# ROBOTIC TOW PLACEMENT FOR LOCAL REINFORCEMENT OF GLASS MAT THERMOPLASTICS

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**SUMMARY:** Glass mat thermoplastics (GMTs) are an established material class that are used to produce complex components, principally for the automotive industry. To further increase GMT utilization, a process has been developed where multiple yarns of commingled glass and polypropylene are heated and placed to a desired geometry on a base layer of GMT. The placed UD is then encapsulated by over moulding a second layer of GMT. The effect of both force (20-80N) and the displacement rate (20-100mm/s) during tow placement on void content and flexural modulus was investigated for nine placement conditions. Placement rate was found to have a significant effect on quality. Void contents were measured again after the over moulding process and a general reduction in porosity was observed. Mechanical tests showed a factor of 2 increase in modulus and a factor of 3 increase in strength for the particular ratio of the two materials studied. Mechanical properties from over moulded samples were measured for tow placement rates of 20, 60 and 100mm/s, with no significant difference in mechanical properties as tow placement rate increased.

**KEYWORDS:** compression moulding, tow placement, consolidation, novel manufacturing

## INTRODUCTION

Composite materials have been used extensively for semi-structural applications in the automotive industry. However, due to the higher material costs of continuous fibre based materials, limited progress has been made in fulfilling the economic demands of structural applications. Table 1 compares the high volume capacity thermoplastic-based processes of injection and compression moulding (flow processes), the stamping of thermoplastic impregnated fabrics (a drape dominated process) and finally integrated compression moulding. Injection moulding offers stiffness through shape complexity but limited intrinsic mechanical properties and creep resistance while giving net shaped components with fast cycle times using high pressure biased equipment and tooling. Moving towards semi-structural materials, GMTs offer increased impact properties while maintaining high shape complexity and added value through functional integration in what is still a high pressure process. At the sacrifice of design freedom, the non-isothermal stamping (drape forming) of aligned fibre textile structures offers high intrinsic stiffness and creep resistance. The lower pressure biased equipment reduces capital costs. However, a net shaped component is only obtained by trimming of more expensive fabric materials and material costs remain an issue for the current economical climate.

An alternative to these conventional processes and the subject of this investigation is an integrated moulding process where the advantages of injection or compression moulding are

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combined with structural inserts [1-4]. These consist of uni-directional (UD) tow or tape comprising intimate blends of UD glass or carbon roving and thermoplastic fibres or powder. It remains a net shaped process and design freedom is maintained with the flow process, where the infrastructure of conventional GMT or injection moulding processing equipment and cycle times can be adopted. Structural properties can be achieved in regions of higher operating load by efficiently placed loops or wire frame inserts of UD materials, either via locally placed pultrusions or tailored geometries where a robotic system is used to place fibres in-situ. Use of the more costly UD materials is limited and these are efficiently used, minimising material cost.

Table 1 A comparison of thermoplastic composite processing techniques

| Process | Design freedom | Mechanical properties | Moulding pressure | Material cost |
|---|---|---|---|---|
| Injection moulding | highest | low | high | low |
| Compression moulding (flow) | high | medium (limited creep) | medium | medium |
| Stamping (no-flow) | low (drape) | high | low | high |
| Integrated compression moulding | medium to high | optimised | medium | variable |

The objective of this work was therefore to develop an integrated compression moulding process where UD tows of commingled glass and polypropylene are placed by robot onto a GMT substrate for subsequent over-compression moulding with GMT. After reviewing the interfacial issues associated with integrated processing, a tow placement facility is described and the effects of placement rate and applied pressure on placed tow properties characterised. The quality of the tow after over-moulding is then discussed and the effect of the UD inserts on mechanical properties measured.

## INTEGRATED COMPRESSION MOULDING

The integrated compression moulding process investigated here is shown schematically in Fig. 1, consisting of compression moulding a base sheet of random fibre based GMT material that is then transferred to a tow placement facility where multiple yarns of commingled glass and polypropylene are heated and placed to a desired geometry. This is then placed back into the compression moulding tool and encapsulated by over moulding a second layer of GMT.

