Analysis of the non-isothermal resin impregnation process of carbon fibre reinforced composite wing spar structure

Pyi Phyo Maung¹, G V Malysheva², Tun Lin Htet³ and G V Drobyshev⁴

¹,²,³ Bauman Moscow State Technical University, 2nd Baumanskaya street, Moscow, Russia
⁴ School №1387, Moscow state budget educational institution, Moscow, Russia

E-mail: pyaephyo@mail.ru, a@inginirium.ru

Abstracts. This paper presents non-isothermal resin impregnation process of high-performance light weight composite wing spar structure for trainer aircrafts. The manufacturing process of the spar is simulated in PAM-RTM software. In this research developed a reliable model of resin impregnation process simulation to determine the exact infusion time and optimize the resin inlet ports for large scale aircraft structure without using the expensive trial and error approaches. The work reported the use of different heating temperature processes to manufacture wing spar from carbon fibre-reinforced epoxy resin matrix composite laminates by using VARI. The influence of heating temperature during the infusion stage on the resin viscosity and impregnation time was analyzed. These results indicate that a proper heating temperature during the infusion process is necessary for quality control and manufacturing time reduction. The error between theoretical simulation and experimental studies is no more than 10%.

1. Introduction

Advanced composite materials have been increasingly used in aviation, aerospace, automobile, shipbuilding due to their complex characteristic of specific strength and modulus, ultralight weight, good fatigue properties and corrosion resistance [1,2]. With the rising demand, manufacturing cost and time are most important factors in the production of composite materials. Generally, composite aircraft structures have been produced by using the prepreg and autoclave forming. Despite the prepregs can offer high quality of product, their applications have been limited due to high costs and service life limitation of prepregs and expensive tooling such as autoclave [3,4]. Vacuum assisted resin infusion (VARI) technologies are widely used to produce the low cost and high-performance aerospace quality large scale complex integral structures such as wing spar, fuselage and wing skin with minimal initial capital costs. In the resin infusion stage, the application of the VARI process depends on resin viscosity so as to achieve uniform and complete impregnation process of fabric [5-6]. Additionally, a proper heating temperature during the infusion process is useful to reduce resin viscosity and consequently reduce the impregnation time, enhance the mechanical properties and increase the adhesion characteristics. However, an improper heating temperature might result in poor impregnation of the preform and produce voids in final cured composite [7,8].

Shojaei and colleagues examined the role of initiators with different reactivities on the process cycle of RTM using numerical simulation to minimize the impregnation time [9]. The results presented that a temperature distribution was created along the resin flow direction for the preheating mould. In order to increase the composite properties, Kedari studied the effect of temperature and inlet pressure of
impregnation process on fiber volume content and void inside the composite laminate manufactured by vacuum assisted resin infusion process (VARI) [10]. The results showed that a high processing temperature and low inlet pressure can produce final parts with high fibre volume fraction and low void content. It is detrimental to the uniformity of curing degree and mechanical properties. In summary, heating process during impregnation is an important factor to change processing efficiency for VARI process, so it should be analyzed carefully to obtain both short cycle time and high-quality products.

Additionally, heating process during the resin impregnation might result in obvious crosslinking reactions during the resin infusion stage, and affect the impregnation of the fibre and the temperature distribution due to the curing characteristics of the resin [11-13]. The aim of this study was to investigate the influence of the heating temperature during the resin infusion stage on the resin viscosity and impregnation time of composite wing spar structure. For this purpose, four kinds of processing cycles with different heating temperature were adopted. This is especially important when using fabrics or tapes with metal coatings [14-16]. The temperature influence on the process and accuracy of simulation were investigated, the authors [17-20] used new types of binders. Simulation of the vacuum infusion process is a required analysis tool to optimize the technological regime and to minimize the cost of trial and error experiment.

2. Flow in a porous medium

In the VARI process, the resin impregnates through a reinforcing material, which can be considered as a porous medium. The flow of resin is described by Darcy’s law, which states that the flow rate of resin per unit area is directly proportional to the pressure gradient and inversely proportional to the viscosity of the resin. The constant of proportionality is called the permeability of the porous materials. It depends on the fabric geometry.

