Investigation of Stamp-Forming Parameters on the Impregnation of Pultruded Beams

B. Turcotte[1*], S. Baril-Gosselin[2], and L. Laberge Lebel[1]

[1] Advanced Composites and Fibers Structures Laboratory (ACFSlab), High Performance Polymer and Composite Systems (CREPEC), Polytechnique Montreal, Montreal, Canada

[2] Automotive and Surface Transportation Research Centre, National Research Council Canada, Boucherville, Canada

* *Corresponding author (brandon.turcotte@polymtl.ca)*

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1. Abstract

Stamp-forming can reshape linear or 2D shapes into more complex 3D geometries, expanding their areas of application. Thermoplastic pultrusion is a fast and continuous manufacturing process capable of producing linear parts, i.e. pultrudates, featuring a constant cross-section. The objective of this study is to find the most influential stamp-forming parameters affecting quality of the forming process, which was characterized in terms of consolidated thickness and width of stamp-formed pultrudates. A stamp-forming cell installed in a high-speed universal testing system was developed for this work. The selected part geometry was an omega shape with a rectangular cross-section. A Taguchi L9 (3^4) orthogonal array featuring four 3-level factors was used to study the processing parameters, which were mould temperature (MT, [60, 100, 140] °C), closing speed (FCS, [15, 100, 400] mm/s), applied pressure (AP, [0.1, 1, 3] MPa) and pressure holding time (PHT, [15, 30, 60] s). An ANOVA analysis revealed that AP had the most influence over the consolidation thickness, followed by MT, FCS and PHT. Conversely, selected parameters had no significant effect on the consolidation width. Most importantly, the work confirmed that stamp-forming can effectively reshape thermoplastic pultrudates, opening opportunities to reduce the cost of automotive composites.

2. Introduction

In recent years, continuous fibre thermoplastic composites have been gaining interest in the automotive industry [1], because unlike thermosets, their processing is reversible. This allows thermoplastic matrix to be reshaped [2], welded and recycled [3]. Also, the absence of chemical reaction can lead to faster manufacturing time, which is of upmost importance for the automotive industry.

A fast way to process thermoplastic composites is stamp-forming [4]. Figure 1 illustrates the four steps of the stamp-forming process used in this study. First, a composite blank is heated up until its temperature becomes greater than the melting temperature of its thermoplastic matrix (Figure 1a). Once the desired temperature is reached, the composite blank gets transferred from the oven to the heated matched-die mould for consolidation (Figure 1b). In order to reduce the manufacturing time and allow crystallization, the mould temperature is kept at an isothermal temperature that lies between the polymer glass transition temperature (T_g) and melting temperature (T_m). Pressure is maintained on the blank through the crystallization process to prevent deconsolidation during the cooling phase (Figure 1c). Finally, the upper die opens and the final part is taken out (Figure 1d).

Pre-consolidated laminates are typically used in stamp-forming processes to produce thin-shell structures. Greater complexity parts with geometrical features and function integration can be obtained by combining stamp-forming with injection overmoulding [5], a process in which a polymer is injected over a composite structure. In such case, composites should only be limited to areas of higher stress levels to reduce cost. Nevertheless, pre-consolidated laminates remain relatively expensive and trimming waste of blanks reduce cost-effectiveness of the material.

A more affordable method to manufacture composites is thermoplastic pultrusion (TP). It produces linear components with a constant cross-section. Such simple geometry limits their area of application. However, using pultrudates as low-cost stamp-forming blanks can widen their geometrical envelope, making them suitable for greater complexity parts and effective local reinforcement for the overmoulding process. To the authors' knowledge, pultruded blanks used in a stamp-forming are not reported in the literature.

