COST-EFFECTIVE MANUFACTURING OF HOLLOW COMPOSITE STRUCTURES BY BLADDER INFLATION MOULDING

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ABSTRACT: The bladder inflation moulding process, combined with the use of commingled yarns of thermoplastic and reinforcing fibres, offers the potential for the cost-effective manufacture of complex-shaped hollow composite parts. Manufacturing cost savings partly result from very short fibre impregnation times, which can be predicted by a consolidation model recently developed. The accuracy of the model predictions was demonstrated by comparison with experimental porosity measurements on tubes made from braided commingled yarns of polyamide-12 fibres and carbon fibres. The economic competitiveness of the bladder inflation moulding process was shown using a cost estimation model applied to bicycle handlebars made from PA12/CF commingled yarns.

KEYWORDS: bladder inflation moulding, manufacturing cost, consolidation model, commingled yarns.

INTRODUCTION

A current industrial challenge in the field of composites is the production of complex hollow parts with an economically competitive process. Some of the limitations of processing techniques such as filament winding, rotomoulding and pultrusion can be overcome by using the bladder inflation (BIM) process [1-3]. Traditionally, this technique involves the manual winding of thermoset prepreg tows around an inflatable polymer mandrel, also known as a bladder. The composite/bladder assembly is then positioned in a mould and placed in a hot press. The bladder is pressurised, compressing the material against the walls of the mould

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cavity. Once the processing cycle is completed, the part is removed from the mould and the bladder tube is extracted, leaving a thin-walled hollow composite structure. Nowadays, a large number of composite tennis rackets are produced in this way [4-5].

Even though cost-effective manufacturing can be achieved with this procedure, it is believed that additional manufacturing cost savings can be made by replacing the thermoset matrix with a thermoplastic alternative, without altering the mechanical performance of the finished product. Compared to cure cycles for conventional thermosets, processing cycles for thermoplastic composites can be much faster (of the order of minutes) if fast impregnation of the fibres by the resin can be ensured. The flow distance for impregnation can be greatly shortened by using commingled yarns (CY), in which thermoplastic filaments are homogeneously blended together with the reinforcing fibres. The advantage of CY over other composite precursors, such as preimpregnated tows or powder-impregnated fibre bundles, lies in their high mechanical flexibility. CY can thus be readily converted into a highly drapeable textile fabric, reducing the likelihood of wrinkles during the forming of complex shapes. The use of a tubular braid of commingled yarns combined with the BIM process seems therefore to be a promising solution for cost-effective manufacturing of complex hollow composite parts, as illustrated in Figure 1.

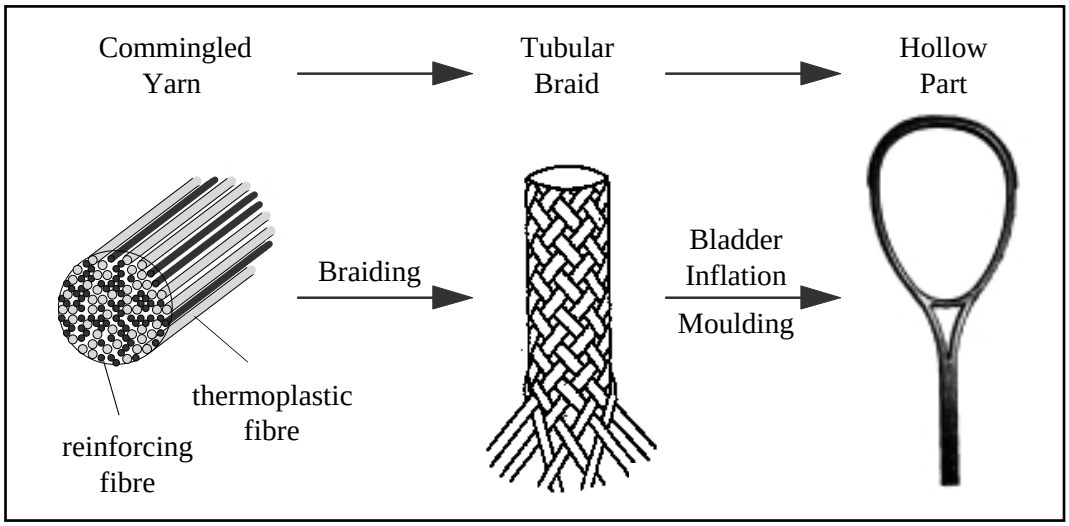

Fig. 1: Manufacture of a hollow composite part by bladder inflation moulding using a tubular commingled yarn braid.

