MANUFACTURING COST COMPARISON OF RTM, HP-RTM AND CRTM FOR AN AUTOMOTIVE ROOF

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Keywords: CRTM, HP-RTM, Cost analysis, Automotive.

Abstract
The manufacturing cost of conventional Resin Transfer Molding (RTM), High Pressure RTM (HP-RTM) and Compression RTM (CRTM) have been analyzed for an automotive roof case. Results from process simulation have been used to define the cycle time, equipment specifications and layout of each technology. The filling time for RTM is 616 s, 228 s for HP-RTM and 30 s for CRTM. The main consequence of the shorter injection times of CRTM is that higher molding temperature can be used, reducing the total cycle time per part. Consequently, for 90,000 parts/year the RTM cell should be equipped with 15 presses and molds, whereas HP-RTM needs 6 and in CRTM cell a single press/mold is enough. The number of presses/molds is more dominant roof cost than other concepts. The total roof cost, taking the CRTM as reference, is 9.2 times and 14.8 times higher for HP-RTM and RTM, respectively.

1. Introduction

Fiber reinforced polymer composites have gained substantial interest over the last years, mainly due to their high specific stiffness and strength, high impact energy absorption per unit of weight, noise suppression capabilities and excellent resistance to fatigue [1]. The high operational costs involved in combination with the intricacy of the manufacturing techniques currently employed have restricted wider industrial use of composites [2]. For that reason, considerable effort has been made in the direction of finding and developing alternative cost-effective routes for manufacturing composite materials. Resin Transfer Molding (RTM) of thermoset polymers is a well-established processing method for niche applications [3]. However, there are still some problems in fabrication of parts having high fiber content (typically greater than 40% for structural applications). Increasing the fiber content decreases the permeability of the preform, leading to long filling time, incomplete impregnation and high void content.

In order to overcome the earlier mentioned problems several strategies have been presented to modify the conventional RTM process. An alternative approach to achieve fast injection into the mold cavity is to use High Pressure RTM (HP-RTM) equipment which allows injecting the resin under high pressure (up to 100 bar) [4]. The high throughput rate results into fast filling of the cavity and hence the resin injection time can be reduced significantly.

Another effective improvement in RTM to reduce simultaneously the mold filling time and void content is to combine the compression into the Resin Transfer Molding. This process is called Compression Resin Transfer Molding (CRTM) and can be a suitable technique to fabricate structural composites having most of advantages of RTM [5-11]. In CRTM, unlike in conventional RTM, the mold is only partially closed when resin injection begins. This increases the cross-sectional area available for the resin flow, and decreases flow resistance by providing high porosity in the reinforcement. In some cases, the mold is opened so that there is a small gap between the fiber surface and the mold wall which facilitates further the resin flow. Once the required amount of resin is injected into the gap and the gate is closed, the mold platen moves down to close the mold and squeeze the resin into the preform, which also undergoes compaction to achieve the desired volume fraction. Therefore, instead of going through the entire fiber stacking in the planar directions as in RTM, the CRTM process wets the fibrous reinforcement by penetrating in the thickness direction.

The driving force for the designers and manufacturers of automotive components is the reduction in cost and weight of parts. The main scope of the present paper is to give an understanding of the comparative cost structures of RTM, HP-RTM and CRTM manufacturing cells for production volumes of 90,000 automotive roofs per year. The last two techniques are considered to be candidates for the cost-effective manufacture of automotive structural parts [4,7].

2. Case study: Automotive roof

2.1. Roof definition

The selected component for the case study is an urban car roof with a circular window (Fig. 1). The main geometrical features of the roof are its projected area (1.72 m^2) and thickness (3 mm). The torsional and bending stiffness of the quasi-isotropic carbon fiber reinforced epoxy composite roof, with a 60% fiber volume fraction, is equivalent to that of a 0.7 mm thick steel one. A production volume of 90,000 parts/year during seven year production period with a three-shift pattern (1754 h/shift and year) with full utilization is assumed for the cost study.

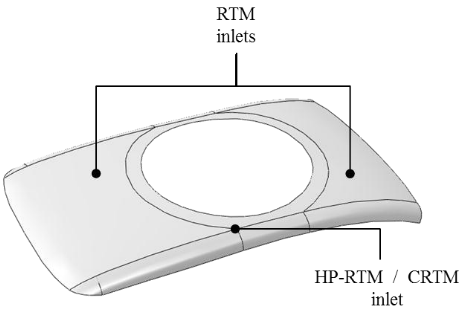

Figure 1. Schema of the automotive roof studied. Its main geometrical features are; 1.72 m^2 projected area and 3 mm thickness.