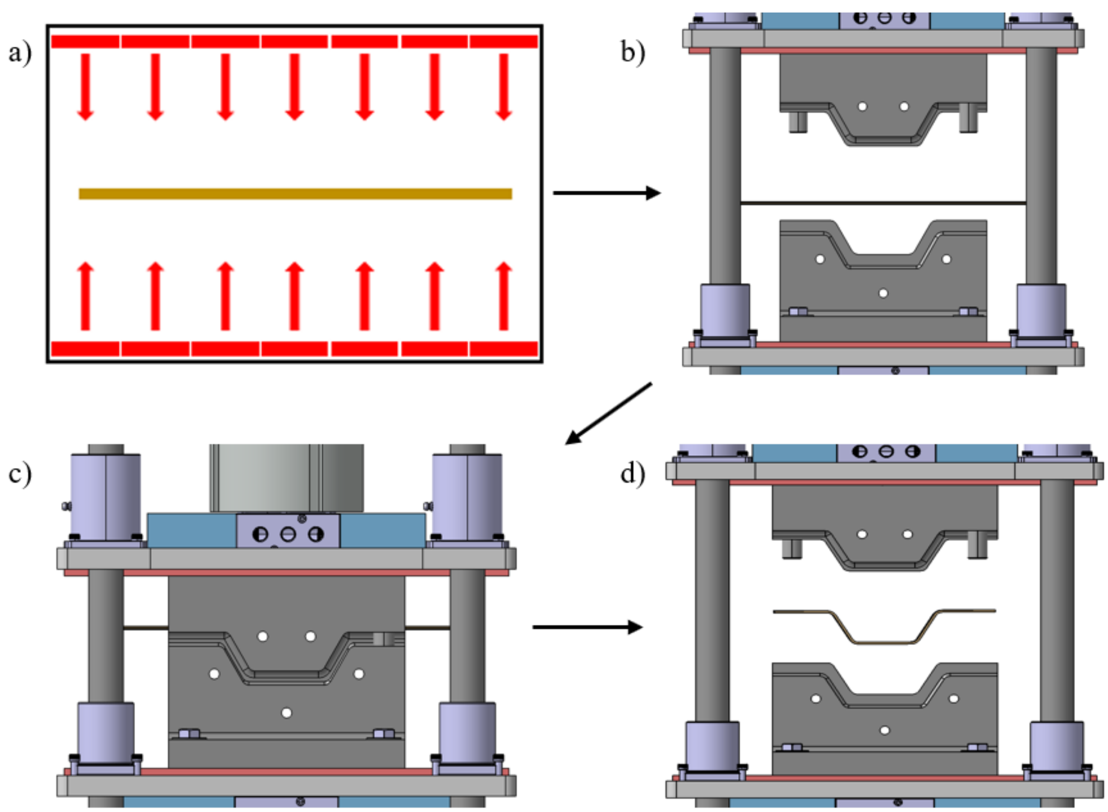

Figure 1. Stamp-forming process used in this study: a) Initial preheating; b) Transfer between the heated matched-die moulds; c) Application of the stamp forming sequence; d) Opening of the upper die and demoulding.

The objective of this work is to study the stamp-forming process for making pultruded blanks that could eventually be used as local reinforcement in injection overmoulding. This is accomplished by performing a design of experiments that evaluates the influence of various stamp-forming parameters on the quality of stamp-formed blanks.

3. Experimental

3.1. Materials

Semi-consolidated co-wound (SCW) yarns (*Concordia Fibers*) made from 21 E-Glass (EG) fibre tows (66 tex) and five polyamide 6 (PA6) tows (100 tex) were used in this study. The final linear density of the SCW yarns was 1 886 tex. The fibre volume fraction of the SCW was 55.4 %. The T_g and T_m of the PA6 matrix are 60 °C and 220 °C, respectively.

3.2. *Pultrusion Apparatus*

A total of 43 SCW were used to produce 3 mm by 15 mm rectangular pultrudates with 1 mm radius corners. The pultrusion system and experimental conditions were the same as the experiment accomplished at 50 mm/min with GF/PA6 without vacuum in [6]. The only exception is the number of SCW used.

