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In-Mold Coating of Composites Manufactured with the Resin Infusion Between Double Flexible Tooling Process by Means of Co-Infusion

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THE FLORIDA STATE UNIVERSITY

COLLEGE OF ENGINEERING

**In-Mold Coating of Composites Manufactured with the Resin Infusion
between Double Flexible Tooling Process by Means of Co-Infusion**

By

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ABSTRACT

As composite materials gain wider acceptance within the transportation industry, it is pertinent to investigate the available coating processes with a view to reduce emissions and associated costs. Current painting processes are not only laborious and time consuming, but expensive and present safety issues. In-mold coating presents an avenue for eliminating on reducing these problems. This work aims to determine the feasibility and develop a methodology for In-Mold Coating (IMC) components manufactured using the Resin Infusion between Double Flexible Tooling (RIDFT) process. Comparisons of the cost and efficiency between a component manufactured by RIDFT and then painted, and a component manufactured by RIDFT IMC process is given. It indicates a 46% savings in capital investment and 55% savings in time while using RIDFT IMC. The viability of in-mold coating RIDFTed components was investigated. This work-in-process, reports on successes and challenges presented, during the co-infusion of a polyurethane enamel paint (DuPont Imron 5000) and a vinyl ester resin (Derakane 470-45).

In this thesis, RIDFT IMC is used to manufacture a double-layered structure consisting of a vinyl ester layer for structural function and a polyurethane enamel coating layer. The two liquids are either simultaneously or sequentially infused into a double flexible mold and are cured. Liquid separation is maintained by a separation layer. Twenty-four case studies have been made to determine the viability of the IMC process. Eight different separation layers were tested to find out the most promising separating material. The specification of the separation layer was made. Several test evaluations were conducted. A Differential Scanning Calorimeter (DSC) is used to test the cure cycle for the resin and the paint. Mechanical testing, Dynamic mechanical analysis (DMA) and tensile tests are used to evaluate the performance of the produced parts. An

Environmental Scanning Electron Microscope (ESEM) was used to evaluate the microstructure of the components. In order to improve the flow of the fluids, several Flow Distribution Channels (FDCs) were made and tested to determine the best configuration.

The experimental results demonstrate that in-mold coating by means of co-infusion may be a viable option for painting RIDFT components with determination of an appropriate separation layer. The paint used in this work dissolves the separation layer. Further work has been suggested to develop a paint formulation that will not dissolve the separation layer.

CHAPTER 1

INTRODUCTION

Over the past four decades, polymer composites have been presented as the material of the future due to their advantages of high strength to weight ratios, corrosion resistance, and functional integration [1]. Nonetheless, the production economics of polymer composites tend to limit their application in the mass production sector. The lead times to manufacture are simply too high. Several production processes are available, with the liquid composite molding techniques being the most amenable to mass production.

Liquid composite molding (LCM) techniques have been used widely to manufacture polymer composite materials. Several variations exist such as Resin Transfer Molding (RTM), Vacuum Assisted Resin Transfer Molding (VARTM), Seemann's Composite Resin Infusion Molding Process (SCRIMP), Resin Infusion between Flexible Tooling (RIFT), and the novel Resin Infusion between Double Flexible Tooling (RIDFT) process. These closed molding techniques also have the benefit of reducing emissions of VOC's by 90% [1]. Once manufactured, composite components undergo a series of finishing processes to prepare the substrate for painting. Some of the current painting methodologies are not only laborious, time consuming and expensive, but may result in the release of materials that are harmful to the environment.

The automotive coatings market has been significantly influenced by the macroeconomic environment, the drive towards lower costs and higher efficiency, technology innovation and sound environmental practice [2]. Environmental concerns

have led the trend to reduce solvent use in coating applications. The latest technology and materials development promise to lower assembly paint-line emissions, eventually eliminating solvents in paint, while improving scratch resistance and the overall durability of a vehicle finish.

It is imperative that methodologies are sought to reduce the costs associated with painting, as well as the negative environmental impacts. In-mold coating (IMC) of composite components may address these issues and can replace the current painting processes by providing desirable benefits to the transport and other relevant industries. This work aims to determine the feasibility and develop a methodology for IMC components manufactured using the RIDFT process.

RIDFT, this novel composite manufacturing technique was conceptualized and developed at the Florida Advanced Center for Composite Technologies (FAC²T). RIDFT is a two-stage process incorporating resin infusion to wet the fiber reinforcement (flow being two-dimensional), and vacuum forming (to create the required geometry). The flow front of the infused resin is two-dimensional and avoids flow complexities common in the three-dimensional flow seen in other liquid composite molding techniques. It employs a single-sided mold, which provides noticeable cost benefits compared with resin transfer molding. A RIDFT equipment with capability for producing part dimensions of 1 ft. (width) x 2 ft. (length) x 0.83 ft. (height) was used in this work. Figure 1.1 shows the RIDFT prototype machine.

Figure 1.1. RIDFT prototype

The idea behind the RIDFT IMC was to co-infuse a resin and a coating material (paint) either simultaneously or otherwise. This is to be performed without opening the RIDFT flexible membranes. In this preliminary IMC study, emphasis will be placed on infusion and not vacuum forming. Forming is regarded here, as a secondary issue that should be studied if the co-infusion methodology is deemed successful.

1.1 Motivation

Developing a one step forming and coating process should reduce processing time, associated costs, emission and labor with obvious advantages to manufacturers.

The comparisons of the cost and efficiency between painting a component manufactured by RIDFT and then painted, and a component manufactured by RIDFT IMC process is given in Tables 1.1 and 1.2. Table 1.1 shows a comparison of the capital investment. It indicates a 46% savings in capital investment while using RIDFT IMC. Table 1.2 shows a comparison of the painting efficiency. The time saving is about 55% while using RIDFT IMC.

Table 1.1. Capital Investment Comparison (Based on part size of 10x6 in²)

Traditional RIDFTed composites manufacturing plus painting processes	Investment (dollar)	RIDFTed IMC	Investment (dollar)
<u>Composites manufacturing</u>		<u>Composites manufacturing incorporating painting into a single process</u>	
RIDFT machine	10000	RIDFT machine	10000
Infrared heat lamp	500	Infrared heat lamp	500
Others	300	Others	300
<u>Painting</u>			
Tools	100		
Oven (Grainger)	8468		
Others	500		
Total	19868		10800
		Total capital investment saving 46%	

Table 1.2. Painting Efficiency Analysis (Based on part size of 10x6 in²)

Traditional RIDFTed composites manufacturing plus painting processes	Time (hour)	RIDFTed IMC	Time (hour)
<u>Composites manufacturing</u>		<u>Composites manufacturing incorporating painting into a single process</u>	
Preparation (material and machine)	2	Preparation (material and machine)	2
Product manufacturing	0.5	IMC product manufacturing	0.5
Drying	1	Drying	1.5
Demolding and Cleaning	1	Demolding and Cleaning	2
<u>Painting</u>			
Preparation (material and machine)	1		
Primary sanding	1		
Primer coat applying	0.5		
Baking primer at 280 ° F	1		
Wet sanding	1		
Sealer applying	0.5		
Dry sanding	1		
Lacquering	0.5		
Initial baking at 140 ° F	0.5		
Final baking at 250 ° F	0.75		
Final sanding and polishing	1		
Total hours	13.25		6
		Total time saving 55%	

1.2 Problem Statement

IMC procedures have previously been successfully developed and used [2]. However, much of the work has been with the compression molding of Sheet Molding Compounds (SMC) to improve their surface quality in terms of functional and cosmetic properties. When injected onto a cured SMC part, IMC cures and bonds to provide a paint-like surface. A method for in-mold coating using thermoformable paint films with the RIDFT process was reported [2] to yield a measure of success. Elsewhere, Gillio *et al* [3] reported work that successfully co-injected two resins using a separation layer.

This work adapted their methodology to the RIDFT technique bearing in mind that the RIDFT process infuses resin between two flexible membranes in contrast to previously reported efforts. It is therefore imperative to develop a method for IMC suitable to the RIDFT process.

1.3 Objectives

The preceding sections have outlined the importance and benefits of IMC. This work has two objectives:

1. The assessment of the viability of co-infusion as applied to the RIDFT process, and
2. The development of a methodology for in-mold coating components manufactured by the RIDFT process.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Over the past four decades, polymer composites have been presented as the material of the future due to their advantages of high strength to weight ratios, corrosion resistance, and functional integration [1]. Nonetheless, the production economics of polymer composites tend to limit their application in the mass production sector. The lead times to manufacture are simply too high. Several production processes are available, with the liquid composite molding techniques being the most amenable to mass production. Techniques such as RTM, VARTM and their variants have been successfully implemented for the manufacture of polymer composite components. Once manufactured, composite components undergo a series of finishing processes to prepare the substrate for painting. Some of the current painting methodologies are not only laborious, time consuming and expensive, but may result in the release of materials that are harmful to the environment. This chapter is devoted to the review of literature pertaining to liquid composite molding techniques and the applicability of in-mold coating technologies to same.