Different cost studies [2,12,13] have shown that the bill of materials is dominant in the total cost of composite components. But, as in the present study the resin and preform selected for RTM, HP-RTM and CRTM are the same, material cost is not considered. The rheological and kinetic parameters of the resin [14], as well as the permeability of the preform [15], are reported in Table 1. The gel time (t_{gel}), which governs when the resin viscosity limits further impregnation of the preform, as a function of the cure temperature (T_{curing}) follows an Arrhenius law [14]:

$$t_{\text{gel}} = A \cdot \exp\left(\frac{E_{\text{a}}}{RT_{\text{curing}}}\right) \tag{1}$$

where E_a is the activation energy, A is a kinetic constant and R is the universal gas constant. The polymerization reaction R_α is calculated by the widely used Kamal and Sourour [16] model.

$$R_\alpha = \left[A_1 \cdot \exp\left(\frac{-E_1}{RT}\right) + A_2 \cdot \exp\left(\frac{-E_2}{RT}\right) \cdot \alpha^{m_1}\right] \cdot (1-\alpha)^{m_2} \tag{2}$$

where A_1 and A_2 are constants; E_1 and E_2 are activation energies; m_1 and m_2 are catalytic constants and T_{abs} is the absolute resin temperature.

Permeability		**Rheological**		**Kinetic**	
K_{xx}	1×10^{-10} (m^2)	E_a	51377 (J/mol)	A_1	0.5963 (s^{-1})
K_{yy}	1×10^{-10} (m^2)	A	3.23×10^{-5} (s)	A_2	57526.44 (s^{-1})
K_{zz}	1×10^{-11} (m^2)			E_1	21514.78 (J/mol)
				E_2	49435.55 (J/mol)
				m_1	0.5874
				m_2	3.2

Table 1. Resin [14] and preform [15] properties for process simulation.

2.2. Cost analysis

Manufacturing cost is the sum of material, equipment, labor and overheads. Labor costs are considered to be equivalents for all studied processes, since they are highly automated. Furthermore, as CRTM is a new process, detailed information is not available to define overhead costs. Thus, process dependent costs for the roof are limited to equipment (injection unit, press and robot), area of the cell, tooling and energy. The cost analysis was carried out using the parametric technical cost model (TCM) proposed by Wakeman *et al.* [12]. TCM divides the process into relevant steps required to manufacture the roof. The process steps for the three RTM variants include: loading the preform into the mold, closing the mold, injecting resin, curing resin, opening the mold and extracting the roof.

3. Results and discussion

3.1. Processing parameters

Mold filling simulations have been carried out using PAM-RTM software. The number of injection gates affects the filling time and is a key issue when optimizing the RTM process [17]. However, as the aim of the present project is to compare the RTM variants, a single injection point is selected for the two most promising processes, HP-RTM and CRTM, and two inlet point for the most unfavorable conventional RTM. The positions of the injection points, however, have been optimized in order to reduce the filling time as much as possible. Fig. 1 shows these injection points location for RTM, HP-RTM and CRTM. For CRTM simulation the gap has a 1.2 mm thickness, which corresponds to the volume of resin at the final roof. The gap permeability is related to the gap thickness [8]. Due to high permeability of the gap, it is supposed that the resin flows exclusively into the gap [7-10], without impregnating the preform. Compression of the CRTM is supposed to be carried out at 0.6 mm/s, adding 2 s to the injection filling time. Injection pressure, filling time and maximum clamping force for each process are reported in Table 2.

Process	Injection pressure [bar]	Filling time [s]	Clamping force [t]
RTM	6	616	81
HP-RTM	60	228	490
CRTM	1	28+2	6

Table 2. Injection pressure, filling time and clamping force calculated by PAM-RTM simulations.

As useful as the clamping force is the pressure distribution at the end of the filling stage. As can be seen in Fig. 2, the distribution is asymmetric in the three RTM variants, justifying the selection of a press equipped with parallelism control device.