To obtain the optimal mechanical performance of the hollow structure after manufacturing, it is necessary to control the processing conditions. The pressure, temperature and time applied during consolidation should be chosen so as to attain the maximum allowable residual porosity to ensure acceptable mechanical properties, at the lowest possible cost. In order to predict void content and estimate manufacturing cost, a consolidation model and a cost model have been developed and are presented below.

PROCESS MODELLING

During consolidation of the tubular commingled yarn braid, it is assumed that all the constitutive yarns are geometrically identical and experience fibre impregnation simultaneously. It follows that the consolidation behaviour of the whole braid can be modelled by the consolidation of a single representative commingled yarn. At the onset of consolidation, the structure of this representative yarn is depicted as cylindrical dry reinforcing fibre agglomerations, with a given distribution of diameter, surrounded by a molten resin pool. The fibre volume fraction of the dry fibre agglomerations varies with the applied pressure, which is assumed to be transmitted hydrostatically by the resin to each agglomeration boundary. Neglecting flow in the fibre direction and considering the resin impregnation rate to obey Darcy's law, the time increment Δt necessary for the resin to advance a distance $\Delta r_i = R_i - r_i$, where R_i and r_i are the positions of the resin flow front in a given fibre agglomeration before and after Δt, can be calculated from:

$$\Delta t = \frac{\eta\left(1-\upsilon_f\right)}{K\left(P_a + P_c - P_v\right)}\left[\frac{r_i^2}{2}\ln\left(\frac{r_i}{r_o}\right) - \frac{R_i^2}{2}\ln\left(\frac{R_i}{r_o}\right) - \frac{r_i^2}{4} + \frac{R_i^2}{4}\right] \tag{1}$$

where η is the Newtonian resin viscosity, υ_f the fibre volume fraction of the dry fibre agglomeration, r_o the initial agglomeration radius, K the permeability, P_a the applied pressure, P_c the capillary pressure (counted as positive when enhancing flow) and P_v the internal void pressure which depends on the flow front position [6]. By summing all the incremental time quantities, the total consolidation time of a fibre agglomeration can be calculated. Assuming that the commingled yarn is comprised of a distribution of n different agglomeration sizes, a size group k comprising N_a^k agglomerations with an initial radius of r_o^k, the void content of the yarn at a certain time step can be evaluated as:

$$V_v = \frac{\sum_{k=1}^{n} \pi N_a^k \left(r_i^k\right)^2 (1-\upsilon_f)}{A_t + \sum_{k=1}^{n} \pi N_a^k \left(r_i^k\right)^2 (1-\upsilon_f)} \tag{2}$$

where V_v is the volume fraction of voids within the yarn and A_t the cross-sectional area of the totally consolidated yarn. Combining Equation (2) with Equation (1) allows the evaluation of the porosity of the commingled yarn, and hence the porosity of the complete braid, throughout the processing cycle.

Figure 2 compares the predicted and measured void contents for braided commingled yarn tubes consolidated by bladder inflation moulding. The commingled yarns are composed of stretch-broken carbon fibres (CF) and staple polyamide-12 (PA12) fibres with a low melt

viscosity [7]. Figure 2 shows that the model predictions correlate very well to the experimental values (determined via immersion according to ASTM D792), thus demonstrating the validity of the proposed consolidation model. Figure 2 also indicates that a good part quality (V_v < 0.5%) can be obtained with a consolidation time as low as 1 minute, at a relatively low processing temperature and pressure.

