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RAPID COMMUNICATION

A novel route for volume manufacturing of hollow braided composite beam structures

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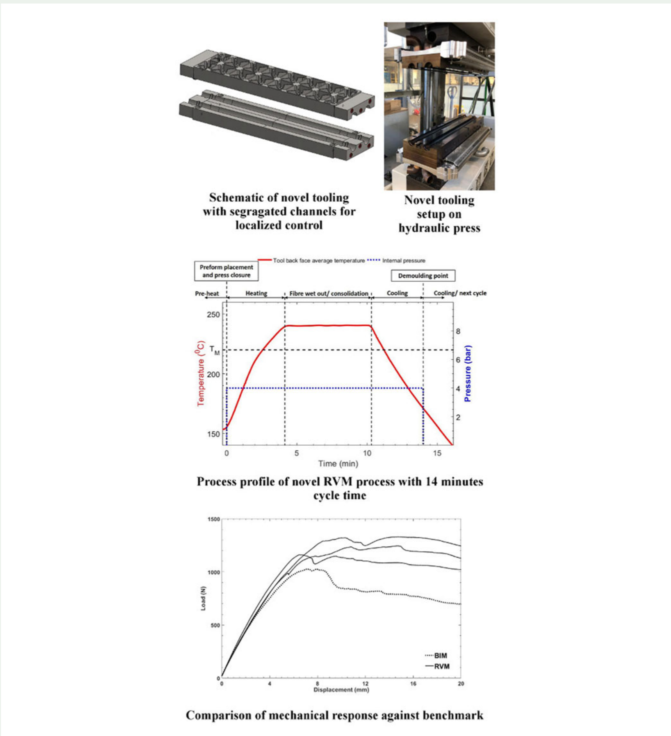
ABSTRACT

This work investigates the application of a rapid variothermal moulding process for direct processing of a braided thermoplastic commingled yarn. The process uses locally controllable, responsive tooling which provides opportunities for optimum part quality and significantly reduced cycle times compared with conventional processes. The proposed process was used to directly manufacture hollow beam structures from dry commingled braided preforms. It was demonstrated that the cycle time using the rapid process was reduced by more than 90% as compared to a conventional bladder moulding process, resulting in a total cycle time of 14 min. Additionally, initial three point flexure test results indicated an improvement in the mechanical performance of the resultant parts as compared to the benchmark.

KEYWORDS
Braiding; bladder inflation moulding; commingled yarn; thermoplastic; variothermal tooling; mechanical testing; high volume

GRAPHICAL ABSTRACT



Introduction

Braiding is an effective method for manufacturing hollow tubular fibre-reinforced composite structures. The method interlaces continuous fibre bundles at a predefined angle resulting in the production of hollow tubular dry fibre preforms, which can then be impregnated with resin. Being an automated low-waste process, braiding finds numerous applications in large scale structural components in the automotive [1–3] and aerospace [4–7] industries as well as in small scale biomedical [8,9] and sports [10] applications. However, a majority of the current applications utilize thermoset matrices, which renders the curing of composites as the cycle-time limiting aspect. Consequently,

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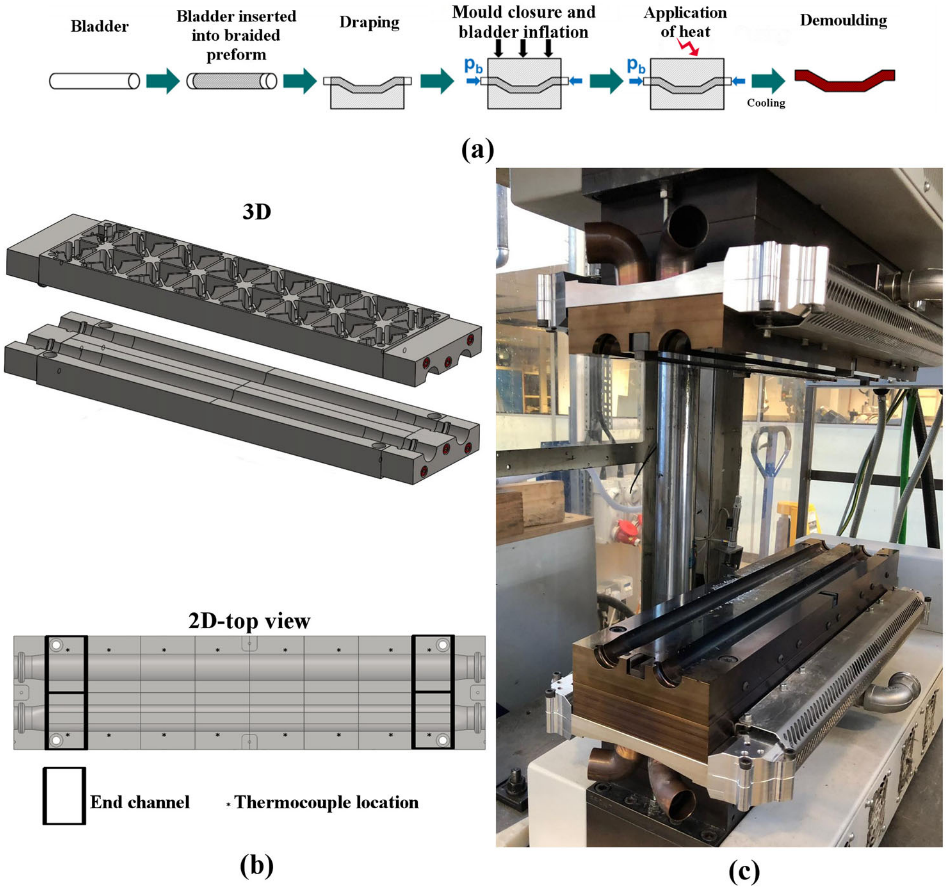