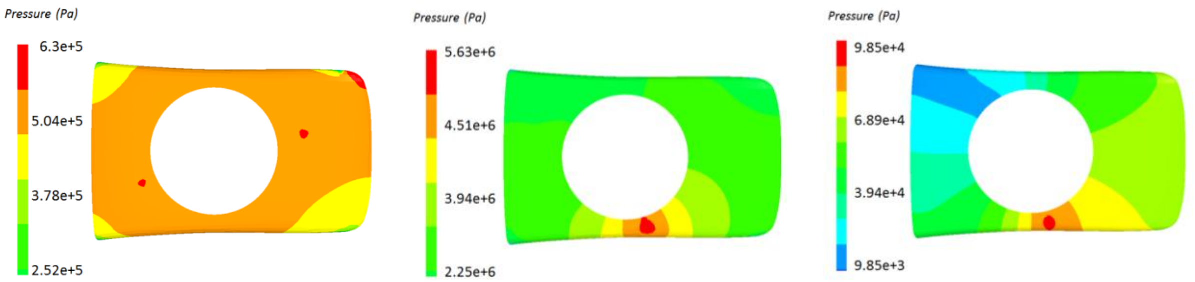

Figure 2. Pressure distributions for RTM (a), HP-RTM (b) and CRTM (c).

Once the filling time is estimated, curing temperature can be selected. Increasing temperature always leads to shorter curing times [18], but also reduces the gel time. Thus, curing temperature should be selected fulfilling that the gel time should be longer than filling time. Based on equation 1, and introducing the filling times from Table 2, the figure 3a shows the cure time for each RTM variants, and the corresponding demolding time for a 80% conversion degree (Fig. 3b). It is noteworthy that injection is assumed to be isothermal, so the injection time and curing times are running simultaneous.

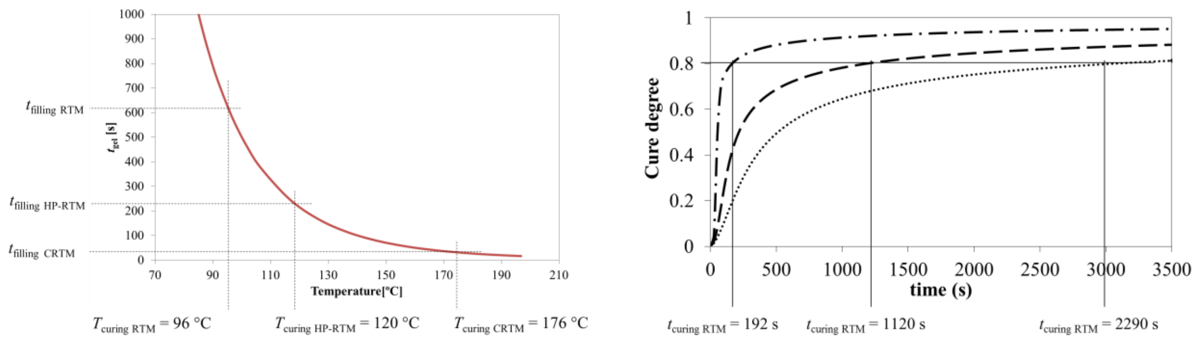

Figure 3. Curing temperature selection as a function of the gel time (a), and demolding time for a 80% conversion (b) for each RTM variant.

In order to calculate the total cycle time for each RTM variant, the preform loading and part extraction, as well as the mold closing and opening, should be added to the curing time. These additional operations are the same for all the studied processes, but their relative contributions are different. Table 3 summarized these cycle times.

Process	Load preform	Close mold	Inject/cure	Open mold	Extract part	TOTAL
RTM	6	2	2290	2	5	2305
HP-RTM	6	2	1120	2	5	1135
CRTM	6	2	192	2	5	207

Table 3. Time for each step of studied RTM variants. All times in seconds.

3.2. Cell cost

Based on the total cycle time, and for a 90,000 roof/year production, the RTM cell should be equipped with 15 presses/molds, HP-RTM with 6, and CRTM with one. The cycle times are so long that one robot for loading the preform and other one for extracting the roof are enough for the three RTM variants. Using all these information, the area of the plant occupied by each cell is 911 m^2, 385 m^2 and 57 m^2 for RTM, HP-RTM and CRTM, respectively.