2.2 Liquid Composite Molding

Several LCM technologies have been successfully implemented to date. Prominent amongst them are RTM and variants such as VARTM, and SCRIMP. Additionally, a novel process known as RIDFT has shown promise. These methodologies consist of placing a dry perform in a closed mold and introducing a catalyzed liquid resin, under pressure or vacuum.

2.2.1 Resin Transfer Molding

The RTM process has been widely used in the automobile industry, because products with large surface areas can be manufactured easily with lower manufacturing costs when compared with compression molding [4]. RTM appears to be a simple four-step process: preforming followed by injection and cure, as shown in Figure 2.1 [4]. In reality, however, it has been found to be relatively complicated in use.

Figure 2.1. Schematic of RTM process

Each step of the process affects subsequent ones. Every decision made affects both processing of the part and the performance of the final part. The microstructure of

the preform must be designed based not only on the thermomechanical loading the part is expected to undergo, but also the influence of the proposed microstructure on the permeability, and therefore the time to fill the mold. Thus also affecting resin selection, viscosity, and processing temperature, which in turn affects selection of tooling material and demolding time. Similarly, injection must reflect the delicate balance among the desire for a short cycle time, the integrity of the microstructure (avoiding processing-induced movement of the reinforcement), the wet-out of fiber bundles, and the removal of entrapped air. As such, resin selection, molding temperature, pressure, and viscosity must be controlled to preserve the preform integrity. Furthermore, tooling must be designed not only for the shape and features of the part but also for the specifics of injection, permeability, cure, and demolding. These are a few examples of the challenges associated with RTM, making it essential that processing and performance issues be considered simultaneously to ensure that the final product is of high quality and yet economical [6].

Perhaps the greatest benefit of RTM relative to other polymer composite manufacturing techniques is the separation of the molding process from the design of the fiber architecture [6]. Having the fiber preform stage separate from the injection and cure stages enables the designer to create uniquely tailored material to fit precisely a specific demand profile. This is accomplished by combining a variety of fiber types and forms. In fact, liquid molding enables attainment of high levels of microstructural control and part complexity compared with processes like compression molding.

Other benefits afforded by RTM include:

- Good surface quality
- Tooling flexibility (Ribs, cores and inserts are easily incorporated)
- Manufacturability of large, complex shapes
- Parts integration

2.2.2 Vacuum Assisted Resin Transfer Molding

VARTM is a variant of the traditional RTM process (Figure 2.2). Developed over the last ten years, the process has been used in both commercial and military applications, including aerospace, ground-based, and marine composite structures. The process has advantages over conventional RTM by eliminating matched-metal tooling costs by using vacuum bagging instead of heavy metal mold, reducing volatile emission, and allowing for low injection pressures. Although VARTM is considered one of the most promising composite fabrication techniques, some technical issues now prevent wide application of the process. In the VARTM technique, material selection, arrangement of the mold's gates/vents, and selection of processing parameters have a significant impact on product quality and process efficiency. Currently, gate/vent location in VARTM tooling design is largely determined on a trial-and-error approach based on the experience of the engineers. Such an ineffective procedure is usually time-consuming and expensive, given the people, facilities, and materials involved.

Figure 2.2. VARTM process

Brouwer *et al* [7] described ways to improve reliability and predictability of the VARTM technology in order to decrease development cost and to make the risk of failures during production as small as possible. First, appropriate methods to achieve void free processing of the composite material are described. Secondly, it is explained how the injection strategy can be optimized by using resin flow simulation software.

2.2.3 Seemann's Composite Resin Infusion Molding Process

The SCRIMP process provides a controlled flow of resin through an in-plane distribution system to infuse a laminate stack. The process offers the ability to pre-form parts by hand, placing a variety of dry reinforcements into a mold, sealing it in a vacuum bag, then pulling a vacuum to compress the fibers and distribute the resin throughout the laminate [8].

SCRIMP, process developed and patented by Seemann's Composites, single sided tooling, and injection achieved through high permeability surface layer to cause the through-thickness-flow, is one major method of LCM. It is a hybrid of RTM and vacuum bagging, and uses a one-sided tool. The high vacuum eliminates any air voids, then resin feed tubes draw in only enough resin to "wet" the laminate. SCRIMP laminate properties in terms of compression strength, flexure, and tension are twice the strength of hand lay-up and significantly stronger than low energy (vacuum bagged) post-cure pre-pregs. There is no entrapped air in a SCRIMP laminate. It only takes 1% void content to reduce flexural strength by 10%! SCRIMP can be used to fabricate large-scale parts such as boat or infrastructure, with low void content. The SCRIMP process is shown in Figure 2.3 [8]. In this figure, vacuum draws catalyzed resin from drums through inlet ports along feed channels molded into the bag to completely infuse the laminate.

Figure 2.3. SCRIMP process [8]

2.2.4 Resin Infusion between Double Flexible Tooling

The RIDFT technique is a novel two-stage process, which incorporates resin infusion and wetting with vacuum forming. The flow front of the infused resin is two-dimensional and avoids flow complexities prevalent in the three-dimensional flow seen in other liquid composite molding techniques. It employs a one-sided mold, which provides obvious cost benefits when compared with resin transfer molding. On-going prototype development of the RIDFT process has yielded positive results. Composite laminates with good surface quality, micro structural characteristics, and mechanical properties have been repeatedly produced with cost savings of 24% when compared with SCRIMP. Okoli *et al* [5] describe the RIDFT process, outlining its merits and presenting its challenges, whilst identifying potential benefits to industry.

Figure 2.4. RIDFT process [5]

RIDFT is a two-stage process – resin infusion and wetting, followed by vacuum forming. As shown in Figure 2.4, dry reinforcement is placed between two membranes. After securing the membranes, resin is infused under a vacuum. The next stage is vacuum forming, during which the membranes are drawn over a male mold (final product shape) by applying a vacuum. The use of a one-sided mold provides huge cost benefits when compared with the RTM process. A cost savings of 24% has been demonstrated when compared with SCRIMP [5]. The final shape mold can be made by rapid prototyping methods with metallic or non-metallic materials, since the mold does not have to withstand high pressures. Furthermore, the mold is not exposed to the resin or the reinforcement, which drastically reduces wear and tear. The limitations of the RIDFT process lies with the forming stage, since only formable geometries can be manufactured using this process.

2.3 Composite Painting Methodologies

In general, painting methodologies as applied to FRP composites may be separated into the following steps:

1. Application of polyfiller
2. Surface grinding for smoothness
3. Application of paint

The automotive coatings market has been significantly influenced by the macroeconomic environment, the drive towards lower costs and higher efficiency, technology innovation and sound environmental practice [9]. Environmental concerns have led the trend to reduce solvent use in coating applications. The latest technology and materials development promise to lower assembly paint-line emissions, eventually eliminating solvents in paint, while improving scratch resistance and the overall durability of a vehicle finish.

In 2002, the worldwide market in automotive paints was worth \$6.6bn [9]. In the last few years, US market for automotive paint have seen a growth on average revenues of 1% above the rate of new car production, but volumes have fallen at the rate of 0.5% per year. This may be attributed to the deployment of more efficient coating equipment and paint with higher solid levels. It is imperative that methodologies are sought to reduce the costs associated with painting, as well as the negative environmental impacts. IMC of composite components may address these issues. IMC has been successfully used for many years for exterior body panels made from compression molded SMC to improve their surface quality in terms of functional and cosmetic properties [9]. When injected onto a cured SMC part, IMC cures and bonds to provide a paint-like surface. Another method for in-mold coating is the use of thermo-formable paint films.

Several forms of in-mold coating have been researched, including the metal plating of SMC [10], and in-mold coating of injection molded plastics [11]. McCarthy *et al* [12] discussed the effects of implementing paint films on different fiber structures. Castro *et al* [13] offered the process model for in-mold functional coating of

thermoplastic substrates. IMC and SMC were taken into consideration here, which separated the process model into three stages: filling, packing and coating.

Toro and Okoli [2] reported on the use of paint films on RIDFTed composite parts. They established the viability of the use of thermo-formable paint films with the RIDFT process. In these experiments, a room temperature cure Vinyl ester resin (Derakane 470-45) was used. They [2] noted that poor adhesion of the paint films used (Avery Dennison – Avloy) constituted a problem. It was also found that the application of heat intended to soften the paint film, brought about premature curing of the resin. A balance was thus sort to enable the softening of the film, without the premature curing of the resin. Further testing is ongoing with paint films from other sources.