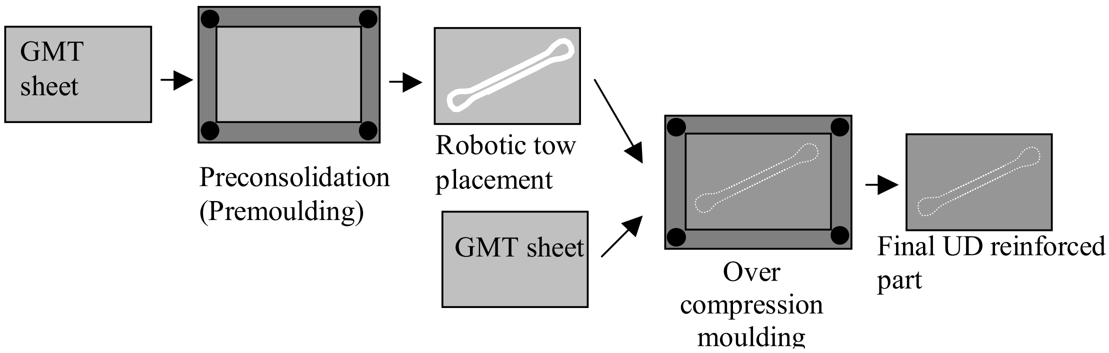



Fig. 1 Schematic for integrated compression moulding of GMT and UD tows

The lower layer is not heated above the melt temperature, but warmed to optimise interfacial conditions and thereby maintain the integrity of the UD material.

Three interfaces of interest during this process are between: the UD-fibres and the GMT substrate sheet obtained during tow placement, the GMT and GMT after over-moulding, and UD and GMT after over-moulding. Following local surface rearrangement and intimate contact between the two surfaces, fusion bonding occurs as a result of inter-diffusion of polymer chains across the interface with re-crystallisation through the new interface completing bond formation during cooling [5]. Interfacial healing depends on pressure, temperature and heat conduction between the two surfaces, where the most important parameter is the average temperature of the two surfaces at the moment of contact. The focus during these experiments was to achieve, for the 3 interfaces, an average interface temperature above the polypropylene melting point at the moment of contact.

## ROBOTIC TOW PLACEMENT

### Equipment and materials

A Stäubli®Unimation robot with 6 degrees of freedom was used to place the UD tow onto the GMT substrate. The placement system consists of a roller, a nozzle and an air-cooling system, illustrated schematically in Fig. 2. Here 5 commingled tows were brought simultaneously into a heating tube before a final, independently controlled, heating nozzle. This gave a tow temperature immediately before placement of nominally 220°C. An metallic roller was used to provide a consolidation force and direct the tow in the desired path. An air-cooling system, using 4bar pressure, was used to cool the tow after placement. This reduced deconsolidation effects and limited displacement of the previously placed material by tensile forces induced by tow placement occurring out of line immediately after placement of the previous section. The GMT substrate was placed on a heating plate, to give a substrate temperature of 85°C with a clamping system to prevent its motion and ensure good thermal contact.

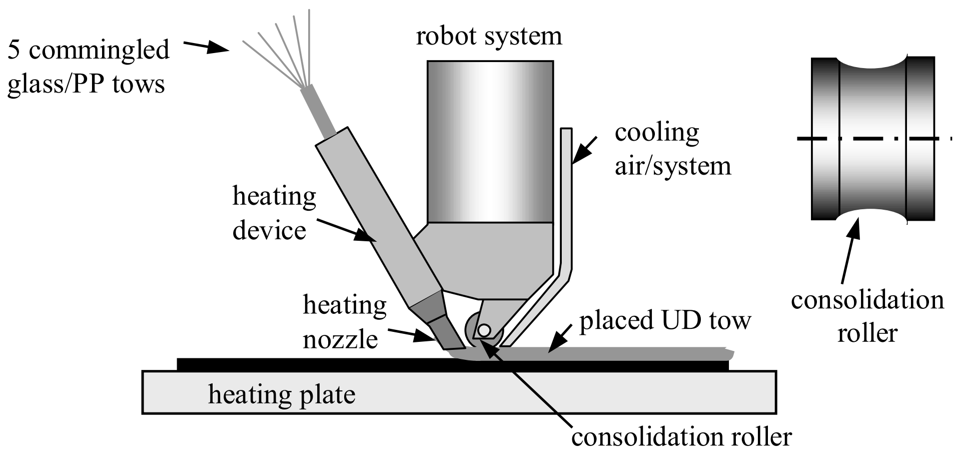



Fig. 2 Tow placement facility schematic

The GMT substrate and over-moulding material was 1.6mm thick Symalit® Slimtec™ (polypropylene with a 30% glass fibre weight fraction, chopped and randomly oriented) and the UD tow was Vetrotex® Twintex™ (polypropylene with a 60% glass mass fraction).