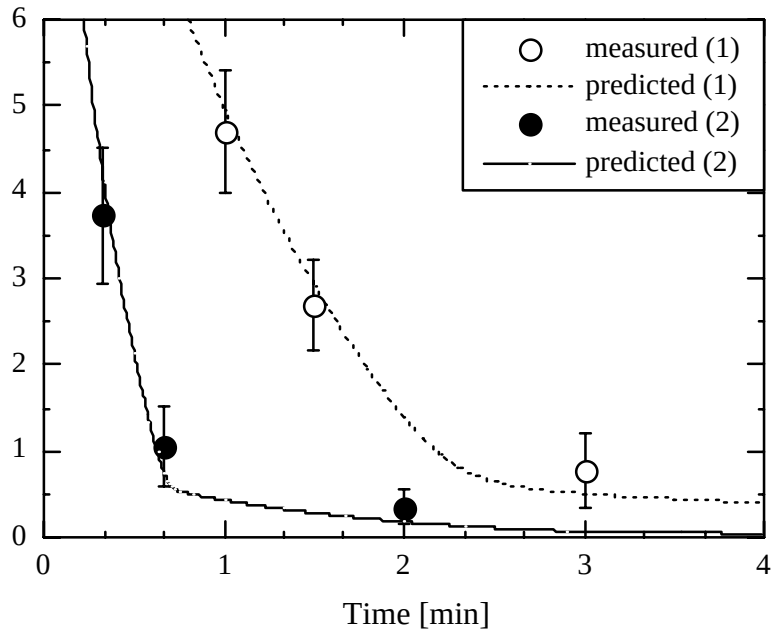

Fig. 2: Variation of void content with consolidation time for PA12/CF commingled yarn braids processed by bladder inflation moulding at (1) 200°C, 5 bar and (2) 240°C, 10 bar.

COST MODELLING

Estimation of manufacturing cost

The total manufacturing cost of a part can be estimated from the sum of the material cost, the labour cost and the overhead cost over the whole sequence of manufacturing steps or operations. The manufacturing cost, C_{MANUF}, associated with a specific operation can thus be expressed as:

$$C_{MANUF} = C_{MAT} + C_{LAB} + C_{OVH} \tag{3}$$

where C_{MAT} is the material cost, C_{LAB} the labour cost, and C_{OVH} the overhead cost.

The material cost, C_{MAT}, can be evaluated as:

$$C_{MAT} = Q\ P\ (1 + F_{scrap}) \tag{4}$$

where Q is the quantity of material, P the material purchase price per unit quantity and F_{scrap} the scrap factor.

Considering manufacturing as a sequence of setup and run activities, the labour cost can be formulated as:

$$C_{LAB} = C_{setup} + C_{run} \tag{5}$$

where C_{setup} and C_{run} are the costs of the setup and run activities, which can be estimated as:

$$C_{setup} = \frac{S_w}{Z} t_{setup} \tag{6}$$

$$C_{run} = F_{pres} S_w t_{run} (1 + F_{rew}) + C_{EQ} \tag{7}$$

where t_{setup} is the setup time (in hours), t_{run} the run time, S_w the worker's hourly wage, Z the number of parts made between two successive setups, F_{pres} the worker's presence factor, F_{rew} the rework factor reflecting unsatisfactory part quality and C_{EQ} the equipment cost. The cost of running the equipment, during the period of time given by t_{run}, can be assessed as:

$$C_{EQ} = \left(D_y + M_y + I_R E_o + U_E \frac{H_{EQ}}{t_{run}} \right) \frac{t_{run}}{H_{EQ}} (1 + F_{rew}) \tag{8}$$

where D_y is the yearly equipment depreciation cost, M_y the yearly equipment maintenance cost, I_R the interest rate on immobilised capital, E_o the initial equipment purchase price, U_E the unit cost of equipment utilities (electricity, water, compressed air, ...), and H_{EQ} the annual number of hours the equipment is operated. Adopting the sum-of-years-digits method for depreciation [8], and assuming the sum of the depreciation cost and the maintenance cost to be constant over the equipment useful life or recovery period, it follows that:

$$D_y + M_y = d_1 (E_o - F_{sal} E_o) + F_{mtn} E_o \tag{9a}$$

$$d_1 = \frac{2}{N + 1} \tag{9b}$$

where d_1 and F_{mtn} are the equipment depreciation rate and maintenance factor for the first year of service, N is the equipment useful life and F_{sal} is the equipment salvage factor after N years.

Overheads include manufacturing charges that are difficult or impossible to attribute to specific components produced, such as supervision, light, rent and insurance. For simplicity reasons, overhead costs are traditionally allocated based on direct labour costs, thus:

$$C_{OVH} = F_{ovh} C_{DL} \tag{10}$$

where F_{ovh} is the overhead factor and C_{DL} the direct labour cost. The latter may be defined as the cost of all "hands-on" effort required to manufacture a part [8].

Accordingly, the direct labour cost is given as:

$$C_{DL} = \frac{S_w}{Z} t_{setup} + F_{pres} S_w t_{run} \left(1 + F_{rew}\right) \quad (1)$$

Case studies

BICYCLE HANDLEBARS

Compared to their metallic counterparts, composite bicycle handlebars are attractive due to their corrosion resistance, their light weight (as illustrated in Figure 3) and their shock absorption capability. However, the relatively high retail price of composite handlebars, as shown in Figure 3, concentrates their use specifically to high-performance mountain bikes [9].