Another viable methodology for in-mold coating is the injection or infusion of liquid paints into a closed mold. This will be discussed in the following section.

2.4 In-mold Coating Technologies

In-mold coating emerged as a viable process several years ago, primarily to reduce the cost of producing strong structural reaction injection molded parts.

Chen *et al* [14], studied the IMC of a thermoplastic substrate by injecting a low viscosity liquid thermoset material onto its surface whilst it was still in the mold. IMCs provides paint-like surface and durability, and is becoming a prevalent way to mass produce, gradually replacing traditional painting. There are two dominant applications for IMC, one is for SMC, which is compression, molded, and the other is for thermoplastic products which is injection molded. The SMC material was coated by slightly opening the mold to lower the coating injection pressure. However, the thermoplastic injection mold is without a shear edge, and would lead to coating leakage if opened. Figure 2.5 shows the tooling difference between the two models.

Figure 2.5. Tooling difference between IMC for SMC and IMC for thermoplastic

Simulation of the coating flow was discussed by Castro *et al* [13~15], using the Hele-Shaw mathematical model to represent the 2-D Newtonian fluid flow. Three stages were identified - filling, packing, and solidification or curing. A major concern is the nozzle location, which is aesthetically imperative, as well as to reduce the trapping of air. The continuous deformation of the thermoplastic substrate is caused by the coating material, and could be discussed by the Pressure-Volume-Temperature (PVT) relationship [13]. Control Volume of Finite Element Method (CV/FEM) was also used to predict the fill pattern and pressure distribution on the coating layer, and then compared with experimental values.

During the experimentation, initiators and inhibitors for coating material were added to activate the coating curing reaction and to prevent the chemical reaction with the thermoplastic substrate, respectively. The Governing equation from Hele-Shaw mathematical model is:

$$\frac{\partial(h\bar{v}_x)}{\partial x} + \frac{\partial(h\bar{v}_y)}{\partial y} = -\frac{dh}{dt} \quad (2.1)$$

where $\bar{v}_x$ and $\bar{v}_y$ are the thickness averaged velocities respectively in the x and y directions:

$$\bar{v}_x = -\frac{S}{h} \frac{\partial p}{\partial x} \quad (2.2)$$

$$\bar{v}_y = -\frac{S}{h} \frac{\partial p}{\partial y} \quad (2.3)$$

where,

$$S(x, y) = \int_0^h \frac{z^2}{\eta(x, y, z)} dz \quad (2.4)$$

In above equations, h is the thickness change of the thermoplastic substrate caused by the coating injection. It is represented by [13]:

$$h = h_s (1 - V / V_o) \quad (2.5)$$

where h_s is the original thickness of the thermoplastic substrate right before the IMC injection; V is the specific volume of the thermoplastic substrate; V_o is the specific volume of the thermoplastic substrate right before the coating injection. The compressibility of the substrate is described by the two-domain Tait PVT model [16].

Under the isothermal assumption, the specific volume is only a function of coating pressure:

$$V = f(p) \quad (2.6)$$

In this work, power-law model is used since it has been found experimentally to adequately predict the rheological behavior of the coating [13].

$$\eta = m \dot{\gamma}^{n-1} \quad (2.7)$$

where m and n are zero-shear rate viscosity and flow index respectively.

There is an obvious "edge effect" along the mold wall on coating flow.

Three main methods are used to observe IMC applied on SMC [13]: The first was the removal of the edge clamps to separate two half molds by a 1mm gap, and then re-close to spread the coating material. The second was the reduction of the clamping force, followed by injection of the coating material. In the third case, the clamping force was maintained and the compressibility of the SMC and injection pressure were

used to apply the IMC. The first is a low-pressure injection method. The second and third, were high-pressure injection methods.

In a previous study, in addition to the pressure gradient caused by the vacuum pressure, gravity and capillary flow effects were also considered [17]. The preform infiltration time is a function of the resin viscosity, the preform permeability and the applied pressure gradient. The infiltration time can be greatly reduced by utilizing a distribution medium with a higher permeability than the preform [18, 19]. Consequently, the resin flows in the distribution medium first and then the infiltration process continues through the preform thickness.

Gillio *et al* [3, 9] developed a co-injection resin transfer molding (CIRTM) process. This process enables two or more resins to be concurrently injected into a mold filled with a still fiber preform. CIRTM enables the manufacturing of co-cured multi-layer, multi-resin structures in a single processing step. A separation layer made of a 0.025 mm commercially available polysulfone film (molecular weight ranging from 6400 to 10,000 g/mole) is used to provide resin compatibility during cure and to control resin mixing. The impermeable separation layer was formed of a polysulfone film sandwiched between two layers of epoxy based adhesive. This solution relies on adhesion mechanisms where epoxy and the amine curing agent disperse and react in the polysulfone barrier layer. The polysulfone film was chosen based on compatibility with the epoxy. Polysulfone is also recognized to toughen the interphase during cure. Additionally, the phenolic is co-cured with the compatible epoxy. The approach provides a toughened co-cured interphase between materials that would not be compatible else. Scaling issues relating the role of transverse permeability in resin mixing were investigated. This research demonstrates that the CIRTM process requires a totally impermeable separation layer if CIRTM is used to manufacture large parts and/or if the resins injected have significantly different viscosities.

Figure 2.6 [3] shows the experimental setup used to manufacture the co-injected specimens. Seven layers of S2-glass (Owens Corning, 933 sizing), twill weave, 18 oz/yd², fabric were used for the phenolic, and the vinyl ester preforms. The vinyl ester adopted in this study was Dow Derakane 411-350, which is a room temperature vinyl ester with a gel time of about 30 minutes. The phenolic adopted was J2027/L,

manufactured by British Petroleum, which cures at about 60°C (140°F). An impermeable separation layer was adopted between the preforms to demonstrate the practicability of this method for large composite structures. The infusion process used in this study is typical of the SCRIMP [8]. The distribution media placed on both sides of the preforms is high permeability material, which accelerates flow across the top and bottom surface of the part while the resin flows through the thickness of the preform. The distribution media drastically decreases fill times and enables thick section parts to be impregnated under vacuum only. The resins were concurrently injected from the two injection locations. Once the part was infused and the resin had cured, the distribution media was removed.

Figure 2.6. Experimental setup used to manufacture the co-injected specimens.

A simplified schematic of the co-injection setup is shown in Figure 2.7 [9]. In the majority of cases, the flow of a polymer inside a mold filled with a stationary fiber bed is modeled using Darcy's law (Equation 2.8).

Figure 2.7. Schematic of the one-dimensional flow model in CIRTM

The macroscopic velocity, u , is given by:

$$u = \frac{k}{\mu} \frac{dP}{dx} \quad (2.8)$$

where k is the permeability of the fiber preform, μ is the viscosity of the resin, and dp/dx is the pressure gradient in the flow direction.

In co-injection, the top and the bottom preforms could have different permeabilities and the resins injected could have different viscosities, leading to different resin velocities between the top and the bottom halves of the mold. The injection is assumed to be at the same pressure since this is the case in the majority of VARTM type processes. In such a case the velocities of the two flow fronts will be given by:

$$u_1 = \frac{k_1}{\mu_1} \frac{P_i}{l_1} \quad (2.9)$$

$$u_2 = \frac{k_2}{\mu_2} \frac{P_i}{l_2} \quad (2.10)$$

It follows that if the ratios of permeability to viscosity are constant in both layers, the flow velocities will be the same. In most applications, this is not the case, and one of the flow fronts will move in front of the other.