### Placement trials with commingled yarns

End outer radii of 15mm were chosen for this study, representing the minimum internal diameter for the direct mounting of a metallic fixture to attach a sub-component to a master assembly. Fig.3 shows the geometry of the placed tow. Larger radii are also possible. The objective at the end radii was to maintain the tow path accuracy. The placement velocity and pressure were varied until a noticeable change in deviation occurred. Thus, once the path deviated (the tow slipped from the programmed path), the maximum turning speed for the given radius and pressure was found, here being 15mms$^{-1}$ for 40N force and a 15mm radius. A larger diameter would result in a higher turning speed; hence this represents the worst case for tow placement rates. Four turns of material were applied in all cases to the substrate, giving 20 yarns of commingled material. A scaling of the facility would enable larger numbers of yarn to be simultaneously placed.

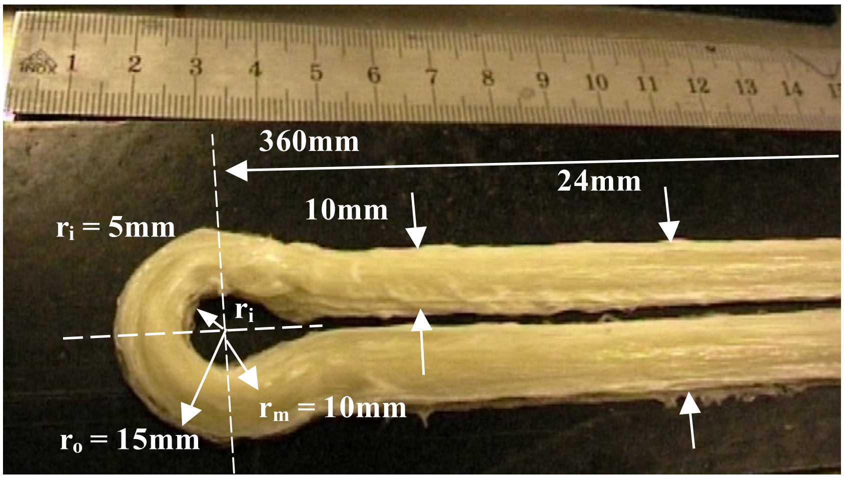



Fig. 3 Commingled glass/PP yarn placed on a GMT substrate

One of the main objectives was to determine how the over-compression phase affected the tow void content, where tow would be placed as fast as possible in the straight region of the preform. Previous work had shown a reduction in placed tow void content following an over-injection moulding cycle [6], hence three different initial void contents were investigated in the straight region of the preform and the porosity after over-moulding compared. In order to understand how tow placement conditions affected the placed tow void content, the placement rate was varied from 20mms$^{-1}$ to 100mms$^{-1}$ and the applied force from 20N to 80N. A full factorial experimental array was used (2 factors at 3 levels), as shown in Table 2.

The effective pressure on the tow by the roller was calculated by estimating the effective contact area and the normal force on the material, given the spring constant of the placement head system. The contact area increased with an increasing number of turns due to the profile of the consolidation roller. For the first turn, 20N, 50N and 80N corresponded to 12 bar, 29 bar, and 46 bar of pressure and for the 3rd and 4th turns to 8 bar, 20 bar and 32 bar of pressure. This represents typical pressures used for non-isothermal compression moulding of commingled fabrics, 15bar to 40bar [7], but with processing here being dynamic with a shorter residence time of the consolidation pressure.

Table 2 The effect of pressure and velocity on the properties of UD glass/PP tow

| Run | Velocity, (mm/s) | Force (N) | 2nd void content, (%) | Modulus, (GPa) |
|---|---|---|---|---|
| 1 | 20 | 20 | 0.8 | 10.7 |
| 2 | 20 | 50 | 0.8 | 11.9 |
| 3 | 20 | 80 | 0.8 | 11.8 |
| 4 | 60 | 20 | 2.8 | 6.5 |
| 5 | 60 | 50 | 4.4 | 8.3 |
| 6 | 60 | 80 | 3.5 | 9.7 |
| 7 | 100 | 20 | 8.0 | 5.4 |
| 8 | 100 | 50 | 4.6 | 5.8 |
| 9 | 100 | 80 | 5.8 | 7.6 |

**Investigation of placed tow quality**

Tow was placed according to Table 2 for nine different conditions. Two specimens of 50mm length were cut from placed tow for each condition, giving four tow specimens per sample. The substrate material was removed and porosities measurement by immersion in water. The void content was measured for each sample as shown in Fig. 4a, with a second test for each sample as shown in Fig 4b, where the centre region of the placed tow was investigated (2nd void content). This enabled a comparison of both void and glass content variation across the width of the placed material. These samples were then divided into 2 parts, Fig. 4c, for dynamic mechanical analysis in 3 point bending, where a rectangular section is required, and for burn-off to measure the glass fraction.