3.3. Stamp Forming Apparatus

The stamp-forming apparatus is shown in Figure 2. It is composed of 3 systems: the heating system, the transfer system and the stamping system. The heating system is composed of an infrared oven (Model 7200, *Leblanco Limited*). The infrared (IR) oven has a maximum output power of 8,600 W. The transfer system is responsible for transferring the pultruded blank to the heating system, and then to the stamping press. The pultruded blank stayed for two minutes in the IR oven programmed at 260 °C. A temperature uniformity survey (TUS) was done and revealed that the coldest and hottest part of the pultrudate reached a temperature of 248 °C and 281 °C, respectively. In the future, further set-up modifications will be accomplished to reduce the temperature variations and to accurately reach the desired temperature. In this study, the preheating temperature (PT) was defined as 265 °C, which was the average of the coldest and hottest temperatures measured. The transfer system transfers the melted pultrudate from the oven to the stamping system in approximately 3 seconds. The stamping system is composed of a high strain-rate universal testing machine (Model 819.160, *MTS*) and heated matched-die moulds. The universal testing machine used a 125 kN load cell. The heated matched-die mould is held at a steady temperature, defined as the mould temperature (MT).

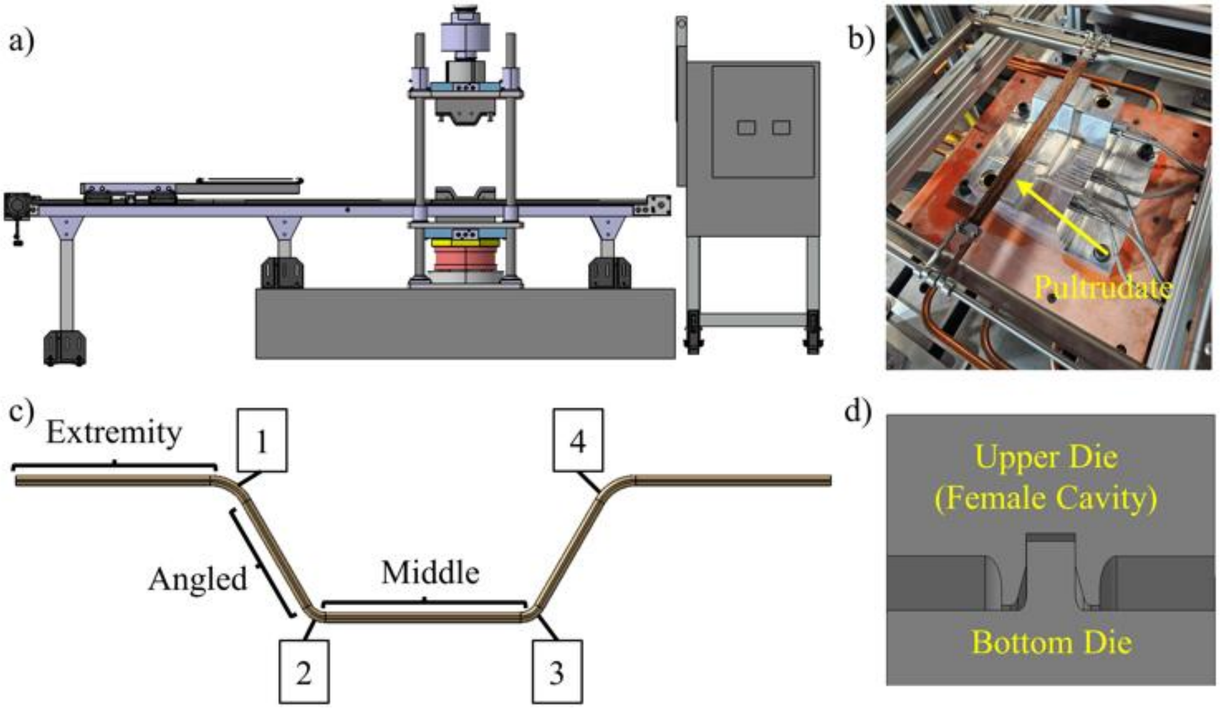

Figure 2. Stamp-forming apparatus: a) Stamp-forming equipment CAD (hydraulic press not shown); b) Close-up of the transfer system; c) Geometry of the stamp-formed pultrudate (with identified sections and angles); d) Close-up of the cross-section of the upper die.