Darcy’s law can be written by

\[ \vec{V} = -\frac{K}{\mu} \nabla P \]  

(1)

Where \( K \) – permeability tensor, \( \mu \) – resin viscosity, \( V \) – Darcy’s velocity, \( P \) – pressure.

In order to preserve the balance of resin mass, the velocity field must satisfy the divergence condition:

\[ \nabla \cdot \vec{V} = 0 \]  

(2)

By combining these two equations,

\[ \nabla \left( \frac{K}{\mu} \nabla P \right) = 0 \]  

(3)

In vacuum assisted resin infusion process flexible plastic vacuum bag were used to reduce the void contents and accelerate the resin flow. In the case of deformable media, considering the resin and the fibre material as incompressible, the equation is declared as

\[ div (\phi \vec{V}) = -div (\vec{V}_r) \]  

(4)

Where \( \phi \) – porosity, \( V_r, V_s \) – velocity of the resin and solid velocity.

Darcy’s law is written as

\[ div \left( \frac{[K]}{\mu} (\nabla P) \right) = div (\vec{V}_r) \]  

(5)

The resin viscosity depends on the temperature during the impregnation process. Temperature dependence of the resin can be written as follow:

\[ \mu(T, \alpha) = B \cdot \exp \left( \frac{T_b}{T} \right) \cdot \left( \frac{\alpha_{gel}}{\alpha_{gel}-\alpha} \right)^{c_1+c_2\alpha} \]  

(6)

Where \( B, T_b, \alpha_{gel}, c_1 \) and \( c_2 \) – constant of the resin characteristic

These characteristic constants of resin system were determined by using the differential scanning calorimetry.
3. Design and materials

3.1 Wing spar structure

Composite wing spar is one of the most critical parts in airframe. The vacuum assisted resin infusion process was used to produce wing spars to ensure the quality of the products and reduce the voids content inside the structure. The length of the spar is 11500mm. Spar wall high is varied from 300mm to 80mm and thickness is 2mm. Spar cap width is 80mm and thickness varied from 10mm at the middle section and to 3mm at the end of the wing tips. The 3D model of wing spar structure was shown in figure 1.

![Figure 1. Rear spar structure](image)

3.2 Materials

The epoxy resin used in this study was RIM 935 (supplied by Hexion). The Cure agents RIM RIM H 936 are a modification of aliphatic and cycloaliphatic amines. Resin properties are shown in table 1. The temperature dependence of rein mixture was determined by using viscometer Brookfield cap 2000 (Fig.2). The reinforcing materials are KDU 1034 unidirectional carbon fibre fabric and INTGL 98141 carbon fibre fabric. The properties of reinforcing materials are presented in table 2.

| Properties                        |   |
|-----------------------------------|---|
| Density [g/cm^n]                  | 1.14 – 1.2 |
| Viscosity [mPas]                  | 400 - 800 |
| Maximum Tg [°C]                   | 150 °C |
| Parts by weight ratio             | 100:29±2 |
| RIM 935/cure agent RIM 936        |   |
| Gel-time (100 grams at 30°C)      | 120 min |
| Thermal conductivity [W/mK]       | 0.11  |
| Specific heat [J/kg.K]            | 1205  |
Figure 2. Temperature dependence of resin mixture

Table 2. Reinforcing materials properties

| Reinforcing materials | Weaving type | Nominal areal weight, g/m² | Resin content in g/m² in laminate | Thickness, mm | Fibre volume content, % |
|-----------------------|--------------|----------------------------|----------------------------------|---------------|------------------------|
| Interglas 98141       | Twill 2/2    | 204                        | 140                              | 0,3           | 39                     |
| KDU 1034              | UD           | 370                        | 260                              | 0,4           | 53                     |

4. Modeling

Modeling of the vacuum infusion process is a necessary tool to optimize the process parameters, location of the resin inlet and outlet lines, and to minimize costly and time-consuming trial and error approaches for large scale structures. A three-dimensional mathematical model has been developed for flow simulation and implemented in the PAM-RTM finite element software to optimize the flow parameters and to predict the resin flow front during the infusion process. The process of impregnation has been taken place inside the heating oven with different values of the heating temperature (Fig. 2). Boundary conditions are shown in figure 3.