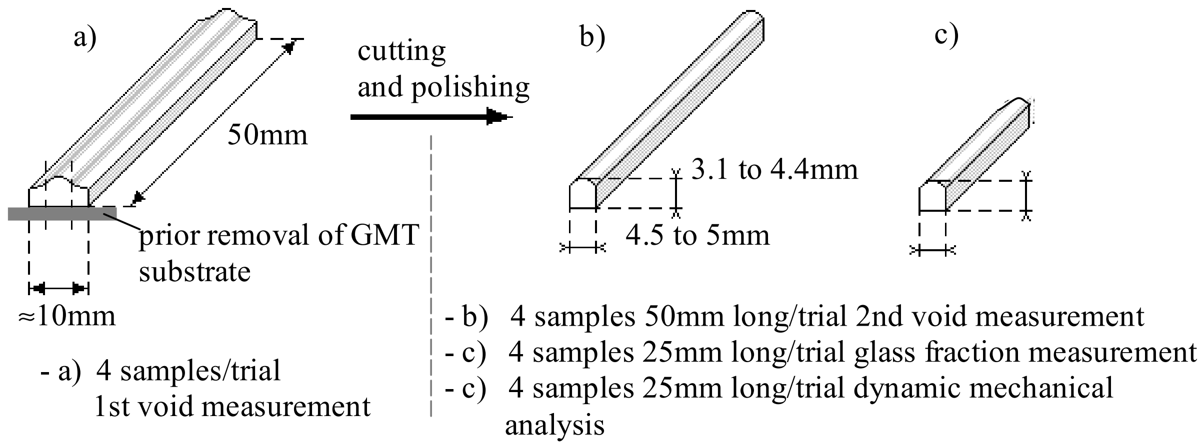



Fig. 4 Specimen cutting and testing layout

A polynomial expression (Equ. 1) was fitted to the data using multiple linear regression to give a statistically based relation of the effect of tow placement conditions, velocity (V), and pressure (P), on subsequent quality. This includes interactions between the two variables. The coefficients for void content and 1/modulus are given in Table 3. These equations are represented in Figs. 5 and 6 for the limits of the processing study. Note that in Fig. 5b 1/modulus is plotted, where a lower z-axis response represents a higher stiffness. Increased placement rates were found to significantly reduce stiffness and increase porosity. Applied force had a smaller effect on both porosity and stiffness at lower placement rates and a larger effect at higher placement rates.

$$Response = \beta_0 + \beta_1 V + \beta_2 P + \beta_3 V^2 + \beta_4 P^2 + \beta_5 VP + \beta_6 P^2 V + \beta_7 PV^2 + \beta_8 P^2 V^2 \quad (1)$$

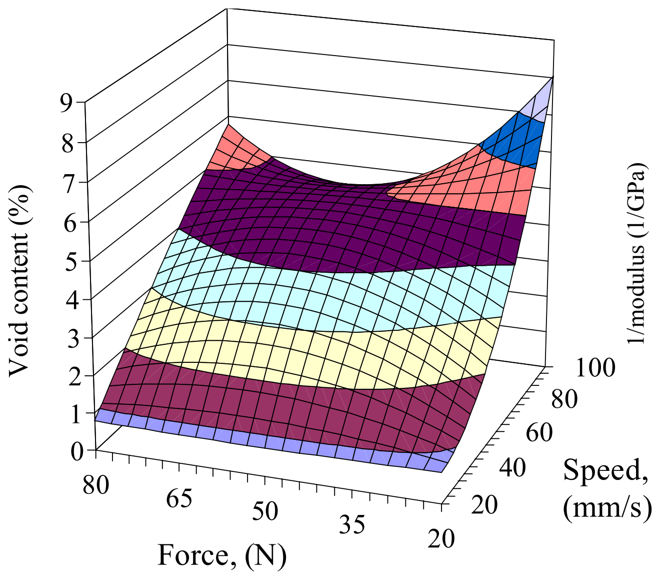
Table 3 Regression coefficients for A) 2nd void content and B) 1/modulus