As the flow moves through the mold, a pressure profile develops in both the top and the bottom halves of the mold. In the case where the cross flow between the two layers is small, these pressure profiles can be assumed to be linear. In this model, both pressure profiles are assumed to be linear. If the ratio of permeability to viscosity is different between the two layers, l_1 and l_2 will be different, and a pressure gradient will form between the top and the bottom halves of the mold. This pressure gradient will drive the transverse flow. The transverse flow will be given by:

$$u_3 = \frac{2k_3}{\mu_1} \frac{P'}{(h_1 + h_2)} \quad (2.11)$$

where k_3 is the transverse permeability of the middle layer, $(h_1 + h_2)/2$ is the distance between the midpoints of the two layers, and P' is the average pressure difference between the two layers. Since both pressure profiles are assumed to be linear, and recalling that the pressure is zero in front of the fluid front (i.e. where the preform is not impregnated), P' is given by:

$$P' = \frac{P_i (l_1 - l_2)}{l_1} \quad (2.12)$$

Here the assumption has been made that the ratio of permeability to viscosity of layer one is greater than that of layer two. Substituting Eq 2.12 into Eq 2.11, yields an equation for the cross flow as a function of the inlet pressure and the position of the flow fronts:

$$u_3 = \frac{k_3}{\mu_1} \frac{P_i (l_1 - l_2)}{l_1 (h_1 + h_2)} \quad (2.13)$$

In Equations 2.11 and 2.13, the viscosity of fluid 1 was used assuming that the ratio of permeability to viscosity of layer one is greater than that of layer two, which is the case in Figure 2.6. Equation 2.13 can be verified in the extreme cases: if the transverse permeability is zero, the transverse flow is zero, if the two flow fronts are at the same location (i.e. $l_1 = l_2$), there is no pressure gradient and the transverse flow is zero.

Gillio *et al* [3, 9], in evaluating these conditions, used a variety of different transverse permeabilities in an attempt to control the transverse flow. The trend observed is that the transverse flow increases rapidly in the initial stages of mold filling,

and subsequently, when the distance between the flow fronts becomes constant, the total transverse flow does not increase significantly.

As to the study of resin flow, complete filling of the mold with adequate wetting of the fibrous preform is the primary objective in most LCM processes, such as VARTM. Incomplete impregnation in the mold leads to the production of defective parts with dry spots. In order to overcome this problem, it is important to simulate resin flow through the preform in modeling the manufacturing process. Flow of resin through fibrous media can be modeled using Darcy's law [17]. The finite element/control volume (FE/CV) method is commonly used to model the resin flow through the preform. A control volume is constructed around each node by subdividing the elements into smaller volumes. The pressure distribution in the resin-filled region can be calculated by use of finite element methods. Darcy's law is applied to obtain the flow rates. The concept of control volume and fill factors is then employed to track the location of the flow front [20]. Sun *et al.* [21] investigated mold filling for the SCRIMP using a high-permeable medium to infiltrate the preform. It was found that the distribution medium could significantly reduce infiltration time. The simulation results also indicated that the infiltration time was a strong function of the permeability of the distribution medium, but was not sensitive to the preform permeability [21].

Hammani *et al* [22] studied the effects of the primary processing variables in the vacuum infusion molding process and presented a 1-D model for the process. The parameters investigated were the compaction of the reinforcement, the permeability, the infusion strategy and the presence of flow enhancement medium. The vacuum infusion molding process differs from the traditional RTM process because the flexible nature of the vacuum bag is coupled to the varying pressure inside the mold cavity. This results in a variation of the cavity thickness during the vacuum infusion impregnation process. In addition to the governing equations deriving the flow model, i.e., Darcy's law and the continuity equation, a new equation was introduced to account for the transverse pressure equilibrium inside the mold cavity during impregnation. Taking into account that the mold cavity thickness is pressure dependent and the permeability is a function of the fiber mat thickness, the theoretical

model produced results in good agreement with the infusion experiment. This approach was also used in the SCRIMP infiltration model developed by Han *et al.* [23]. The total external pressure applied to the composite is equal to the sum of the resin pressure and the pressure supported by the fiber network. For the VARTM process, the external pressure applied is the atmospheric pressure (P_{atm}):

$$P_{atm} = P_R + P_F \quad (2.14)$$

where P_R is the resin pressure and P_F is the fiber pressure (pressure supported by the preform).

For a standard VARTM process, the resin pressure is maintained at 1 atm in the injection reservoir and 0 atm at the flow front (vacuum side)

During the infiltration process, the resin pressure in the preform rapidly increased to the atmospheric pressure. This resulted in an increase in preform thickness, which led to a reduced panel fiber volume fraction ranging from 45.5% to 49.7%. The compaction at the flow front was shown to be a complex combination of wetting deformation caused by resin lubrication and of spring-back deformation caused by the increasing resin pressure and corresponding decreasing preform pressure. The present results showed agreement with observations by Williams *et al.* [24] for the RIFT process.

2.5 Durability of Surface Coatings

The ability to paint (coat) and cure resin in one-step will certainly advance composites manufacturing. Nonetheless, the methodology for sustaining or improving durability and appearance of products should be the premise of implementing IMC. Thus, measuring durability is of paramount importance.

Yamamoto *et al* [10] described a test method for durability of surface finish. The scratch test mentioned was to evaluate the adhesion with a width of 10mm made on the plated layer using a cutter knife, and the end of the flawed layer was pulled from both sides by a tension tester at an angle of 90° to the surface, to measure its peel strength. The surface quality was evaluated by a fluorescent lamp put 2 m apart from the test plate,

so that the lamp is reflected in the plate and five panelists ranked the degree of its reflection. The mean value of their score was used. When the lamp is reflected in the same state as its original, it is ranked 10th. When the lamp is not reflected at all, it is ranked first. This ten level ranking method was used.

2.6 Summary

In applying the in-mold coating to the process today known as RIDFT, the unique approach to integrating flexible coatings with substrates is a natural fit for market segments such as automotive, agricultural, construction equipment, marine, lawn and garden, and aerospace.

In-mold coating systems could yield numerous benefits including a high-gloss Class A finish without orange peel, runs, dust or chipping. More recently, two-color in-mold techniques fabricated from thermoplastic co-injection machine have maximized the esthetic value of the process. Significantly, such attributes can generally be achieved with tremendous savings of time and material.

Numerous benefits from a design and engineering perspective have become possible. These include: the ability to achieve complex cavity side geometry, flexibility in the design, an ability to achieve higher levels of mineral fillers, and expanded options for gating to ensure proper entrance velocity. CAD and diagnostic capabilities have added to the ability to provide design assistance and to anticipate optimum choices for effective processing [13].

In-mold coating will provide processing benefits to the RIDFT process by eliminating the need for post painting steps such as cleaning, degreasing, sanding, and priming. These procedures may constitute up to half of a product's total cost. Moreover, IMC will make composites manufacturing more environmentally friendly with the obvious reduction of VOC's.

CHAPTER 3

EXPERIMENTAL METHODOLOGY

3.1 Resin Infusion between Double Flexible Tooling Equipment

The RIDFT equipment used in this work was shown in Figure 1.1. It is capable of making parts 1 ft. (width) $\times$ 2 ft. (length) $\times$ 0.83 ft. (height). The sealing frames are shown in Figure 3.1. The frames are made of aluminum box sections and are used to place the flexible (silicone) diaphragms. The reinforcing fibers used in this work are BGF 7781 satin weave fibers. Dow Derakane 470-45 epoxy-based vinyl ester resin was used. The coating material used is the DuPont Imron 5000 system.

Figure 3.1. RIDFT equipment showing top and bottom sealing frames

3.2 Manufacture of In-mold Coated Laminates

In this section, a description of the methodology for the manufacture of RIDFTed IMC components will be given. The idea was to infuse two fluids into the flexible diaphragms of the RIDFT equipment either concurrently or consecutively. The setup followed a modified approach of the work of Gillio *et al* [9]. The initial RIDFT co-infusion setup is given in Figure 3.2. This is denoted RIDFT IMC-1.

Figure 3.2. Schematic cross-sectional and detailed view of RIDFT IMC-1

In this setup, the fiber preform is placed between the flexible diaphragms. Two flow ports are used to infuse the resin (below) and the coating material (above). A separation layer is used to separate the flow of the two fluids. This assembly differed from that of Gillio *et al* [9] (Figure 2.6) in that there was neither need for the inclusion of distribution media nor release plies. Furthermore, the RIDFT process uses two flexible membranes. The RIDFT process uses a temporary vacuum assisted flow distribution channel (FDC) to enable rapid fluid flow (Figures 3.3 and 3.4). This is removed once sufficient flow is achieved. The FDC works by temporary pulling up selective portions of the top silicone membrane. This creates a temporary set of channels, which enable fluid flow.

Figure 3.3. Schematics of flow distribution channel cross-section

Figure 3.4. RIDFT temporary flow distribution channel

3.2.1 Materials

This thesis describes the preliminary results of in-mold coating assessment studies made using paint, resin, fiber reinforcement and separation layer. The paint used was polyurethane enamel DuPont Imron5000 and the resin used was a room temperature cure vinyl ester resin (Derakane 470-45). The fiber reinforcement used here was satin woven glass fibers (BGF) 7781. The separation layer used included paper, vacuum bagging film, release film, Ferro prepak film, Avloy base web-film, SC-15 impregnated fibers and polyvinyl alcohol.