Figure 1. (a) Step-wise illustration of BIM process (Adapted from [31]); (b) Schematic of the RVM tool faces showing segregated channels & (c) Customized tool face with the PtFS setup mounted onto the press.

in spite of the rapid preform production ability of the braiding process, current applications remain limited to the high-value low-volume range. This bottleneck could potentially be overcome by using hybrid fibre-thermoplastic matrix material systems. They are a blend of thermoplastic filaments with reinforcement fibres, which could be directly processed, thus reducing the time and equipment (plant/tooling requirement) for resin injection. Moreover, their short impregnation paths [11] accelerate fibre wet out and consolidation. Hybrid systems are available in several forms such as commingled, core-spun, co-knit, co-wrapped etc. [12]. Among the available hybrid yarns, commingled thermoplastic yarns are more suitable for braiding because of their easy handleability [13,14] and relatively superior drapeability. Previous literature shows several instances of incorporation of commingled thermoplastic yarns in a braiding process [15–19].

Conventionally, bladder inflation moulding (BIM) has been found feasible for producing hollow composite components [20]. Being a simple and effective technique for consolidation of thermoplastic composites, BIM was also proposed for fabrication of hollow lightweight parts in sports [21,22] industries. The high volume potential of using BIM for processing braided commingled fabric was presented in the past [23,24]. However, there was a lack of manufacturing readiness because of the impractical routes used for pursuing high heating/cooling rates. This paper addresses the need for a high volume production route and presents a rapid variothermal process concept for the first time. The process allows rapid heat up and cool down, thus providing the potential of achieving shorter processing cycles. A conventional BIM process was used as a benchmark for comparison. Findings of this work can help industry in developing more confidence in braided thermoplastic composite manufacturing technologies specifically from the high volume-manufacturing viewpoint.

Material

The braided preforms used in this work were produced by braiding three layers of a commingled fabric using a 64-carrier O.M.A. maypole braider [25]. The braiding parameters were set to result in a braid angle of 25° in the final parts. A commingled glass/polyamide 6 yarn from Coats [26] with fibre volume fraction of 55% was used. PA6 was chosen because of its favourable characteristics for high volume applications in the automotive industry [27]. The melting point and recrystallization temperatures