| | $\beta_0$ | $\beta_1$ | $\beta_2$ | $\beta_3$ | $\beta_4$ | $\beta_5$ | $\beta_6$ | $\beta_7$ | $\beta_8$ |
|---|---|---|---|---|---|---|---|---|---|
| A | 6.26 | -0.35 | -0.32 | 0.0042 | 0.0029 | 0.0193 | -1.74E-04 | -1.91E-04 | 1.71E-06 |
| B | 0.035 | 0.004 | 0.0009 | -2.67E-05 | -4.76E-06 | -1.04E-04 | 7.20E-07 | 1.04E-06 | -8.63E-09 |

Increasing placement speed from 20mm/s to 100mm/s reduced the tow placement time from 100s per part to 40s per part, with a corresponding increase of the void volume fraction by a factor of 2.75. Maximum and minimum placed stiffness were 11.75GPa and 5.35GPa.

One issue with the flexural method is that it assumes a rectangular section, which as Fig. 6 shows is not the case for lower placement rates. If the upper surface is assumed to represent the radius of the roller, it is possible to calculate the loss of section $\Delta S$ of the samples, compared to a rectangular one, and hence to estimate the higher properties of the actual sample. Taking sample 3 as an example, $\Delta S$ = 2.595 - 1.746 = 0.849mm$^2$, and $S_{rect}$ = 15.400mm$^2$ $S_{sample}$ = 14.551mm$^2$. This results in an underestimate of 6% for this sample, and hence Fig 5b would be raised at lower rates corresponding to samples 1 to 3.

To examine the structure of the placed tow on the GMT substrate, macrographs were taken of the nine samples, with the runs 3 and 9 compared in Fig.6. A clear change can be seen in the shape of the material and of the consolidation quality. Increased placement rates affected the integrity of the tow shape, with runs 7 to 9 showing a marked change from runs 1 to 3. To further investigate the trends observed in Figs 5 and 6, micrographs were taken of the 9 runs to investigate general consolidation quality, void size and location and glass content distributions. Fig. 7 compares the microstructure of runs 3 and 9, showing a section of the placed tow in a linear region on the GMT substrate.



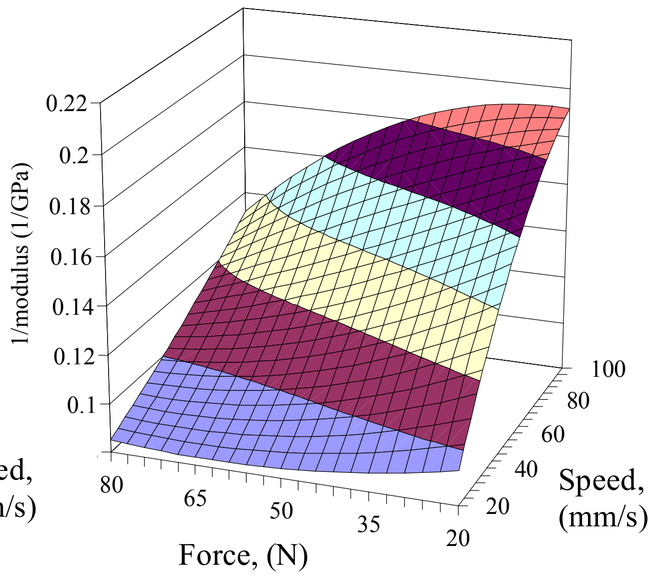




Fig. 5 Evolution of void content and 1/modulus with pressure and placement rate

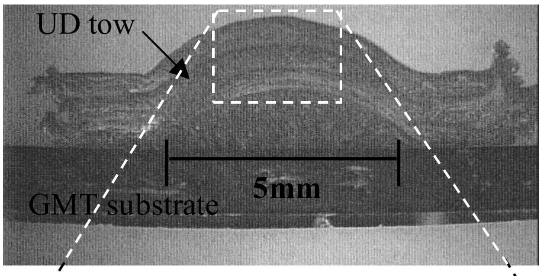



Fig. 6a Placement condition 3 (20mm/s, 80N force)