The coating material used in RIDFT IMC is polyurethane enamel DuPont Imron5000 paint. This is a high-performance, low VOC (<3.5 lbs/gal RTS), two component polyurethane enamel. Acetone is one of the organic ingredients in this paint. The average density of the inactivated paint is 1.173 gm/ml [25].

The substrate material used is a room temperature cure vinyl ester resin, Derakane 470-45. The average inactivated density is 1.03 gm/ml. Polyester resins have been used widely in composite products in various commercial and industrial markets for many years. Applications include boat structures, automobile panels, shower stalls, building panels, and corrosion resistant tanks and pipes. Recent pressure to obtain higher performance composites at a lower cost has motivated interest in vinyl-ester systems because they possess superior corrosion resistance and mechanical properties compared to polyesters (in some cases they approach epoxy properties) while

maintaining similar ease of processing characteristics, especially in liquid molding processes [26].

The components of a typical vinyl ester resin are illustrated in Figure 3.5. Vinyl esters are usually supplied in the form of a solution of a diacrylate oligomer in styrene, with a ratio of oligomer/styrene of 55/45 for the Derakane 470-45. The oligomer is formed from the reaction of a Di- Glycidyl Ether of Bisphenol-A (DGEBA) epoxy resin with an ethylenically-unsaturated carboxylic acid such as methacrylic acid. For this reason vinyl ester resins are also often referred to as “epoxy-vinyl ester” resins even though there are no reactive epoxide groups remaining in the oligomer. Styrene acts as a reactive diluent for the high viscosity oligomer. Thus, a vinyl ester resin is actually a copolymer of styrene and a vinyl ester oligomer [26].

The structures of polystyrene molecules are usually depicted as shown in Figure 3.6 [26], because of their enormous size. A molecule of high quality polystyrene can contain millions of monomer units.

Figure 3.5. Vinyl ester resin monomeric components [26]

Figure 3.6. Polystyrene molecular structure [26]

Polystyrene is many units of styrene linked together to form a long chain of styrene shown in Figure 3.7. Polystyrene is a polymer which is cross-linked to provide extra stability in keeping its shape. Air (or other common gas) can be blown into molten polystyrene (plastic) to create a light and foamy material called styrofoam. This air-filled product is good for packing and insulation. One separation layer used in this thesis is Ferro prepak film made of polystyrene.

Figure 3.7. One equation for styrene polymerization [26]

Organic liquids are good at dissolving the organic polystyrene molecule. Acetone and vinyl ester are organic liquids so they are good at dissolving the organic polystyrene molecule. The Imron5000 paint includes acetone and other organic components. This thesis experiment shows the paint and vinyl ester resin breaking the crosslinks between the polymers of polystyrene dissolving the Ferro prepak film. The tests on the separation layers are discussed in Chapter 4.

3.2.2 Co-Infusion Setup

Since co-infusion has never been tried with the RIDFT process, this work took an iterative empirical approach to determine an experimental setup that functions sufficiently to enable the assessment of the viability of co-infusion as a means for in-mold coating. As such, Figure 3.5 outlines the iterative approach followed. This proposes that the initial setup as show in Figure 3.2 is followed and parts manufactured. In the following sections, another two setups in accordance with different requirements are made and described. Experiments are done following the approach in Figure 3.5. First, select one of the three setups. Second, prepare the material and equipment. Third, manufacture parts. Fourth, demold and final clean. Fifth, trouble shouting and discuss to see if possible to improve the process. Sixth, do the evaluation tests of DSC, DMA, tensile tests and ESEM. If the outcome is undesirable, the improvements are implemented.

Although the schematic of the RIDFT IMC-1 shown in Figure 3.2 indicates the use of polysulfone film as the separation layer, the idea from the work of Gillio et al [3]. It was abandoned in the RIDFT experiments due to its poor formability/drapeability. It is necessary that all materials used in the RIDFT process have excellent formability/drapeability in order to meet the requirement of the second process, forming onto three-dimensional mold. Setup of RIDFT IMC-1 includes top layer and bottom layer that are separated by a separation layer. The top layer includes fiber reinforcement and surface veil. The fiber reinforcement is for coating flow. The surface veil is for better surface finish. In some cases, to try this configuration without a surface veil is necessary if the effect of the surface veil is not good. The bottom layer includes only fiber reinforcement for structural function. Several runs of RIDFT IMC-1 setup were carried out using different separation layer materials. The results are discussed in the following chapter.

Figure 3.5. RIDFTed IMC approach

A second setup RIDFT IMC-2 was designed, to improve on the processing issues resulting from RIDFT IMC-1. This is shown in Figure 3.6. In this case, the difference with RIDFT IMC-1 was the removal of the glass fibers that were formerly placed over

the separation layer and beneath the surface veil.

Figure 3.6. Schematic cross-sectional and detailed view of RIDFT IMC-2

Further improvements were made to the setup. Figure 3.7 shows the RIDFT IMC-3 setup. In this case, the surface veil in RIDFT IMC-2 was removed. The drawback with this setup was significantly reduced permeability. The placement of the silicone diaphragm directly over the separation layer meant that the coating liquid had to squeeze its way between the two. This proved impossible. A FDC (Figure 3.4) was used to solve this problem. The evolution of FDC channel design to find the best flow speed and the least dry areas left after releasing the FDC will be described in Chapter 4.

Figure 3.7. Schematic cross-sectional and detailed view of RIDFT IMC-3

Figure 3.8 shows the experimental setup. The top of the picture shows a vacuum valve from which the vacuum that powers the process is pulled. The bottom of the picture shows the inlet ports for the two fluids.

Figure 3.8. RIDFT IMC setup

3.2.3 Material Preparation

According to Dupont, the Imron 5000 is to be mixed 3:1 with ez-3461s and is usually baked at 180 °F for 30 minutes. If baking is not available, the 389s or 8989s accelerators, also from Dupont, speed the cross linking to accelerate the cure. 193S and 194S are the normal activators used in the Imron 5000, but for RIDFTed IMC application, it was thought better to use the ez-3461s since it has Teflon, and allows for easier release from the flexible mold. Acetone may be used to reduce the viscosity of the paint, but it is not the best reducer available. Dupont makes some reducers that are a blend of solvents for maximum performance. Table 3.1 gives information on the Dupont Imron 5000 system [25].

Six layers of BGF 7781 satin weave glass fibers were used for each run. The glass fabrics were cut to 10 in × 6in. Surface veils were prepared for certain runs and cut to the same dimensions as the reinforcing fabrics.

The resin was catalyzed, assuring a suitable gel time. A mixture of 2% MEKP and 0.30% CONAP was used for all experiments, gel time at room temperature was between 20-30 minutes, and at 180 ° F between 20-30 minutes. Infusion of resin was initiated within 20 seconds of the addition of the MEKP solution to the resin CONAP mixture. As for the paint DuPont Imron 5000, a mixture of 33% activation EZ-3461S and 0.78% accelerator S was employed for all experiments, gel time at room temperature was between 60-90 minutes, and at 180 ° F, between 20-30 minutes. Infusion of paint was initiated within 20 seconds of the addition of the accelerator MasterTint 8989S to the mixture of paint Imron5000 and activation EZ-3461S. Approximately total 6 - 8 minutes were allowed to elapse, as fibers were completely infused. The time included 2 minutes for paint infusion, 2 - 4 minutes for heat lamp heating process, and 2 minutes for resin infusion. This time was consistent and only deviated by +/- 1 minute. Heat lamp would raise the system temperature to 350-400°F. The next step after infusion would be 5 minutes heat lamp use. Time zero was set once infusion was completed and all test parameters were set from this time.

Table 3.1. Information on the Imron 5000 system [25]

TYPE	A high-performance, low VOC (<3.5 lbs/gal RTS), two component polyurethane enamel.			
DESCRIPTION	Imron® 5000™ is designed to deliver the premium quality and performance of standard Imron® Polyurethane Enamel at a maximum applied VOC of 3.5 lbs/gal. The Imron® 5000™ line includes factory package, mixing machine and lead-free capability.			
SUGGESTED USES	A high-gloss, extremely durable, chemical and solvent resistant air-dry enamel that is available in both solid and metallic colors. It is an extremely versatile product and is recommended for use on aircraft, commercial vehicles, trucks, trailers and other applications where superior performance and appearance is required.			
MAXIMUM SERVICE TEMPERATURE	200°F (92°C) in continuous service			
POT LIFE	a.) 2 hours at 70°F (21°C) b.) 2-4 hours at 70°F (21°C) with 2 oz MasterTint® 389S™ per activated gallon c.) 45 minutes at 70°F (21°C) with 1 oz MasterTint® 8989S™ per activated gallon			
CURE TIME AT RECOMMENDED THICKNESS – 77°F (25°C)& 50% RH		Without Accelerator	w/MasterTint® 389S™	w/MasterTint® 8989S™
	Dry to Touch	4-6 hours	1-2 hours	.5-1 hour
	Tack Free	10-12 hours	2-4 hours	1-2 hours
	Tape Free	12-24 hours	4-6 hours	2-4 hours
	Dry to Assemble	72 hours	72 hours	72 hours
	Product may be force dried 30 min at 140-160°F (60-71°C) after a flash time of 15 minutes following application of final coat.			