The stamp-forming sequence is divided into specific steps. It starts when the heated pultrudate arrives at the stamping station. The first step is defined as the period when the upper die closes rapidly on the lower die until a separation distance between dies of 5 mm is reached. The stamping velocity in this step is a process parameter and is defined as the fast-closing speed (FCS). The separation distance was chosen to be superior to the deconsolidated thickness (4.2 mm) of pultrudates, following the heating phase. Therefore, the upper die is stopped before applying pressure on the load cell located under the bottom die. In the following step, defined as the slow approach, the closing speed of the upper die decreases to 2 mm/s until a certain force is reached. This closing speed was chosen so that the approach would be sufficiently fast to occur within 1 second. When the transition force was reached, the machine switches to a force-controlled mode. Then, a specific force ramp is applied to reach the targeted consolidation force. The targeted consolidation force is calculated from the desired consolidation pressure, called herein the applied pressure (AP). The force is calculated by multiplying the pressure by the projected area of the female cavity (215.9 mm × 19 mm = 4102.1 mm^2). The transition force and force ramp were experimentally determined, within the physical limits of the universal testing machine, to ensure that the consolidation pressure was applied within one second. Table 1 shows the force settings for each targeted consolidation pressures.

Table 1. Transition force and force ramp pairs for each targeted pressure to achieve a nominal force ramp duration of 1 s.

Targeted pressure (MPa)	Targeted Force (N)	Transition force (N)	Force Ramp (N/s)	Nominal Force Ramp Duration (s)
0.1	410	310	100	1
1	4100	1100	3000	1
3	12300	2300	10000	1

The frequency of data acquisition was set to 1024 Hz during this whole phase. The targeted force was then held for a specific duration, called herein the pressure holding time (PHT). When the PHT has passed, the upper die opens at a constant speed of 10 mm/s. The frequency of data acquisition during the PHT phase was 102.4 Hz. Afterwards, the stamp-formed pultruded blank was removed from the transfer system by hand.

The stamping sequence was programmed in the *Multipurpose Elite* program from *MTS TestSuite*. The whole stamp-forming sequence was controlled by a *LabView* program that linked the oven door opening, transfer system and trigger for the universal testing machine together to start the stamping sequence.

Figure 2c shows the final geometry of the stamp-formed blank having two extremity sections, two angled sections and one middle section, linked by corners 1 to 4. During preliminary experiments, it was observed that deconsolidated fibres could slip out of the bottom male part angles 1 and 4 during the closing phase. During the closing phase, the sample was first trapped in the middle section of the female part of the upper die (Figure 2d). The sample was then secured by the female vertical edges on angles 2 and 3 (Figure 2c). Then, the sample was dragged down to the bottom mould with the next contact being the male part of the bottom die at angled sections 1 and 4. Since the sides of pultrudates were not constrained, fibres often moved out of their intended moulding surfaces and could get trapped between the vertical sections of the female and male dies of the mould. Trapped fibres caused important friction, diverting pressure away from the pultrudates, resulting in lower compaction forces than desired. To counter this, a 25 mm-wide Kapton tape wrapping was applied on the samples after pultrusion, at the intended positions of corners 1 and 4. The Kapton wrapping was partially slit, leaving only 1 mm of complete circumferential wrapping at each extremity of the wrapping. The wrapping broke during stamping, allowing fibres to fill the mould cavity but preventing them from flowing into the gaps between dies. This reduced greatly the friction forces during the fast-closing phase of the upper die and allowed better control over the actual consolidation pressure. The Kapton tape was removed after cooling. It should be noted that for industrial manufacturing, tighter mould tolerances would compensate the need for the Kapton tape.

3.4. Design of Experiments

A Taguchi L9 (3^4) orthogonal array featuring 4 3-level factors was used for studying the effect of processing parameters. The chosen design of experiments is shown in Table 2. The selected factors were MT ([60, 100, 140] °C), FCS ([15, 100, 400] mm/s), AP ([0.1, 1, 3] MPa) and PHT ([15, 30, 60] s).

Table 2. Taguchi L9 design of experiments for the stamp-forming study.