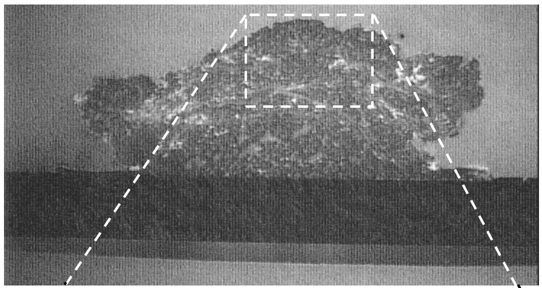


Fig. 6b Placement condition 9 (100mm/s, 80N force)

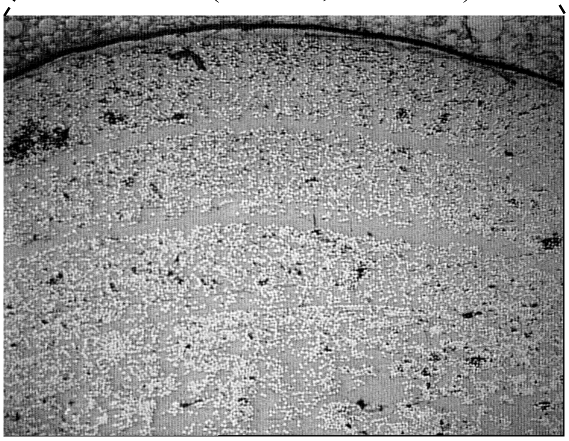


Fig. 7a Placement condition 3 (20mm/s, 80N force)

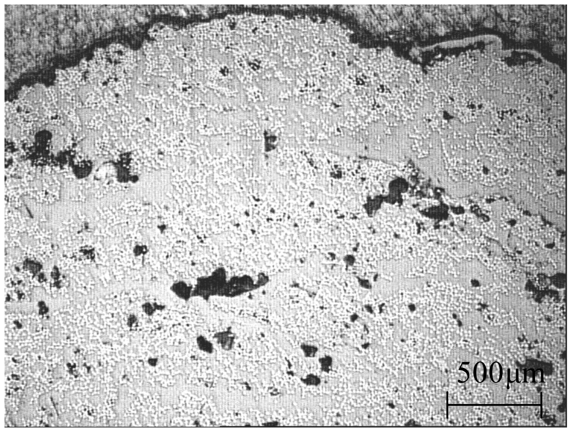



Fig. 7b Placement condition 9 (100mm/s, 80N force)

Void analysis confirmed the flexural test data, where a clear increase in the number and size of voids was observed, with a greater tendency for an increased speed than for a decreased pressure. Voids were randomly located rather than decreasing with the number of tow layers placed, with the implication that consolidation was approximately equal for all layers. For low placement speeds (run 1 to 3), voids were small and infrequent and generally inside areas of locally high glass concentrations. A thin glass fibre free polypropylene region separated each tow layer. As the speed increased, the voids increased in size and number and the borders between successive layers became indistinct.

The first set of void content specimens (Fig. 4a) showed a trend of increasing porosity with increasing placement rate. Some in-plane flow of polypropylene was observed for higher placement pressures, prompting the second set of measurements (Fig. 4b) to characterise the bulk tow properties under the radius of the roller. The porosity values obtained from these trimmed samples were lower than those calculated for the first immersion test. Microscopy confirmed that a significant fraction of the voids were located at the edges of the placed sections, considered due to lower pressures at the edge of the roller. The burn-off tests (Fig. 4c) gave fibre mass fractions in the centre region up to 3.8% higher than the 60% of the original tow, confirming observations that an increased polypropylene fraction occurred in the borders.

## OVER-MOULDING OF UNI-DIRECTIONAL TOW PREFORMS

In order to study the effect of the over-moulding process on the void content in the UD-tows, three placement velocities corresponding to three different initial void contents were selected, as shown in Table 4. A force of 80N was applied in the straight regions, reducing to 40N and a constant velocity of 15mm/s in the radii. Five samples were produced for each run, with 5 additional samples produced from standard GMT as a benchmark.