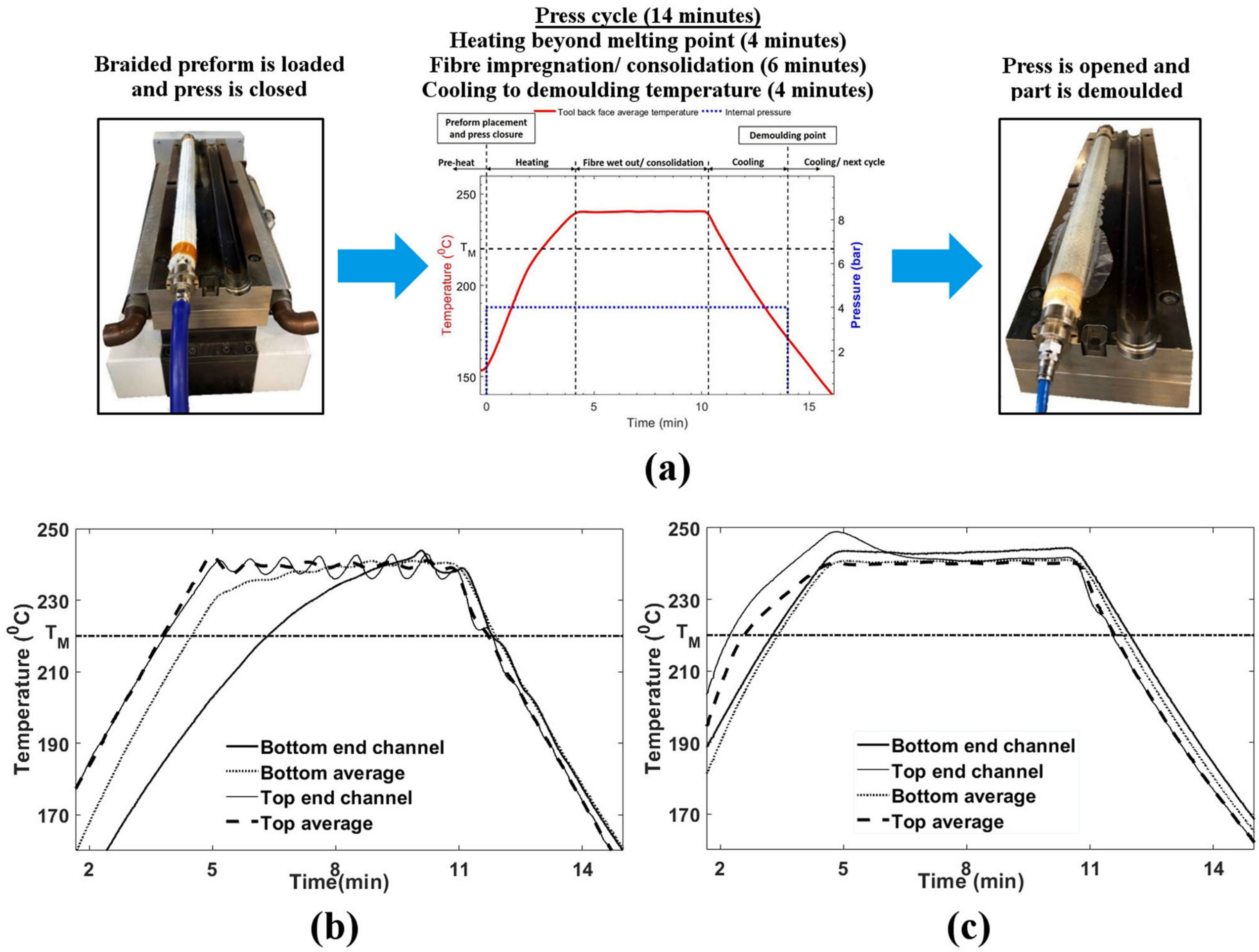


Figure 2. (a) Steps involved in RVM process with pressure and temperature profile during press cycle; Average and end-channel temperature profiles of the top and bottom tool halves (b) before and (c) after employing PtFS control features. Note: the material temperature was approximately 10°C above the plotted tool back face temperature.

of the PA6 used are approximately 221°C and 185°C respectively.

Rapid variothermal moulding

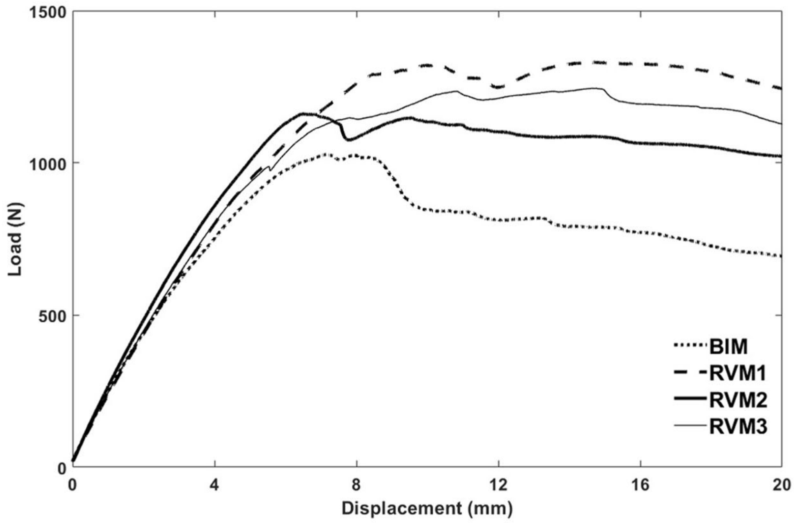
The proposed novel rapid variothermal moulding (RVM) setup is an integration of three key components:

i. Elements of the conventional BIM process: The steps involved in a conventional BIM process are explained schematically in Figure 1(a).
ii. Patented PtFS (Production to Functional Specification) [28] concept by Surface Generation Limited: The PtFS technology enables rapid heating and cooling of customized moulding tools. The reverse faces of the tools are machined into an array of thin-walled channels. Each channel has a dedicated heater below the tool face and a supply of compressed air. Controlling the heat and compressed air supply to each channel separately potentially allows for rapid heat up and cool down as well as precise local control over the temperature in each zone of the part being moulded. A software facilitates real-time monitoring and control of the process cycles across each channel. An existing compression moulding PtFS setup [29,30] at WMG with a total of 32 channels (16 on each tool half) was used with custom-made tool faces. A three dimensional schematic of the tool with the segregated channels is shown in Figure 1(b). As shown in the figure, the tool has two adjacent mould cavities out of which only one was used in this work. Figure 1(b) also shows the top view of the tool with marked thermocouple locations. The end channels of the tool are also highlighted in the figure. Monitoring the temperature of these end channels is critical as they would incur relatively greater heat loss to ambient atmosphere as compared to the other channels.
iii. Hydraulic press: The application of a press enables rapid opening and closure of the tools, thus reducing the time between cycles. A 100 ton Dassett hydraulic press was used in this work. The customized tool faces were mounted with the PtFS setup on the press as shown in Figure 1(c).

Figure 2(a) shows a step-wise description of the RVM process. The tool was preheated to 150°C,

	Test span (mm)	Thickness (mm)	Outer Diameter (mm)	Mass (g)
RVM1	400	1.99 ± 0.19	34.85 ± 0.21	183.8
RVM2	400	1.71 ± 0.35	34.81 ± 0.17	173.1
RVM3	400	1.97 ± 0.04	34.81 ± 0.07	178.6
BIM	400	1.92 ± 0.06	35.02 ± 0.18	170.5

(a)



(b)

Figure 3. (a) Three-point flexure testing setup with specifications of test specimens; (b) Load-displacement response of the BIM and RVM beams.

following which a braided preform with a bladder was placed into the tool cavity and the press was closed. The temperature was increased to 250°C at a rate of 40°C/min and then held at 250°C for 6 min. After cooling down to 180°C, the part was demoulded. The temperature was further reduced to 150°C and the tooling was prepared for the next cycle. An internal bladder pressure of 0.4 MPa (4 bar) was applied. At the time of the press trials, this was the maximum available pressure due to limitations of the manufacturing environment. A set of preliminary trials were performed to improve the thermal response of the tool. The available electrical heating power was adjusted for each channel on the basis of the monitored temperature. Moreover, during the cooling phase, the channel with the slowest response was designated as the rate-governing channel for the entire tool, which resulted in a slow but uniform cooling rate of approximately 20°C/min. The implementation of these features resulted in a significant improvement in temperature-time profile, particularly in the consolidation phase, as depicted in Figures 2(b,c). The entire part cycle lasted for approximately 14 min.

A conventional BIM process in use at Composite Braiding Limited for industrial production of components served as benchmark. A two-part steel tool was designed and used for moulding of the braided fabric, which was heated using an industrial oven. After placing the closed mould into the oven, the temperature was increased to 240°C and the bladder was internally pressurized to 2 MPa (20 bar). The pressure and temperature were maintained for 10 min, following which the tool was cooled and the part was subsequently demoulded at a temperature of approximately 140°C. The entire process cycle including demoulding and tool separation took 4 h, which is limiting for high volume production.

Mechanical testing

For comparing the beams manufactured using the BIM and RVM processes, a quasi-static three-point flexure test was used. The test was performed at a rate of 10 mm/min using an Instron 5800 R test machine equipped with a 100 kN load cell. The test setup is shown in Figure 3(a) with the details of the test specimens. Three RVM beam specimens were tested, however, only one industrially produced BIM beam specimen was available. The load-displacement curves are depicted in Figure 3(b). The average stiffness and peak load of three RVM beam specimens were higher by 12% and 17% as compared to the BIM specimen. It is believed that internal thermal stresses (generated because of uncontrolled cooling across the part) and matrix degradation [32,33] (a consequence of the part being above the melting point of PA6 for long duration) play a role behind the relatively poorer performance of the BIM specimen.

Conclusions

A novel RVM process was developed providing a route for volume production of thermoplastic braided structures. A conventional bladder moulding technique was used as a benchmark. As compared to a cycle time of 4 h in BIM, RVM parts took 14 min to manufacture. The ability to monitor and control the discrete channels of the tool individually resulted in a uniform temperature profile throughout the part. First mechanical test results indicated superior performance for RVM beams as compared to the single BIM specimen. The study suggests promising prospects for braided composites directly manufactured *via* the RVM process that provides greater control over manufacturing parameters along with 90% cycle time reduction. Further work aimed at establishing correlations between the manufacturing parameters and part quality is ongoing and will be subsequently reported.

Disclosure statement

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