Experiment Number	Experiment Identification	MT [°C]	FCS [mm/s]	AP [MPa]	PHT [s]
#1	60-15-0.1-15	60	15	0.1	15
#2	60-100-1-30	60	100	1	30
#3	60-400-3-60	60	400	3	60
#4	100-15-1-60	100	15	1	60
#5	100-100-3-15	100	100	3	15
#6	100-400-0.1-30	100	400	0.1	30
#7	140-15-3-30	140	15	3	30
#8	140-100-0.1-60	140	100	0.1	60
#9	140-400-1-15	140	400	1	15

3.5. Characterization

Stamp-forming data, such as the position of the upper die and the applied force on the pultrudate during the stamping sequence, were extracted and analyzed. Each sample that was produced has had its thickness and width measured five times in the middle section without Kapton wrapping. The measurements were taken with a digimatic micrometer (MDC-1'' SX, *Mitutoyo*). Thicknesses and widths were measured before heating, after heating and after stamping to study the geometrical evolution of the samples throughout the entire process. An ANOVA analysis comparing the signal-to-noise (S/N) ratio of the final thickness of all experiments was accomplished. The smaller-the-better S/N ratio [7] was chosen. The reason is that the smaller the final thickness of the final stamp-formed part is, the better the consolidation would be. A higher value of S/N ratio would give the best result (smallest thickness). For the width, no statistical analysis was done, as little variation was observed due to the part being constrained by the mould cavity.

4. Results and Discussion

During all stamp-forming experiments, no resin was squeezed out during the stamp-forming process. The slit Kapton tape wrapping ruptured for all experiments where the AP was 1 MPa and 3 MPa. When the AP was 0.1 MPa, the Kapton wrapping deformed, but did not rupture. Imprints caused by the Kapton tape could be seen in the corners where it was installed. Since the tape caused deformation in the corners of samples where it was installed, only the middle section was measured for its thickness and width.

4.1. Upper Die Position Velocity and Applied Force Evolution during Stamp-Forming

Figure 3 shows the curve of the upper die position and AP for its three levels (60-15-0.1-15, 140-400-1-15 and 100-100-3-15). Figure 3a), c) and e), show the full stamp-forming sequence. A close-up of the displacement-controlled phase was added for clarity as it happened quickly compared to other phases. The force-controlled phase can be identified by its decreasing force. It is followed by a dwell phase that maintains a constant force. Finally, the last phase is the mould opening where the force and mould position return to zero, with the prior occuring instantaneously.