Figure 3. Boundary conditions of resin impregnation process

The resin inlet flow channel is located at the middle line of the spar wall mold. The resin viscosity function relates temperature depended viscosity and cure degree. Injection pressure is 1 Pa and vent pressure 0 Pa. Initial temperature of heating room is 25°C. Modelling temperature are 35°C, 50°C and 55°C. Filling pressure along the wing spar structure is also shown in figure 5.
The simulation results showed that the heating temperature of the oven during the impregnation process accelerate the impregnation process. More higher temperature allows to start the curing process. The optimal heating temperature must be chosen. The comparison results of rear, front and middle inner spar impregnation processes are shown in table 3.

Table 3. Simulation results of impregnation process

| Wing spars         | Heating temperature, °C | Duration, [s] |
|--------------------|-------------------------|---------------|
|                    | 25          | 35  | 50  | 60  | 4600 | 3980 | 2330 | 2210 |
|                    | 4340        | 3740 | 2020 | 1970 |
| Middle inner spar  | 3450        | 2430 | 1090 | 1040 |

5. Experimental

The composite laminates were prepared inside the wing spar mold by the VARIM method, as illustrated in figure 6. Three layers of INTGL 98141 carbon fibre fabrics were stacked overall inside the mold. And 31 layers unidirectional carbon fibre fabrics KDU 1034 were stacked on the vertical wall of the mold (Spar cap). The Peel ply, permeable medium and distribution mesh were laid over the surface of the fabric successively. The distribution mesh was terminated at a gap 40 mm from the end of the fabric laminate preform. In order to monitor the temperature variation inside the preform during
the curing process, 5 thermocouples were inserted into the fabric layers, as shown in figure 6. The experimental results are shown in table 4.

![Image](image_url)

**Figure 6.** Experimental VARI process of wing spar structure

**Table 4.** Experimental results of impregnation process

| Wing spars          | Heating temperature inside the oven, °C | Duration, [s] |
|---------------------|-----------------------------------------|---------------|
|                     | 25                                      | 35            | 50            | 60            |
| Rear spar           | 4940                                    | 4230          | 2540          | 2480          |
| Front spar          | 4750                                    | 4010          | 2435          | 2215          |
| Middle inner spar   | 3880                                    | 2650          | 1320          | 1250          |

The manufacturing process of the spar is simulated in PAM-RTM software, which uses the vacuum infusion technique, unlike the traditional wet lay-up method. In this research developed a reliable model of resin impregnation process simulation to determine the exact manufacturing time and optimize the resin inlet ports for large scale aircraft structure without using the expensive trial and error experimental approaches.

6. Conclusion

The results of theoretical and experimental studies of the kinetics of the impregnation process depending on the heating temperature were carried out. The manufacturing process of the spar is simulated in PAM-RTM software. In this research developed a reliable model of resin impregnation process simulation to determine the exact infusion time and optimize the resin inlet ports for large scale aircraft structure without using the expensive trial and error experimental approaches. The work reported the use of different heating temperature processes to manufacture wing spar from carbon fibre-reinforced epoxy resin matrix composite laminates by using VARI. The relationships among heating temperature, resin viscosity and impregnation time were analyzed. It was found that, in infusion stage a high heating temperature was useful to reduce the total impregnation time. In the case of 60 °C heating temperature, the impregnation time is shortest. However, too high heating temperature effects pre-crosslinking process of resin and to the mechanical properties and nonuniform properties along the resin flow direction. When a higher heating temperature was used, poor resin and fibre impregnation at the resin outlet were responsible for the lower mechanical properties. These results indicate that a proper heating temperature during the infusion process is necessary for quality control and production time reduction. The error between theoretical simulation and experimental studies is no more than 10%.
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