The cost of the presses, the injection machine, the molds, the robots and the occupied plant area are reported in Table 4. The cost of the presses for each RTM variant is calculated using the clamping force as the only affecting parameter. Injection system for HP-RTM are expensive, whereas for RTM and CRTM conventional are enough. Molds for HP-RTM, as the internal pressure is higher, should be stronger than for RTM and CRTM, but the cost is assumed to be the same. The difference in robots costs, even if they are identical, is due to the fact that the control becomes more complex as the number of presses increases.

Process	Press [k€]	Injection system [k€]	Mold [k€]	Robot [k€]	TOTAL [k€]
RTM	460 (×15)	170 (×15)	80 (×15)	205	10855
HP-RTM	700 (×6)	300 (×6)	80 (×6)	150	6630
CRTM	383	170	80	110	743

Table 4. Cost of the equipment for RTM, HP-RTM and CRTM.

3.4. Energy cost

The energy consumption is assumed to be limited to those of the press and of the mold heating system for curing. Press energy consumption depends on the clamping force, and the cycle time. Hydraulic systems waste a 30% of the minimal power as the fluid circulates at a constant pressure, regardless of the amount of work carried out. Additionally, in order to compensate the internal pressure generated into the mold cavity, a maintenance pump should be used. These two characteristic values depend on the maximum clamping force of the press, and are reported in Table 5 for each RTM variants.

The mold dimensions are 600 mm × 2500 mm × 3000 mm. The energy consumed for keeping the curing temperature has been calculated assuming that the isolation with the press platen is perfect. It is also assumed that the thickness of the steel (50 W/km^2) mold wall is 500 mm, and it is covered with a 20 mm thick isolator (0.243 W/km^2). The air is considered to be at 25 ºC and have a convection heat transfer coefficient of 5.8 W/km^2. The energy consumed curing the composite for each RTM variant is reported in Table 5.

Process	Press				Mold/curing	
	Nominal power [kW]	Maintenance power [kW]	Energy [kWh]	Cost [€/part]	Energy [kWh]	Cost [€/part]
RTM	22	4	6.79	0.679	1.47	0.147
HP-RTM	66	8	8.78	0.878	0.74	0.074
CRTM	7	2	0.23	0.023	0.20	0.020

Table 5. Energy consumption and related cost. Energy cost € 0.1/kWh [13].

3.5. Roof cost

The final roof costs, with the main contributions factors, are summarized in Table 5. Taking the CRTM as reference, roof cost manufactured by HP-RTM is 9.2 times higher, and RTM one 14.8 times. The equipment and tooling costs, and specially the number of units, are the most relevant contributors, since they represent approximately the 90% of the total cost in the three studied RTM variants. Otherwise, the number of presses has a direct effect on the cell area, so the incidence could be stated as high as 94%. From the energy efficient point of view CRTM is also the best, and HP-RTM the less competitive.

Process	Equipment & Tooling [€/part]	Plant [€/part]	Energy [€/part]	TOTAL [€/part]
RTM	17.23	0.911	0.826	18.97
HP-RTM	10.52	0.385	0.952	11.86
CRTM	1.17	0.057	0.043	1.279

Table 6. Roof cost summary. The plant operating cost is assumed to be € 90/m^2/year [13].

4. Conclusions

The cost of an automobile roof has been estimated for three RTM variants, conventional RTM, HP-RTM and CRTM. The main conclusion is that the cost for CRTM is the lowest one, whereas that for HP-RTM is 9.2 times higher and for RTM 14.8 times higher. The reason for such differences is the shorter injection time required for CRTM that allows setting a higher molding temperature and fastens the curing of the composite, resulting in a shorter cycle time for manufacturing a roof. The main consequence is that, for manufacturing 90,000 roof/year, the CRTM cell should be equipped with a single press/mold, whereas 6 are necessary for HP-RTM technology, and 15 for conventional RTM. The plant area is also directly proportional to the number of presses, so costs are also higher for RTM and HP-RTM.

Simulation results also demonstrates that the lower clamping force is for CRTM (6 t), followed by RTM (84 t) and finally by HP-RTM (490 t). Thus, CRTM molds, presses and injection machines are considerably cheaper. Fast curing and low pressure presses for CRTM have an additional benefit; the energy consumption is 19 times lower than in RTM, and 22 times lower that of HP-RTM.

So, it can be postulated that CRTM is a promising manufacturing process for big area and simple geometrical automotive parts, as it is fast and energy efficient, and the initial investment is also lower than the alternatives studied.

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