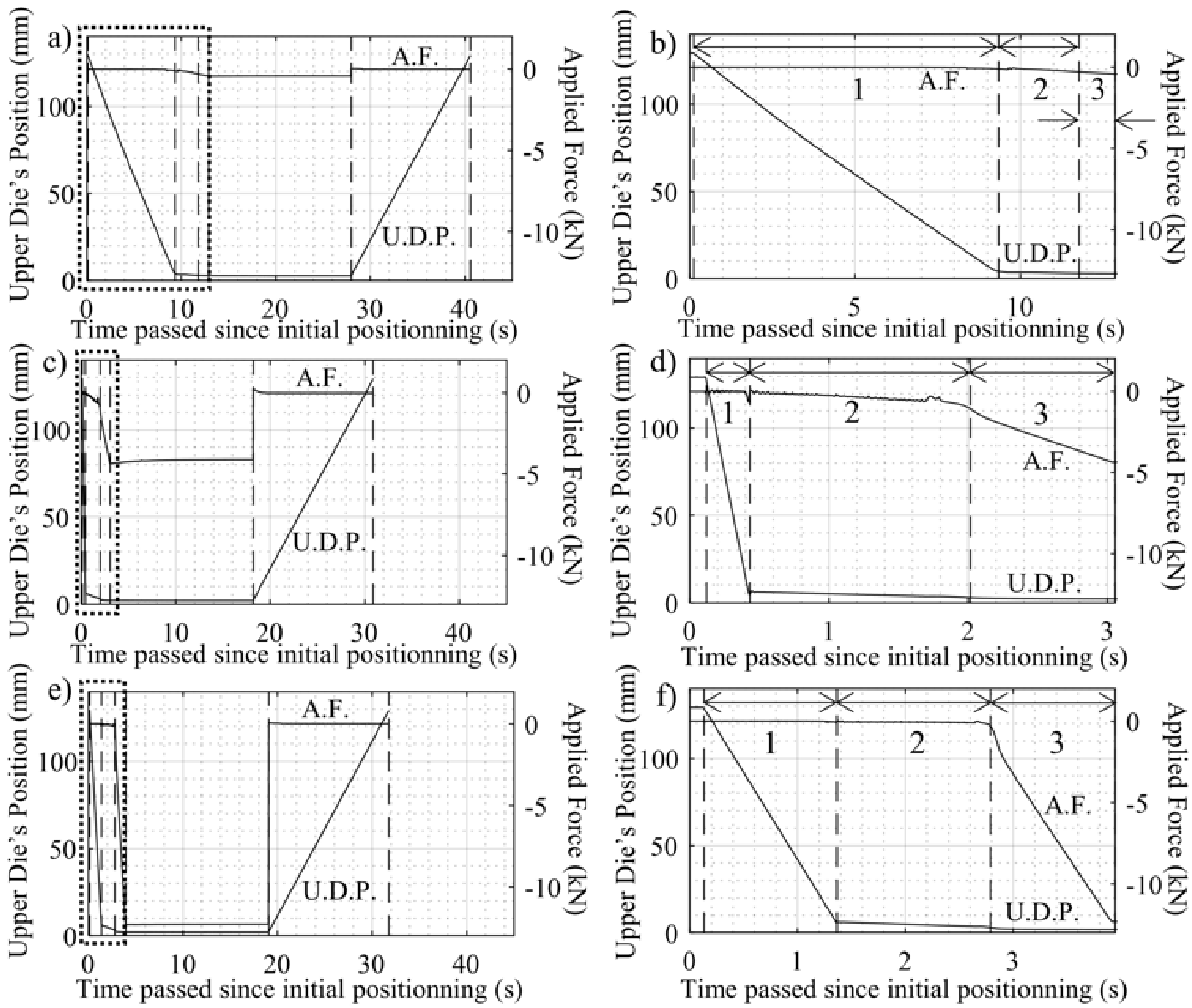

Figure 3. Upper Die Position (U.D.P.) and Applied Force (A.F.) during the stamp-forming sequence of: a) 60-15-0.1-15 (full sequence); b) 60-15-0.1-15 (displacement control part); c) 140-400-1-15 (full sequence); d) 140-400-1-15(displacement control part); e) 100-100-3-15 (full sequence); f) 100-100-3-15 (displacement control part).

Figure 3b), d) and f), show a close-up on the initial rapid steps of the stamp-forming sequence. Zone 1 corresponds to the FCS phase. The slope of the ramp corresponds to the FCS, which is different for every shown cases. Zone 1 in Figure 3b) show a slope of 15 mm/s with a duration of 9.2 s. Zone 1 in Figure 3d) show a slope of 400 mm/s with a duration of 0.3 s. Zone 1 in Figure 3f) show a slope of 100 mm/s for a duration of 1.2 s. Zone 2 is the final approach phase where the closing velocity decreases to 2 mm/s. Its duration varies between each shown cases due to slight variability in the upper die position during phase transition caused the control system of the press. Hence, the stopping height could deviate from the 5 mm target. In general, the Zone 2 duration is approximately 2 s. Zone 3 corresponds to the force application ramp and lasts until the targeted compaction force is reached. In all shown cases, the duration of the force ramp was approximately 1 s, as programmed, illustrating the precision of the stamping cell.

4.2. Evolution of Thickness and Width

Table 3 shows the different measurements made on analyzed samples with their standard deviation (S.D.).

Table 3. Thickness of the middle section of different samples during the stamp-forming process.