This means that the testing procedure was conducted in two phases. Phase one included coating and wetting of fibers through infusion. This portion of the experiment took less than 8 minutes. The second phase was when all testing parameters were conducted; the heat lamp was then used for about 5 minutes until manufactured part was completely dry. Effects of production variables such as duration of heat application and number of separation layer were investigated.

3.2.4 Equipment Preparation

The equipment used in this work is shown in Figure 1.1. A thorough understanding of the material safety data sheets (MSDS) was necessary for all chemicals used in this work. Prior to experimentation, the vacuum pump was checked for oil. The equipment was then cleaned to remove any contaminants. The two silicone sheets are wiped over with a mold release agent. Precut reinforcing fibers are then placed on the bottom silicone sheet. The separation layer, which has been precut approximately one half inch larger than the fiber on each side, is then placed over the fibers. The purpose of increasing the separation layer dimensions was to reduce the possibility of resin/coating mix along the edges. A layer of reinforcing fiber or/and surface veil was placed on top of the separation layer, depending on the particular experimental setup used.

Three flow media and three tubes were used (Figure 3.2). The flow media enable easy pull of vacuum. Flow media were used to create flow of the resin and coating. One was placed on top of the separation layer (for coating), and the second, beneath the separation layer (for resin). A third flow medium, was placed at the opposite end of the mold, and connected to the vacuum source. This enabled the infusion of the fluids. Once the top silicone layer frame was in place, the setup was complete. This whole assembly was then placed under a vacuum force. Once vacuum is applied, the frames seal. The vacuum serves three purposes: it removes the air, thus reducing the number of voids in the composite, and compacts the fibers. It also creates a pressure difference, which drives the coating and resin into the spaces between the fibers.

A number of baseline panels were manufactured and tested and the results from all specimens were compared. Two baseline panels were manufactured with a singular fluid material: one with a vinyl ester matrix and one with a coating matrix. The main purpose of these baselines was to assess the performance of the co-infused parts.

3.3 Mechanical and Microstructural Evaluation

In order to evaluate the quality of the manufactured components, it was necessary to carryout mechanical and microstructural studies. The degree of cure was determined by obtaining the glass transition temperature T_g from thermal analysis using Differential Scanning Calorimetry (DSC). DSC testing can reveal whether the curing was complete or not. DSC technique is a suitable tool because of its sensitivity and versatility in designing experimental procedures intended to make clear changes in crystalline content and distribution. Changes in crystallinity features can be followed in a semi-quantitative way and the selectivity to some crystalline entities studied. The crystallization and melting behavior of RIDFTed IMC was studied by means of DSC. The measurements were carried out by a TA Instruments Modulated DSC, under a nitrogen atmosphere, at temperatures from 20–300 °C. The calibration of the temperature and heat flow scales at the same heating rate was performed every five to ten parts. A determination of the crystalline forms of RIDFTed IMC was performed with identical conditions of the heating-cooling- heating process, at a temperature scanning speed of 10 °C/min in the temperature range 20–300 °C and isothermal for 5 minutes at 300 °C. Identification and relation of the peaks to the crystalline fractions was made on the basis of the DSC melting curves of the non-coated RIDFTed parts. For the DSC studies of RIDFTed IMC, small samples (about 5mg) were prepared. The samples were not dried before measurement. The specimens were placed in the test container using a burette and weighed (2-6 mg). The container was sealed and testing proceeded. The DSC data were analyzed and are presented in Chapter 4.

Dynamic mechanical analysis (DMA) testing can provide a comparable result to that of conventional curing. DMA is a powerful tool available for the study of the

viscoelastic properties of materials. In a dynamic mechanical test, the sample stiffness and energy loss can be measured. The sample stiffness will rely on its modulus of elasticity, and the modulus measured relies on the selection of geometry and mode of strain, which means that Young's modulus applies to tension and compression, shear modulus to torsion. Nevertheless, for materials that exhibit time dependent deformation, such as polymers, the mentioned modulus must include a time to be valid. DMA testing offers a powerful advantage by measuring the time dependent loss or storage of energy simultaneously. Samples were cut from composites in the perpendicular direction to the reinforcing fibers, using a MK-370 tile saw, to dimensions about 60mm × 13mm. The DMA data were analyzed and presented in Chapter 5.

The preliminary DMA specimens from Part 10 and 11 were cut from the location of the part shown in Figure 3.9.

Figure 3.9. Specimen cut-out sections for preliminary DMA for Part 10 and 11

Tensile tests were conducted using a MTS material testing equipment to evaluate the strengths and elastic modulus of the manufactured components. Testing was in accordance with ASTM D3039 [27]. Specimens were cut using a MK-370 tile saw to dimensions 200mm × 25.4mm × thickness (Table 5.6). Aluminum end tabs (50mm × 25.4mm × 3.2mm) were locally bonded to the composite specimens. Composite specimens were manufactured using:

- i) Non-coated: Resin 300gm + MEKP 2 % + CoNap catalyst 0.3% (%by weight)
- ii) IMC: a. Resin 150gm + MEKP 2 % + catalyst 0.3% (%by weight)
- b. Paint Imron-5000 50gm + activator ez-3461s 33% + accelerator 8989s 1%

The strain rate was 2mm per minute. Young's modulus was determined by:

$$E_x = (\Delta P / \Delta l)(l / bd) \quad l: \text{gage length of measuring instrument}$$

Ultimate axial tensile stress, $\sigma_x = P/bd$ P: maximum load, b: width, d: thickness

An Environmental Scanning Electron Microscope (ESEM) was used to evaluate the microstructure of the manufactured components. The results are presented in Chapter 5. All of the specimens from Part 13 and Parts 15~18 prepared for tensile tests and DMA were cut from the location of the part shown in Figure 3.10.

Figure 3.10 Specimens cut-out sections for tensile test and DMA

CHAPTER 4

CASE STUDIES

4.1 Case Study Details

This work-in-process, reports on successes and challenges presented, during the co-infusion of a polyurethane enamel paint (DuPont Imron 5000) and a vinyl ester resin (Derakane 470-45). Twenty-four case studies are detailed in this Chapter, following the methodologies described in Chapter 3. The first two cases were initial runs conducted during the development of the experimental methodology. Results pertaining to these cases are discussed in this chapter. The improvement of the FDC is described in Cases 10~15.

4.1.1 Case 1

Compared to traditional RIDFT process, this setup had an additional infusion inlet for paint. The paint and the resin were infused at the same time. The infusion resulted in excessive race tracking with the resin and paint flowing in divergence with the designed trajectory. Figure 4.1 shows Part 1 resulted from this experiment.

Table 4.1 shows the processing parameters of the setup. The percentages of ez-3461s and 8989s were in weight percentage of Imron 5000. The percentages of MEKP and CONAP were in weight percentage of vinyl ester resin. Tube diameter refers to inner diameter.

Table 4.1. Processing parameters for Part 1

Item	Description
Structure type	Only reinforcing fiber layer between two silicone layers
Tube diameter to liquid inlets	0.5 in
Channel	N/A
Type of reinforcing fiber	7781 glass fibers
Number of layer of reinforcing fiber	6
Separation layer material	N/A
Surface veil	N/A
Coating material	Imron5000 50.8 g + 33% ez-3461s + 1.2% 8989s
Substrate material	Vinyl ester resin 150 g + 2% MEKP and 0.30% CONAP

Figure 4.1. Part 1

4.1.2 Case 2

The tubes on coating inlet and resin inlet were changed to smaller diameter tubes compared with Part 1 setup. The reduction in the tube diameter increased the vacuum pressure at the infusion inlets. The setup was based on RIDFT IMC-1 (Figure 3.3).

The separation layer used in this trial was an impermeable vacuum-bagging film. The infusion was successful. The liquids flowed as desired, wetting the fibers above

and below the separation layer. However, after demolding, the part separated along the plane of the bagging film, due to its poor adhesive nature. Nonetheless, co-infusion was achieved. Figure 4.2 shows the results from this experiment.

Table 4.2 shows the processing parameters of the setup. The percentages of MEKP and CONAP were in weight percentage of vinyl ester resin. Tube diameter refers to inner diameter.