Table 4 Tow placement conditions and porosity before over-compression

| | Force, (N) | Velocity, (mm/s) | Void content, (%) |
|---|---|---|---|
| Run 3 | 80 | 20 | 0.8 |
| Run 6 | 80 | 60 | 3.5 |
| Run 9 | 80 | 100 | 5.8 |

The over compression moulding cycle, shown schematically in Fig.1, used a Schwabenthan hydraulic press, a Reinhardt forced convection hot air oven and a smaller laboratory hot air oven. During the over-moulding process, the interface quality and thus the properties of the whole part depended on the temperature at the moment of contact between the two GMT-sheets. Two different ovens were necessary to heat the upper layer (with the UD-tows) and the lower GMT-sheet to different temperatures (non-isothermal conditions). Processing consisted of preheating the upper GMT-sheet with UD-tow to ~160°C ($T_1$ in Fig. 8). This temperature was just below the polypropylene $T_m$ in order to prevent detachment of the UD tow from the GMT. In parallel, the lower GMT-sheet was heated to ~225°C ($T_2$ in Fig. 8). In order to quantify the temperature evolution during transfer from the oven to the press and to determine the average interface temperature at the moment of contact, thermocouple measurements on the two GMT-sheets were performed. The average temperature of the two plates at the moment of contact (corresponding to the point in Fig. 8 where the temperature of the colder plate starts to raise again due to thermal exchange with the hotter plate) was then used to estimate the interface quality and to optimise temperature settings and operation steps during over-moulding. This gave an average interfacial

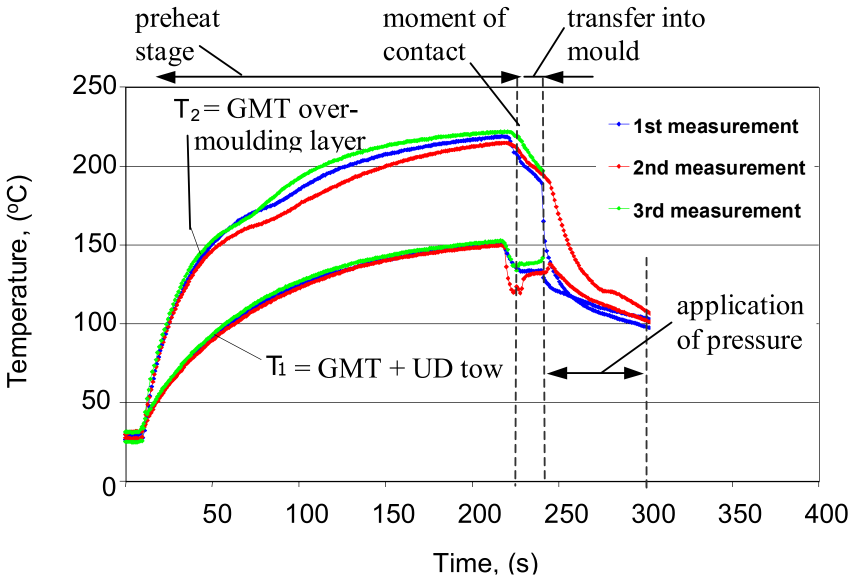



Fig. 8 Preheat cycles prior to integrated compression moulding

temperature at the moment of contact of the two plates of 170°C. The two sheets were then placed together in the mould (at 80°C) before 200 bar pressure was applied for 60s, after which the component was removed.

## EFFECT OF TOW PLACEMENT CONDITIONS ON FINAL QUALITY

Void contents were measured again after the over-moulding process and a reduction in porosity was observed. Fig. 9a) and b) show void contents and distributions after over-moulding for placement speeds of 20mm/s and 100mm/s, both with a placement force of 80N. Observations of failure mechanisms and micrographs showed that the interface between GMT-GMT together with GMT-UD obtained by the over-moulding operation were of high quality. Failure was not observed to occur along those interfaces. Large voids, of diameter>100 µm, were found in the GMT between and beside the two UD-tows. These voids are considered due to shrinkage from


a) Run 9, 100mm/s velocity

b) Run 3, 20mm/s velocity

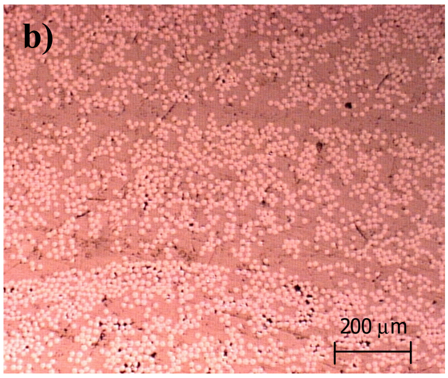



Fig. 9 Tow consolidation levels after over-moulding cycle

insufficient pressure compensation during solidification and crystallisation. The prior crystallisation of thinner regions of the part limits further increases in pressure in the thicker region, i.e. between the tows [7]. A qualitative comparison between the void size and content in the UD-region before and after over-moulding showed that additional consolidation takes place during over-moulding leading to smaller voids and, as observed, lower void contents. Measurement of the void content after over-moulding is in progress to confirm this observation.