	Initial Pultrudate	Pultrudate after Preheating	Sample #1	#2	#3	#4	#5	#6	#7	#8	#9
Thickness (S.D.) [mm]	2.78 (0.09)	4.3 (0.3)	3.16 (0.01)	2.513 (0.002)	2.267 (0.004)	2.364 (0.004)	2.236 (0.005)	2.82 (0.05)	2.206 (0.007)	2.73 (0.03)	2.24 (0.02)
Width (S.D.) [mm]	14.69 (0.04)	16.6 (0.8)	18.73 (0.06)	18.86 (0.03)	18.86 (0.03)	18.84 (0.03)	18.84 (0.03)	18.85 (0.02)	18.82 (0.04)	18.82 (0.01)	18.87 (0.04)

Results show that the thickness and the width of pultrudates increase significantly after the preheating phase, displaying the extent of the deconsolidation. Afterwards, samples get reconsolidated during the stamp-forming process. This can be observed by their smaller thickness and increased width. Comparing the various experiments, it is observed that all the widths after stamp-forming are very similar. This confirms that in all cases, fibres could flow and fill all of the cavity. Conversely, for the thickness, results are very different. In some cases, the final thickness is thicker than the initial thickness of the pultrudate, indicating poor consolidation. This shows that stamp-forming parameters have a strong influence on the quality of the consolidation. Table 4 and Table 5 show the analysis for the final thickness of all tested samples.

Table 4. Thickness results and S/N ratio for all tested samples.

Sample Identification	Thickness Measurement [mm]	S/N Ratio [dB]
60-15-0.1-15	3.16 ± 0.01	-10.01
60-100-1-30	2.513 ± 0.002	-8.00
60-400-3-60	2.267 ± 0.004	-7.11
100-15-1-60	2.364 ± 0.004	-7.47
100-100-3-15	2.236 ± 0.005	-6.99
100-400-0.1-30	2.82 ± 0.05	-9.00
140-15-3-30	2.206 ± 0.007	-6.87
140-100-0.1-60	2.73 ± 0.03	-8.72
140-400-1-15	2.24 ± 0.02	-7.02

Table 5. ANOVA analysis for the tested stamp forming parameters influence on the thickness.

Parameter	Level 1	Level 2	Level 3	Delta	Rank
MT	-8.37	-7.82	-7.54	0.83	2
FCS	-8.12	-7.90	-7.71	0.41	3
AP	-9.24	-7.50	-6.99	2.25	1
PHT	-8.01	-7.96	-7.77	0.24	4

In Table 5, the ANOVA analysis shows that the stamp-forming parameter that has the most influence (i.e. parameter with the highest delta) is AP. Experiments featuring a higher consolidation pressure led to thinner samples and potentially decreased porosity due to greater resin flow filling the voids. The second parameter of importance is MT. The mould temperature controls the cooling rate. If the mould is hotter, the cooling rate is slower, which leads to increased crystallinity in the thermoplastic matrix. Crystals have a higher density than the amorphous phase of the thermoplastic matrix. This causes the final volume to be smaller than the initial volume and could offer one explanation why samples made with a hotter mould are thinner. Additionally, reduced cooling rates at higher mould temperatures delay solidification of the thermoplastic, allowing more time for the polymer to flow, thereby further reducing thickness. FCS is the third most influential stamp-forming parameter. It controls the amount of time require to transfer the pultrudates from the oven to the mould and reach the targeted force. Faster closing speeds reduce the cooling time of the hot pultrudate in ambient air. Finally, PHT is the least influential stamp-forming parameter. Longer dwell time at the compaction pressure allows more time for the crystals to form during the cooling phase, which may contribute slightly to thickness reduction.

