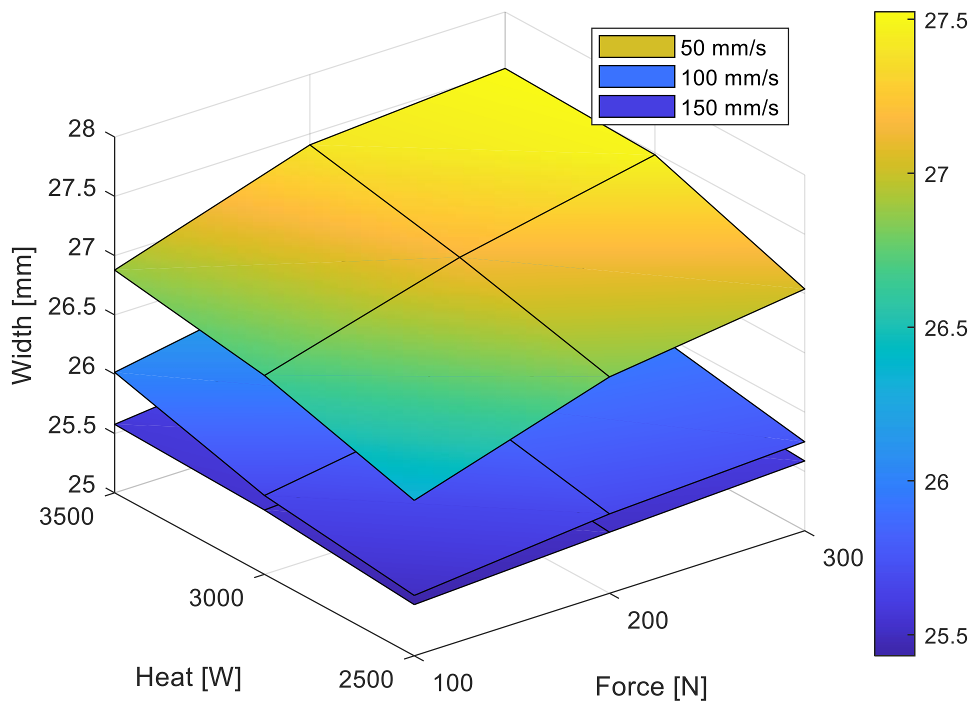

Figure 4 Surface map of parametric influence on width spread

5 CONCLUSIONS

Force and width correlation models were obtained for different process parameters for standard (1-inch) tape width for the implementation of the inline width tessellation concept. A near quadratic fit for standard force (100N-300N) application is established. Parametric study highlights the influence of process velocity on tape width change. A higher width change rate is observed at higher heat input. Surface map can be used to model material behavior that can then be used for gap elimination and path planning. The sensitivity of width towards changes in layup parameter are also test-bench dependent. The type of heat source, initial width of the tape and hardware restrictions define the scope of the model and ultimately the process window for robust control. A vast range of possibilities for width variation and gap elimination exist based on the system characterization.

The IWT concept presented here will allow improvement in laminate quality received during ATL. Gaps elimination should result in improved mechanical performance, what will be verified in future research work. The IWT concept helps in improving process productivity, reliability and accuracy by detecting, rectifying and controlling selective manufacturing defects. The design flexibility related to the scale and shape (shape conformity) of resulting laminates gives the process immense potential, that has so far been offered only by 3D printing.

Future work would include extending the parametric study to characterize width when adjacent and top plies are laid. Mechanical performance tests would be performed to analyze the effect of gap elimination via IWT concept. Finally, an online feedback control would be modelled taking into consideration both material variability (as supplied raw tape material) and parametric influence. Such a model could benefit from machine learning methods, with the aim of establishing width spread for optimized process parameters. This could then be further used for rework and rectification.

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