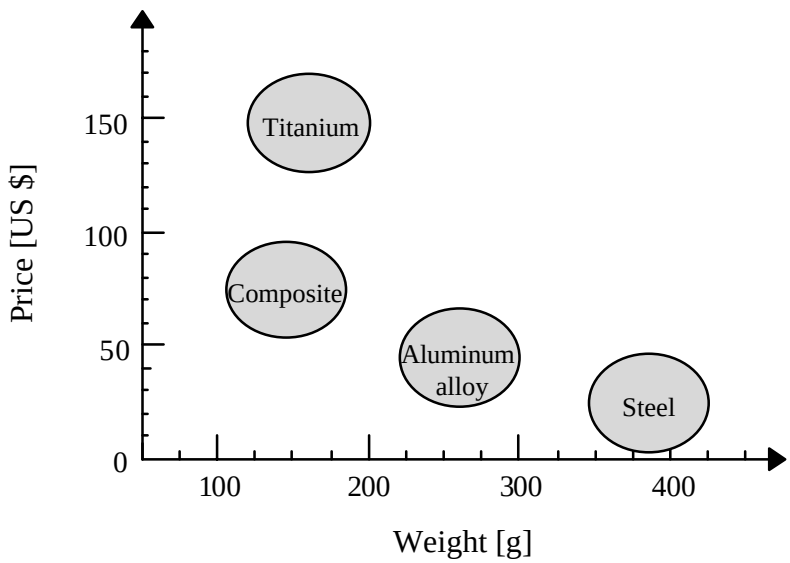

Fig. 3: Typical retail price and weight of bicycle handlebars presently on the market. (January 1999)

Nevertheless, the use of PA12/CF commingled yarns, combined with the BIM process, could provide a profitable alternative to the conventional thermoset composite handlebars manufactured by filament winding or resin transfer moulding. A cost analysis was therefore carried out for a standard 580 mm long handlebar, using four overlaid PA12/CF commingled yarn braids of 20 mm diameter, resulting in a total weight of 123 g. The assumed manufacturing operation sequence is detailed in Figure 4, and the data used for the cost calculations is given in Table 1. A material scrap factor of 3.45% was used, since it was considered that a 600 mm long handlebar must be produced to obtain a 580 mm long part of

acceptable quality. The use of two moulds was considered in order to create a continuous process, resulting in the process steps shown in Figure 4. In addition, one worker was considered to be necessary. The total manufacturing cycle time per part was assumed to be 5 minutes, as seemed reasonable from the experimental consolidation experiments, the results of which are presented in Figure 2. It was also assumed that 10 parts could be manufactured using the same bladder. Finally, the cost of the equipment utilities (electricity and compressed air) was considered to be negligible.

Table 1: Model input data for the manufacturing cost estimation of a composite bicycle handlebar made by bladder inflation moulding.

Quantity of material	Q (A)	123.0	[g]
	Q (B)	0.58	[m]
Material purchase price	P (A)	76.5	[CHF/kg]
	P (B)	15.0	[CHF/m]
Scrap factor	F_{scrap}	3.45	[%]
Equipment purchase price	E_o (1)	100'000	[CHF]
	E_o (2)	2'000	[CHF]
	E_o (3)	3'000	[CHF]
	E_o (4)	3'000	[CHF]
Equipment useful life	N (1)	15	[ ]
	N (2)	15	[ ]
	N (3)	5	[ ]
	N (4)	5	[ ]
Equipment salvage factor	F_{sal} (1)	20	[%]
	F_{sal} (2)	0	[%]
	F_{sal} (3)	0	[%]
	F_{sal} (4)	0	[%]
Equipment maintenance factor	F_{mtn}	1	[%]
Equipment utilities	U_E (I)	0	[CHF]
	U_E (II)	0	[CHF]
Worker's wage	S_w	20	[CHF/hr]
Worker's presence factor	F_{pres} (I)	0	[%]
	F_{pres} (II)	100	[%]
Setup time	t_{setup} (I)	0	[min]
	t_{setup} (II)	0	[min]
Run time	t_{run} (I)	5	[min]
	t_{run} (II)	5	[min]

Rework factor	F_{rew}	5	[%]
Interest rate	I_R	8	[%]
Overhead factor	F_{ovh}	75	[%]

A: braided PA12/CF commingled yarn fabric
B: Silicon rubber bladder
I: see Figure 4
II: see Figure 4

