Production and Analysis of Process Parameters for GFRP Composites

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Abstract:

Glass fiber reinforced composites are experiencing growing demand across various industries including aerospace, military, and transportation due to their superior mechanical properties compared to traditional materials. A custom Resin Transfer Moulding (RTM) setup with a central resin injection system was developed to produce high-quality E-glass chopped strand/polyester composites with different volume fractions and resin injection pressures.

Flow visualization techniques were employed to observe resin impregnation into the reinforcement and measure parameters such as filling time, flow front velocity, Reynolds number, permeability, and voids.

In this study, three types of composites were fabricated using E-glass chopped strand fiber preforms (with 4, 5, and 6 layers) reinforced with polyester resin at five different resin injection pressures (P1 = 0.2 MPa, P2 = 0.25 MPa, P3 = 0.3 MPa, P4 = 0.35 MPa, and P5 = 0.4 MPa).

Keywords: Microstructure analysis, RTM Method, Reynolds number, Permeability.

1 Introduction

GFRP composites offer superior mechanical strength compared to mainstream plastic materials and even outperform metals in terms of strength-to-weight ratio. They can be Moulded without requiring external heating, although their strength properties are slightly lower than carbon fiber. These composites have found diverse applications across commercial, military, and space sectors, including high-performance airplanes, boats, autos, wind turbine blades, and more.

Various manufacturing techniques are employed to produce composite parts, with Resin Transfer Moulding (RTM) emerging as a favored method due to its ability to produce high-quality products cost-effectively while offering good control over emissions and flexibility in production.

1.1 Applications of GFRP

Space:

Satellites, space centers, launch vehicles, spaceports, remote manipulator arm, payload bay doors, antenna struts and ribs, high-gain antenna, etc.

Aircraft:

Floorings and panels of airplanes, drive shafts, elevators, rudders, landing gear doors, bearings, etc.

Marine:

Offshore construction (seawater piping, stairways and walkways, firewater piping, grating, fire and blast walls, cables and ropes, storage vessels, etc.), valves and strainers, fans and blowers, propeller vanes, gear cases, condenser shells, etc.

Automotive:

Body panels and doors, engine blocks, drive shafts, automotive racing brakes, clutch plates, filament–wound fuel tanks, push rods, bumpers, frames, rocker arm covers, etc.

1.2 Proposed Approach

In this research, a modified Resin Transfer Moulding (RTM) setup featuring a central resin injection port was devised to investigate various resin injection pressures and layer counts, aimed at assessing pertinent process parameters. Commercial simulation software, RTM Worx, was employed to conduct simulations to estimate resin impregnation or filling times.

2. Methodology and Materials

During the RTM process, fiber pre-forms are introduced into a Mould. Subsequently, the Mould is sealed, and resin is injected into the Mould cavity at a specified pressure. Following injection, the resin is allowed to cure. The complex interactions between different reinforcement types can lead to various resin flow patterns during production. However, precise positioning of injection and vent valves ensures optimal resin flow patterns. A schematic representation of the resin transfer Moulding system is depicted in Figure 1