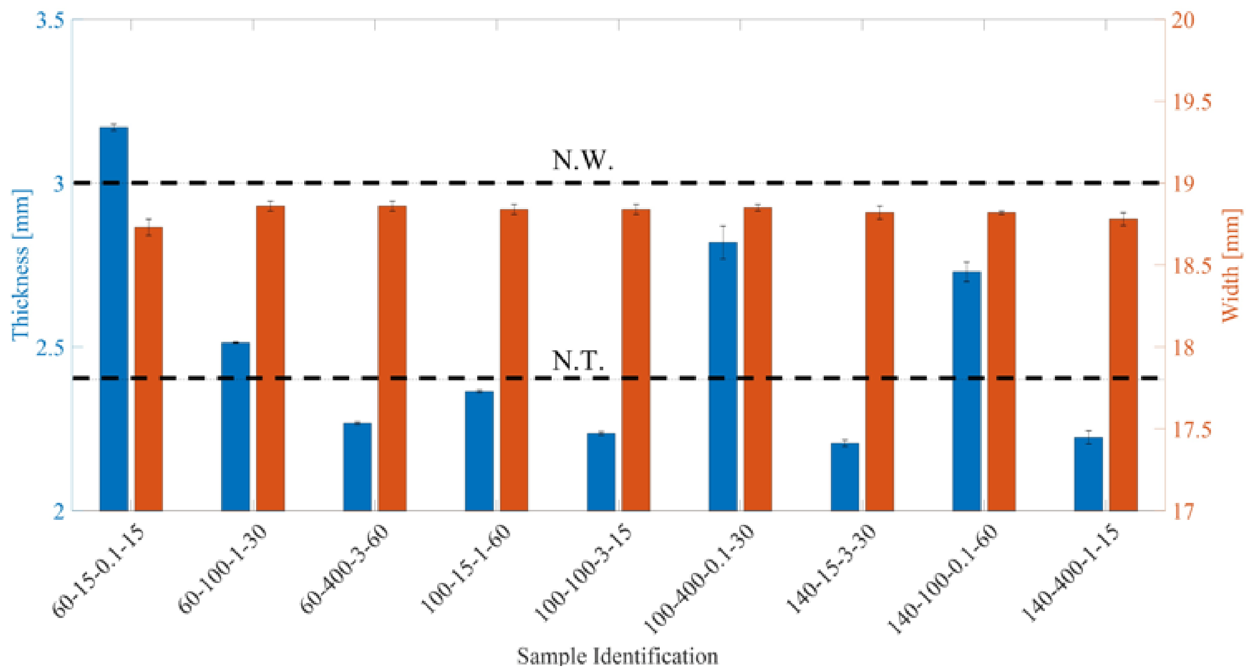

Figure 4. Histogram of the thickness and width for all tested samples. Nominal width (N.W.) and nominal thickness (N.T.) are indicated by dashed lines.

Figure 4 shows the summary for the thickness and width measured on all tested samples. The variation between the measured thicknesses is greater than the variation between the widths. This is expected because the width is defined by the geometry of the cavity, which has a nominal width (N.W.) of 19 mm. Samples never reached the nominal width due to shrinkage that occurred during cooling. For the thicknesses, stamp-forming parameters had a strong influence on this dimension. As discussed previously, this is explained by the stamping parameters that have significant effect over the quality of the consolidation. It can be noted that even though the mould was designed with the intent of reaching a nominal thickness (N.T.) of 2.4 mm at full consolidation, several samples could be compressed further. This is likely attributable to the smaller size of the pultrudates used for the experiments compared to the idealized dimensions used in the design of the mould cavity. Finally, more in-depth statistical analysis is needed to find the absolute contribution of each stamp-forming parameters and potential combination effect.

4.3. Future Work

For future work, a Taguchi L18 (3^5) design of experiment containing the pre-heating temperature (PT) as a parameter will be accomplished. More characterization experiments will be conducted to quantify the quality of the consolidation; the final angles will be measured, the roughness average (Ra) will be taken, the void content will be analyzed by pyrolysis according to the ASTM D2734 standard and short-beam strength tests will be accomplished according to the ASTM D2344 standard.

5. Conclusion

An L9 orthogonal array design of experiments was successfully conducted on the stamp-forming of pultruded GF/PA6 beams for studying the effect of various processing parameters. All different combinations of stamp-forming sequences that were planned were successfully accomplished by the hydraulic press. Results showed that the dimension of the mould cavity controlled the width of the final part. On the other hand, the thickness was strongly affected by the processing parameters and could be used assess the quality of the consolation. The applied pressure had the most influence on the consolidation. A more complete design of experiment with increased characterization will be accomplished in the future to find the parameters that maximize mechanical properties of the final stamp-formed part.

6. References

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