Table 4.2. Processing parameters for Part 2

Item	Description
Structure type	RIDFT IMC-1
Tube diameter to liquid inlets	0.25 in
Channel	N/A
Type of reinforcing fiber	7781 glass fibers
Number of layer of reinforcing fiber	6 (3 for Top layer, 3 for Bottom layer)
Separation layer material	Vacuum bagging film
Surface veil	Yes
Coating material	Vinyl ester resin 100 g + 2% MEKP and 0.30% CONAP
Substrate material	Vinyl ester resin 100 g + 2% MEKP and 0.30% CONAP

Figure 4.2. Part 2- Left: Showing whole part. Right: Showing detached layers

4.1.3 Case 3

In this case, the setup was similar to Figure 3.8 (RIDFT IMC-2). There was however, no separation layer. A bleeder layer was placed above the glass reinforcement. The paint raced ahead of the resin, reaching the vacuum port before the resin. This resulted in poor wetting of the fibers by the resin. The resulting surface finish was poor, since the bleeder layer, which ended up as part of the component, absorbed the paint. The surface was soft to the touch. Furthermore, since there was no separation layer, the paint mixed with the resin. Figure 4.3 shows the results from this experiment.

Table 4.3 shows the processing parameters of the setup. The percentages of ez-3461s and 8989s were in weight percentage of Imron 5000. The percentages of MEKP and CONAP were in weight percentage of Vinyl ester resin.

Table 4.3. Processing parameters for Part 3

Item	Description
Structure type	RIDFT IMC-2 without separation layer
Tube diameter to liquid inlets	0.25 in
Channel	N/A
Type of reinforcing fiber	7781 glass fibers
Number of layer of reinforcing fiber	6
Separation layer material	N/A
Surface veil	Bleeder AIRTECH Airweave [®] N 4
Coating material	Imron5000 50.1 g + 33% ez-3461s + 1.2% 8989s
Substrate material	Vinyl ester resin 150 g + 2% MEKP and 0.30% CONAP

Figure 4.3. Part 3

4.1.4 Case 4

In this study, the aim was to evaluate the potential for the coating material (paint) to flow over the resin during simultaneous infusion, and without using a separation layer. Figure 4.4 shows the results from this experiment. The paint would not flow on top of resin. The paint has a tendency to mix with the resin, since the density of the paint is greater than that of the resin.

Table 4.4 shows the processing parameters of the setup. The percentages of ez-3461s and 8989s were in weight percentage of Imron 5000. The percentages of MEKP and CONAP were in weight percentage of vinyl ester resin.

Table 4.4. Processing parameters for Part 4

Item	Description
Structure type	RIDFT IMC-2 without separation layer
Tube diameter to liquid inlets	0.25 in
Channel	N/A
Type of reinforcing fiber	7781 glass fibers
Number of layer of reinforcing fiber	6

Table 4.4 continued

Separation layer material	N/A
Surface veil	Yes
Coating material	Imron5000 50.3 g + 33% ez-3461s + 1.2% 8989s
Substrate material	Vinyl ester resin 150 g + 2% MEKP and 0.30% CONAP

Figure 4.4. Part 4

4.1.5 Case 5

In Case 4, the paint had the gravitational tendency to mix with the resin flowing beneath. It was thus decided to investigate the effect of having the coating material flow beneath the resin in Case 5. The infusion inlet ports were thus reversed, with the paint at the bottom and the resin on top. The paint and the resin were infused at the same time. The resulting component is shown in Figure 4.5. It can be observed that the resin did not flow over the paint. The paint flow seems to be restricted to the right side (Figure 4.5a), and the resin restricted to the left. This may have resulted from the simultaneous

infusion of paint and resin. Perhaps the result may have been different if the paint was infused prior to the resin. Furthermore, the resin and paint boundary exhibited some mixing in the middle.

Table 4.5 shows the processing parameters of the setup. The percentages of ez-3461s and 8989s were in weight percentage of Imron 5000. The percentages of MEKP and CONAP were in weight percentage of vinyl ester resin.

Table 4.5. Processing parameters for Part 5

Item	Description
Structure type	RIDFT IMC-3 without separation layer
Tube diameter to liquid inlets	0.25 in
Channel	N/A
Type of reinforcing fiber	7781 glass fibers
Number of layer of reinforcing fiber	6
Separation layer material	N/A
Surface veil	N/A
Coating material	Imron5000 49.2 g + 33% ez-3461s + 1.2% 8989s
Substrate material	Vinyl ester resin 150 g + 2% MEKP and 0.30% CONAP

Figure 4.5a. Top side view of Part 5

Figure 4.5b. Bottom side view of Part 5

4.1.6 Case 6

This study was conducted to evaluate the importance of a separation layer to the IMC setup. RIDFT IMC-1 setup was used (Figure 3.3). No surface veil was used. The paint and the resin were infused at the same time. Paper was used as separation layer. As with Case 5, the resin and the paint were restricted to their flow regions. This ‘zoning’ trend, infers it may be better to infuse the fluids systematically, infusing the more viscous fluid first. Furthermore, both liquids permeated through paper and mixed. It can thus be inferred that the separation layer needed should be impermeable. The impermeable layer should also be able to adhere to both liquids after infusion. Figure 4.6 shows the results from this experiment.

Table 4.6 shows the processing parameters of the setup. The percentages of ez-3461s and 8989s were in weight percentage of Imron 5000. The percentages of MEKP and CONAP were in weight percentage of vinyl ester resin.

Table 4.6. Processing parameters for Part 6

Item	Description
Structure type	RIDFT IMC-1 without surface veil
Tube diameter to liquid inlets	0.25 in
Channel	N/A
Type of reinforcing fiber	7781 glass fibers
Number of layer of reinforcing fiber	6 (3 for Top layer, 3 for Bottom layer)
Separation layer material	Copy paper
Surface veil	N/A
Coating material	Imron5000 50.8 g + 33% ez-3461s + 1.2% 8989s
Substrate material	Vinyl ester resin 150 g + 2% MEKP and 0.30% CONAP

Figure 4.6a. Top side view of Part 6

Figure 4.6b. Bottom side view of Part 6

4.1.7 Case 7

A new separation layer, FERRO#MC08 prepak film, was introduced based on the findings of the previous experiments. This is a polystyrene based product, which dissolves in the organic liquids. The resin which contains styrene is an organic liquid. The solubility in the resin means that the issue of formability, which would have been presented by the use of a separation layer in the RIDFT process, became moot. The aim was to infuse the paint and resin simultaneously to observe the reaction. The setup was the RIDFT IMC-2 illustrated in Figure 3.7. As with previous experiments, the paint and the resin were infused at the same time, resulting in observed 'zoning'. Furthermore, the resin was found being able to penetrate the separation layer in 3 seconds, and the paint was found that although the polyurethane enamel does not contain styrene, it was still able to permeate the FERRO#MC08 prepak film after 60 seconds and permitted the mixing of the fluids observed (see Figures 4.7 c,d,e and f). Figures 4.7 a and b show the results from this experiment. The paint was investigated the reason to penetrate the polystyrene separation layer. The paint was found to include at least one organic

constituent which is acetone.

Table 4.7 shows the processing parameters of the setup. The percentages of ez-3461s and 8989s were in weight percentage of Imron 5000. The percentages of MEKP and CONAP were in weight percentage of vinyl ester resin.

Table 4.7. Processing parameters for Part 7

Item	Description
Structure type	RIDFT IMC-2
Tube diameter to liquid inlets	0.25 in
Channel	N/A
Type of reinforcing fiber	7781 glass fibers
Number of layer of reinforcing fiber	6
Separation layer material	FERRO#MC08 prepak film
Surface veil	Yes
Coating material	Imron5000 50.8 g + 33% ez-3461s + 1.2% 8989s
Substrate material	Vinyl ester resin 150 g + 2% MEKP and 0.30% CONAP

Figure 4.7a. Top side view of Part 7

Figure 4.7b. Bottom side view of Part 7

Figure 4.7c. 1 second after Vinyl ester contact with FERRO#MC08 prepak film

Figure 4.7d. 3 seconds after Vinyl ester contact with FERRO#MC08 prepak film

Figure 4.7e. 1 second after Imron5000 contact with FERRO#MC08 prepak film

Figure 4.7f. 60 seconds after Imron5000 contact with FERRO#MC08 prepak film

4.1.8 Case 8

The RIDFT IMC-1 setup was followed. However, unlike previous cases, it was decided to first infuse the paint since the paint dissolves the separation layer more slowly. This would prevent the ‘zoning’ previously observed. No surface veil was used. Three glass fiber layers were placed on top of the separation layer and five beneath the separation layer. The paint was infused to about 90% of component length when resin

infusion was initiated. This setup provided the best result compared to previous experiments. However, it was determined that 90% paint lead fill length was excessive since the resin did not have time to fully infuse before the paint got to the maximum fill length. Therefore, the Part 8 surface shows several bumps which is because the air coming in for insufficient vacuum. The paint lead fill length is thus reduced to 75% in future cases. Furthermore, it was proposed to increase the width of the flow media at final section, in order to increase the surface area for absorbing excess fluid in the case were one fluid reached the end gate before the other. Figure 4.8 shows the results from this experiment. The paint seeping through was observed.