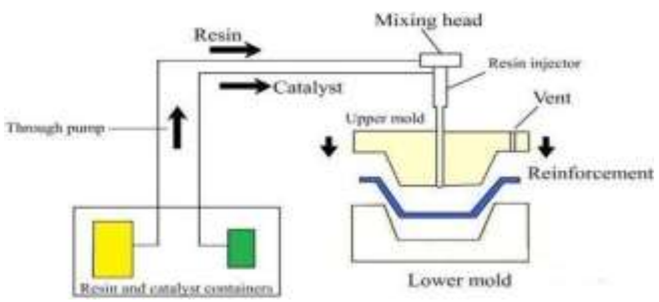


Figure 1 Schematic Diagram of Resin Transfer Mould

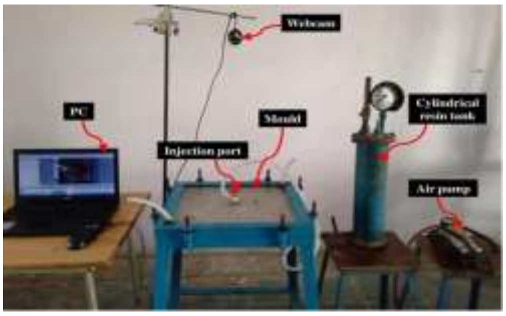
2.1 Significance of Process Variables

Resin Transfer Moulding (RTM) presents cost-saving advantages in labor and material costs compared to other manufacturing methods. The filling process during Moulding is critical for ensuring the sound quality of composite components. The filling time is influenced by resin injection pressure, where higher pressure can lead to Mould deformation, fiber washout, and void formation, while low pressure prolongs filling time and may affect fiber wettability and permeability, thereby impacting product performance Therefore, moderate injection pressure and filling time are essential. The location of the injection port is also important to prevent issues like fiber washout and maintain composite quality. Injection pressure should be sufficient to prevent gelation issues, as it affects resin speed and clamping forces in the Mould, ultimately impacting resin distribution to prevent voids and preserve mechanical properties.

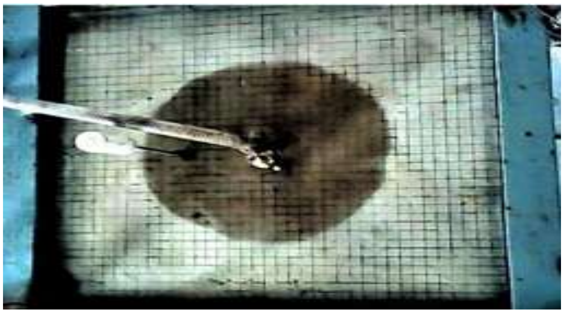
3 Experimental Procedures

3.1 Production of Custom Resin Transfer Moulds

The equipment was designed to facilitate uniform resin flow throughout the preform, ensuring complete wetting. Unlike conventional Moulds, the resin transfer Mould was specifically tailored for this purpose. To achieve this, an aluminum square Mould (H30 grade-6082) was fabricated to produce laminates with dimensions of 400 mm x 400 mm x 5 mm. The Mould comprised a square, translucent acrylic sheet and lid. Grid lines in squares were etched onto the acrylic sheet to aid in measurements.



(a)



(b)

Figure 2 Experimental setup (a) customized resin transfer mould and (b) resin flow pattern

3.2 Process Parameters

To evaluate the quality of composites produced using the customized RTM, various process parameters were studied, including mold filling time, flow front velocity, Reynolds number, and permeability.

3.2.1 Permeability

Permeability, defined as the resistance offered to resin flow in the fiber reinforcement, is a crucial parameter. It depends on the progression of resin flow and significantly influences the quality of composites. Permeability is closely related to the resin flow front velocity.

Various methods can be employed to determine permeability, such as concurrent permeability measurement, fiber-optic methods, image processing, cross-transport phenomenon , and fractal geometry models.

In this study, permeability was calculated using Equation (3.1).

$$\text{Permeability, K} = \frac{Q.\eta}{A.P} ln\left[\frac{r_f}{r_i}.r_i\right] ------3.1$$

where, Q = Volumetric flow rate

r_f = Size of radial flow front

r_i = Size of the initial injection radius

η = Viscosity of resin

A = Cross sectional area of the preform

P = Resin injection pressure

Radial flow front size,

$$r_f = \sqrt{\frac{Q}{\epsilon.\pi.H}.t + {r_i}^2} ---------3.2$$

where,

ϵ = Porosity

H= Cavity height of the mould

t = Mould filling time

The quantity of pores within the preform is termed as porosity. Porosity was assessed using Equation (3.3).

$$\text{Porosity}, \varepsilon = 1 - \frac{N.A_w}{\rho_f.T_m} ---------- 3.3$$

where,

N = Number of layers

A_w = Total weight of a layers

ρ_f = Density of the fiber

T_m = Thickness of composite laminate

3.2.2 Flow Front Velocity

Flow front velocity refers to the displacement of injected resin as it progresses during the impregnation process over time. This velocity is influenced by various factors including resin viscosity, the number of layers in the preform, permeability, and the arrangement of fibers in the mold.