1: hot press
2: cooling system
3: mould_1
4: mould_2

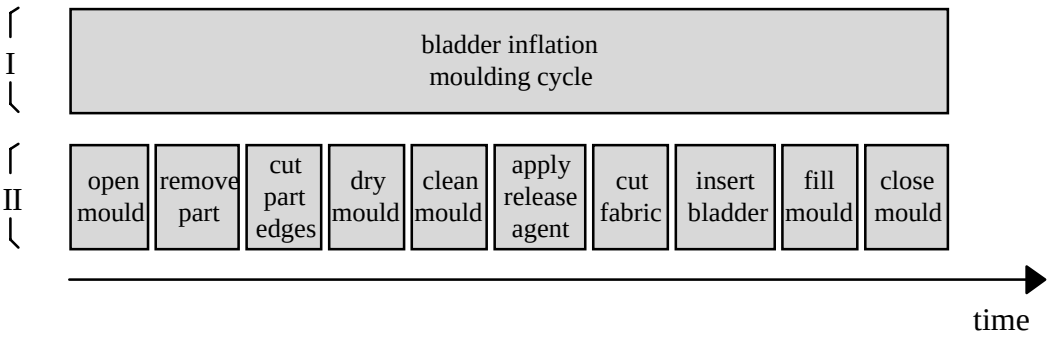

Fig. 4: Operation sequence for the manufacturing of bicycle handlebars by bladder inflation moulding, considering two parallel moulds.

Figure 5 shows the manufacturing cost of a PA12/CF bicycle handlebar made by bladder inflation moulding, as a function of the number of parts produced annually. For an annual production of 5000 parts, the model predicts a manufacturing cost of 18.1 CHF/part or 12.5 US$/part, which is less than 25% of the retail price for a traditional composite handlebar (as reported in Figure 3). This confirms the potential economic benefit of using the CY/BIM combination for the production of bicycle handlebars.

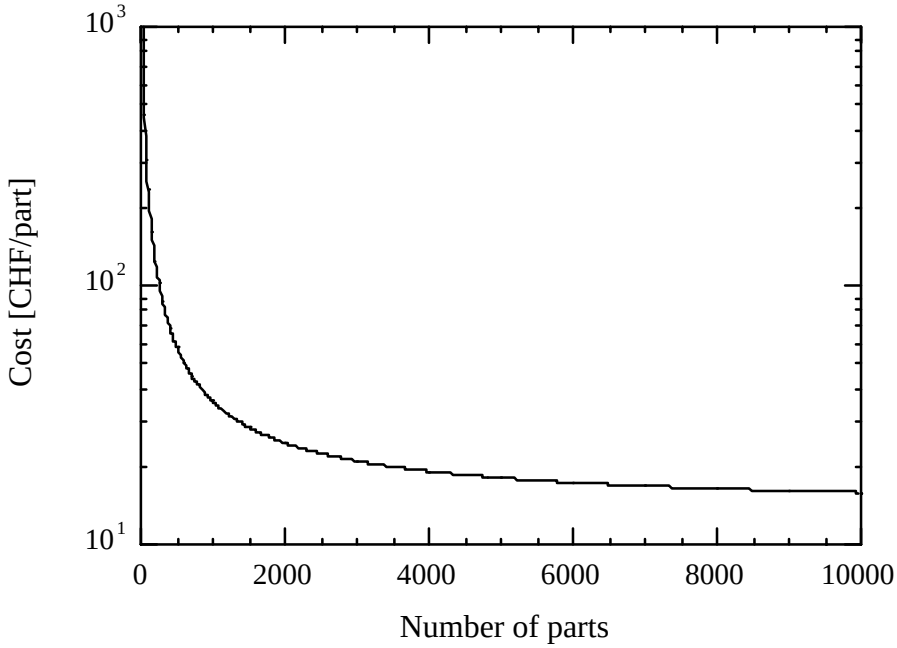

Fig. 5: Manufacturing cost of a composite bicycle handlebar made by bladder inflation moulding, as a function of the number of parts produced annually.

CONCLUSION

In this study, a consolidation model and a cost estimation model were presented. These models were applied to hollow composite parts made from PA12/CF commingled yarns processed by bladder inflation moulding. The validity of the consolidation model for the prediction of the composite residual void content as a function of the processing parameters was demonstrated. It was also found that a porosity of less than 0.5% can be reached with a consolidation time of as low as 1 minute. The cost estimation model allows the assessment of the manufacturing costs and the capacity required in a production cell. As demonstrated for bicycle handlebars, the CY/BIM combination offers high potential for cost-effective manufacturing of complex hollow composite structures.

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