Table 4 Effect of tow placement rate on final mechanical properties

| Sample | $\sigma_{max}$ [MPa] | $E_T$ [GPa] | $\varepsilon_T$ [%] |
|---|---|---|---|
| GMT | 50.4 ± 1.5 | 4.7 ± 0.4 | 1.2 ± 0.2 |
| 20 mm/s | 151.5 ± 8.7 | 10.8 ± 1.6 | 1.6 ± 0.2 |
| 60 mm/s | 156.2 ± 5.5 | 10.6 ± 1.4 | 1.6 ± 0.2 |
| 100 mm/s | 150.8 ± 10.8 | 10.3 ± 2.0 | 1.6 ± 0.2 |

Mechanical tests showed a factor of 2 increase in modulus and a factor of 3 increase in strength for the particular ratio of the two materials studied. Mechanical properties from 5 samples at each condition were measured for 20, 60 and 100mm/s, with no significant difference in mechanical properties as tow placement rate increased, as shown in Table 4. The modulus decreased slightly with increasing placement velocity but the variation was small (~6%) and within the confidence limits of the mechanical tests. Hence before over-moulding, an increased placement rate or a decreased placement pressure resulted in a lower stiffness and an increased void content. After over-moulding, increased placement rates did not significantly affect the stiffness or strength of specimens. Therefore higher placement rates can be used to reduce cycle times without a mechanical property penalty. Further work is underway to characterise long term behaviour.

## CONCLUSIONS

The mechanical properties of GMTs have been tailored locally via UD tow inserts, offering the design freedom of flow moulding materials with local structural properties. For the step of manufacturing the UD tow inserts, tow placement trials showed that increasing placement speeds from 20mm/s to 100mm/s reduced the tow placement time from 100s per part to 40s per part, with a corresponding increase of the void volume fraction from 0.8% to 5.8%. Maximum and minimum placed stiffness were 11.75GPa and 5.35GPa. Over-moulding trials of the UD tow inserts have shown that the ultimate tensile strength of the over-moulded samples increased by a factor 3 and the elastic modulus by a factor 2 for GMT with placed UD-tows compared with standard GMT. However, no correlation between the tow placement velocity and the strength or stiffness of the over-moulded samples was observed. This requires further investigation but these initial results indicate that tow placement velocities of up to 100mm/s have a negligible influence on the mechanical properties of the over-moulded samples. Hence the potential exists for the economic local placement of UD fibres at higher velocities without important losses of strength and rigidity, thereby maximising the effect of an integrated materials approach.

## ACKNOWLEDGEMENTS

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## REFERENCES

1. Patent PCT/IB96/00467, “Process for the manufacture of polymer and/or composite products and related equipments”, *Ecole Polytechnique Fédérale de Lausanne*, 1995.
2. Bourban, P.E., Bögli, A., Bonjour, F., Månson, J-A.E., “Integrated processing of thermoplastic composites”, *Composites science and technology*, Vol. 58, 1998, pp. 633-637.
3. Wakeman, M.D., Bourban, P.-E., Bonjour, F., Månson, J-A.E., “A novel manufacturing cell for a new generation of composite processing and applications”*, Proc. of ICCM-12*, Paris, July 5th - 9th, 1999.
4. Wakeman, M. D., Bourban, P.-E., Bonjour, F., Månson, J.-A.E, “Integrated Processing of Polymers and Composites via a Novel Manufacturing Cell”, SAMPE-ACCE-DOE Advanced Composites conference, Detroit, 1999.
5. Smith, G.D., Plummer, C.J.G., Bourban, P.-E., Månson, J.-A.E, “Non-isothermal fusion bonding of polypropylene, accepted in Polymer, 2001.
6. Bourban, P.-E., Bonjour, F., Bernet, N, Wakeman, M.D., Månson, J-A.E., “Integration of Polymer and Composite Materials for Enhanced Design Freedom and Cost-Efficiency”, Proc. of ICCM-12, Paris, July 5th - 9th, 1999.
7. Wakeman, M.D., Rudd, C.D., "Compression Moulding of Thermoplastic Composites”, in Comprehensive Composite Materials, Ed. A. Kelly and C. Zweben, Vol 2, pp 915-963, 2000.