3.2.3 Reynolds number

Reynolds number is a dimensionless quantity used to predict similar flow patterns in different fluid flow situations, and it is characterized by the ratio of inertial and viscous forces. Darcy's law is typically valid for determining the Reynolds number within the range of 1 < Re < 10. In regions of complex flow structures near particle contact points, the size and frequency of turbulent events increase with the Reynolds number. Therefore, the Reynolds number is essential for describing the mode of resin flow, and it depends exclusively on resin injection pressure and reinforcement, which in turn affect filling time and flow front velocity.

As the reinforcement increases, the filling time also increases while the flow front decreases. An increase in Reynolds number alters the flow pattern at certain injection pressures. At these pressures, voids and mechanical properties may vary before and after injection. Hence, to predict the type of resin flow, the Reynolds number was determined using Equation (3.4). Additionally, the type of flow was classified based on the Reynolds number into laminar for Re < 10, transitional for 10 < Re < 300, and turbulent for Re > 300.

Reynolds number is a dimensionless quantity used to predict similar flow patterns when different fluid flow situations occur. It is characterized by the ratio of inertial and viscous forces. Darcy's law is only valid to provide the Reynolds number in the region of $1<R_e<10$

$$\text{Reynold's number} = \frac{\rho_r . U . d_p}{\mu(1-\epsilon)} \qquad - - - - - - - - 3.4$$

Where,

ρ_r = Density of resin

U = Resin velocity

d_p = length of the flow

μ = dynamic viscosity

ϵ = porosity

3.2.4 Volume fraction of fiber

The fiber volume fraction is the percentage of fiber volume present in the entire volume of FRP composite. RTM is employed generally when high fiber volume fraction is aimed and good quality of surface finish is needed. When the mould is loaded with fiber, the fibers overlap due to un-even shape of the mould. This overlapping creates larger volume fraction in the mould. This region is filled with resin and remaining portion remains unfilled. This leads to production of components with un-desirable quality. The filling time and resin flow depend on volume fraction of fiber.

There are various methods to determine the fiber volume fraction. The volume fraction of glass fiber was determined by using Equation (3.5).

$$Volume\ Fraction\ Fiber, V_f = \frac{\rho_{af}.n}{\rho_f.h} \quad ------3.5$$

where,

ρ_{af} =Areal density of fiber mat

n = Number of fiber mats

ρ_f = Density of fiber

H = Lamina thickness

4.4.5 Void content

A void is the empty space filled with gas instead of solid material present in nearly all composite materials. Voids are unoccupied pores in the material. They are the typical result of imperfections in the manufacturing process. They reduce mechanical properties of the finished composite. They can act as crack nucleation sites, propagate cracks and cause even catastrophic failure.

The void formation reduces material durability. A few types of voids can exist in composites depending upon the properties of matrix and type of manufacturing process. In particular, a very viscous resin can produce voidsin the finished composite because it cannot freely penetrate into the space between the fibers. It may also happen when the fibers are packed tightly together. If the matrix does not freely penetrate into the space between the fibers, the air present at the space will never be pushed out and replaced with resin. The air stays inside the composite and causes serious void issues.

The expression for determining void content is given by

$$\text{Void Content}, V_f = M_d \left[\frac{W_r}{\rho_r} + \frac{W_f}{\rho_f} \right]$$

Where,

M_d = Measured density

w_r = Resin weight

w_f = Glass fiber weight

ρ_r = Density of resin

ρ_f = Density of fiber

3.3 Filling time, flow front velocity and Reynolds number

The filling times obtained from flow visualization study for the three types of composites processed at five preferred injection pressures are presented in Table 3.1.

Table 3.1 Mould filling times at five preferred injection pressures

Injection pressure	Filling time (s) for		
	Four layers	Five layers	Six layers

P_1	32	38	43
P_2	23	29	32
P_3	17	23	26
P_4	14	19	22
P_5	12	16	19

For the composites produced at same injection pressure, the filling time increased with increased number of layers (fiber volume fraction) in preform. The reason for this may be small pores present in the reinforcement at higher fiber volume fractions. The filling time for preform of 4 layers was less at all five selected resin injection pressures as compared to those of other composites. The resin flow front velocities determined from the filling times are presented in Table 3.2. These values indicate the flow front velocity of resin under certain injection pressure. The flow front velocity increased with increased injection pressure and decreased with increased number of layers.

Table 3.2 Flow front velocity at different injection pressures

Injection pressure	Flow front velocity (m/s) for		
	Four layers	Five layers	Six layers
P_1	0.0120	0.010	0.008
P_2	0.0171	0.0128	0.0115
P_3	0.0220	0.0165	0.0147
P_4	0.0264	0.020	0.0172
P_5	0.0306	0.0233	0.020

The velocity of resin for composites manufactured at the same injection pressure decreased as preform layers increaseddue to increased mould filling time. This may be due to reduced volumes of pore spaces in preform. Therefore, the resin moved more slowly to impregnate the fiber.

Table 3.3 Reynolds number at five selected injection pressures

Injection pressure	Reynolds number for		
	Four layers	Five layers	Six layers
P_1	82.73	37.36	15.20
P_2	186.14	103.78	56.81
P_3	330.93	149.44	127.83
P_4	517.08	336.24	227.2
P_5	745.59	415.12	355.10

The resin flow regions have been identified as transition (for R_e<300) and turbulent (for R_e>300). The Reynolds number increased with increased injection pressure and decreased with increased number of layers. Reynolds number decreased for composites moulded at same resin injection pressure due to reduced velocity of resin. Resin flow was turbulent at injection pressure P_4 for 4 and 5 layered composites. Interestingly, the high injection pressure P_5 has contributed to an irregular flow for composites of the three different volume fractions.

3.4 Void content and permeability

The voids appeared in composites were determined in percentages and are presented in Table 3.4. The percentage of voids in the composite decreased with increased fiber volume fraction at the same injection pressure due to the creation of uniform flow fronts across small pore spaces of the material. However, the lowest void volume fractions of 1.75% at P_2, 1.54% at P_3 and 1.46% at P_4 were noticed in the respective composites because of superior fiber impregnation. At other resin injection pressures, the void content was increased. These voids induce stress concentrations in the composites during loading.

Table 3.4 Void content at different injection pressures

Injection pressure	Void content (%) for		
	Four layers	Five layers	Six layers
P_1	1.82	1.62	1.4
P_2	1.74	1.61	1.51
P_3	1.84	1.53	1.54
P_4	1.85	1.65	1.44
P_5	2.03	1.71	1.57

Table 3.5 Permeability at different injection pressures

Injection pressure	Permeability (m^2) for		
	Four layers	Five layers	Six layers
P_1	0.0001432	0.0001206	0.0001113
P_2	0.0001646	0.0001243	0.0001154
P_3	0.0001752	0.0001338	0.0001210
P_4	0.0001803	0.0001376	0.0001216
P_5	0.0001821	0.0001416	0.0001224

Table 3.5 gives the permeabilities measured for the present composites at preferred injection pressures. Permeability decreased with increased fiber volume fraction at same injection pressure. The composite samples of 4, 5 and 6 layers contained permeabilities of

0.00016 m^2, 0.00013 m^2 and 0.00012 m^2 at optimal injection pressures.

Conclusions

- The fabricated customized RTM was successfully employed to manufacture the chopped strand GFRP composite laminates without any deformation of the mould, edge effect and formation of dry spots at the preferred resin injection pressures with three different fiber volume fractions.
- Better impregnation of fiber has been observed due to central gating system. Flow visualization study was conducted to determine the resin filling time without any sort of hindrance in visualization.
- Resin filling time increased with increased number of preform layers. Reynolds number was calculated based on front flow velocity and resin flow patterns were clearly marked into transition and turbulent regions.
- The optimal injection pressure was suggested based on resin flow pattern and percentage of voids present in moulded composites. In these composites, good fiber impregnation occurred.

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