Table 4.8 shows the processing parameters of the setup. The percentages of ez-3461s and 8989s were in weight percentage of Imron 5000. The percentages of MEKP and CONAP were in weight percentage of vinyl ester resin.

Table 4.8. Processing parameters for Part 8

Item	Description
Structure type	RIDFT IMC-1
Tube diameter to liquid inlets	0.25 in
Channel	Yes, traditional
Type of reinforcing fiber	7781 glass fibers
Number of layer of reinforcing fiber	8 (3 for Top layer, 5 for Bottom layer)
Separation layer material	FERRO#MC08 prepak film
Surface veil	N/A
Coating material	Imron5000 50 g + 33% ez-3461s + 1.2% 8989s
Substrate material	Vinyl ester resin 150 g + 2% MEKP and 0.30% CONAP

Figure 4.8a. Top side view of Part 8

Figure 4.8b. Bottom side view of Part 8

4.1.9 Case 9

In this case, the setup was the RIDFT IMC-2 shown in Figure 3.7. The paint was first infused and then the resin was infused. The co-infusion process was successful with the use of the traditional FDC as seen in Figure 3.5. The FDC was used for both the paint and resin infusion steps. The use of FDC was found to accelerate the flow speed. Figure 4.9 shows the results from this experiment.

Table 4.9, shows the processing parameters of the setup. The percentage of ez-3461s and 8989s were in weight percentage of Imron 5000. The percentage of MEKP and CONAP were in weight percentage of Vinyl ester resin.

Table 4.9. Processing parameters for Part 9

Item	Description
Structure type	RIDFT IMC-2
Tube diameter to liquid inlets	0.25 in
Channel	Traditional
Type of reinforcing fiber	7781 glass fibers
Number of layer of reinforcing fiber	6
Separation layer material	FERRO#MC08 prepak film

Table 4.9 continued

Surface veil	Yes
Coating material	Imron5000 50 g + 33% ez-3461s + 1.2% 8989s
Substrate material	Vinyl ester resin 150 g + 2% MEKP and 0.30% CONAP

Figure 4.9a. Top side view of Part 9

Figure 4.9b. Bottom side view of Part 9

Figure 4.9a shows the top side view of Part 9, revealing the coarse surface. The RIDFT IMC-2 setup was thus not suggested to use because bad surface finish. Figure 4.9b shows the bottom side view of Part 9, revealing the paint seeping through the separation layer, FERRO#MC08 prepak film.

4.1.10 Case 10

This experiment followed the RIDFT IMC-3 set up shown in Figure 3.8. As such, there was no surface veil. Resin infusion was initiated one second after paint infusion was initiated. The FDC was used. Dry areas, which stemmed from the use of

the traditional FDC, were noticeable. Some ‘zoning’ was also noticeable; indicating that the infusion differential time was too short. Figure 4.10 shows the results from this experiment.

Table 4.10 shows the processing parameters of the setup. The percentages of ez-3461s and 8989s were in weight percentage of Imron 5000. The percentages of MEKP and CONAP were in weight percentage of Vinyl ester resin.

Table 4.10. Processing parameters for Part 10

Item	Description
Structure type	RIDFT IMC- 3
Tube diameter to liquid inlets	0.25 in
Channel	Traditional
Type of reinforcing fiber	7781 glass fibers
Number of layer of reinforcing fiber	6
Separation layer material	FERRO#MC08 prepak film
Surface veil	N/A
Coating material	Imron5000 50 g + 33% ez-3461s + 1.2% 8989s
Substrate material	Vinyl ester resin 150 g + 2% MEKP and 0.30% CONAP

Figure 4.10a. Top side view of Part 10

Figure 4.10b. Bottom side view of Part 10

Figure 4.10c shows the traditional FDC and roller used. The traditional FDC was used to accelerate the fluid flow in between the two silicone-layer molds, corresponding to the theory in Figure 3.3. The roller was used to reduce the dry areas after releasing the FDC.

Figure 4.10c. Traditional FDC and roller were used

Figure 4.10d. Dry areas following use of traditional FDC

4.1.11 Case 11

This setup also followed RIDFT IMC-3. Resin infusion was initiated two minutes after paint infusion began. The traditional DFC was used. Heat was applied for two minutes to the surface of the upper silicone membrane to accelerate the drying of the paint in order to reduce the permeation of the paint through the separation layer. Figure 4.11 shows results from this experiment.

Table 4.11 shows the processing parameters of the setup. The percentages of ez-3461s and 8989s were in weight percentage of Imron 5000. The percentages of MEKP and CONAP were in weight percentage of vinyl ester resin.

Table 4.11. Processing parameters for Part 11

Item	Description
Structure type	RIDFT IMC-3
Tube diameter to liquid inlets	0.25 in
Channel	Traditional
Type of reinforcing fiber	7781 glass fibers
Number of layer of reinforcing fiber	6
Separation layer material	FERRO#MC08 prepak film
Surface veil	N/A
Coating material	Imron5000 50 g + 33% ez-3461s + 1.2% 8989s
Substrate material	Vinyl ester resin 150 g + 2% MEKP and 0.30% CONAP

Figure 4.11a. Top side view of Part 11

Figure 4.11b. Bottom side view of Part 11

Figure 4.11a shows the top side view of Part 11, revealing the glossy surface. Figure 4.11b shows the bottom side view of part 11, revealing the paint seeping through the separation layer, FERRO#MC08 prepak film. This was despite the attempt at drying the paint. The left side of the Figure 4.11b was more transparent, which also showed the uneven mixing of paint and resin. The surface finish was shinier and glossier than the one with use of surface veil by visual inspection.

4.1.12 Case 12

This setup also followed RIDFT IMC-3. Two layers of separation layer were used. The aim was to determine if the thicker separation layer would affect the paint to prevent seeping it. The paint and resin inlet ports were overlapping and placed in the center. A 2" x 4" additional impermeable vacuum bagging film was placed in between the two inlet ports to enhance the resistance to the paint seeping through. Resin infusion was initiated two minutes after paint infusion began. During these two minutes, heat was simultaneously applied to the surface of the upper silicone membrane to accelerate the drying of the paint. This was also to reduce the permeation of the paint through the separation layer. The traditional FDC was used at each infusion steps and released while heat was applying. Figure 4.12 shows the results from this experiment.

Table 4.12 shows the processing parameters of the setup. The percentages of ez-3461s and 8989s were in weight percentage of Imron 5000. The percentages of MEKP and CONAP were in weight percentage of vinyl ester resin.

Table 4.12. Processing parameters for Part 12

Item	Description
Structure type	RIDFT IMC-3
Tube diameter to liquid inlets	0.25 in
Channel	Traditional
Type of reinforcing fiber	7781 glass fibers
Number of layer of reinforcing fiber	6
Separation layer material	FERRO#MC08 prepak film
Surface veil	N/A

Table 4.12 continued

Coating material	Imron5000 50 g + 33% ez-3461s + 1.2% 8989s
Substrate material	Vinyl ester resin 150 g + 2% MEKP and 0.30% CONAP

Figure 4.12a. Top side view of Part 12 Figure 4.12b. Bottom side view of Part 12

Figure 4.12a shows the top side view of part 12, revealing the glossy surface. Figure 4.12b shows the bottom side view of part 12, revealing the paint seeping through the separation layer, two layers of FERRO#MC08 prepak film. This was despite the attempt at drying the paint and adding an additional layer of separation layer. The left side of the Figure 4.12b was not more transparent which also showed the more even mixing of paint and resin than part 11 because the concentration of paint and resin inlet ports.

4.1.13 Case 13

This setup also followed RIDFT IMC-3. A different FDC was developed, named non-channeled FDC, which is shown in figure 4.13. The aim was to pull up a large area from upper silicone membrane and avoid dry areas after releasing FDC. The dry area example was previously shown in Figure 4.10d. However, the experiment showed the infusion was not fluent and was too slow, which took more than 10 minutes for infusion and was not able to finish. The non-foamed FDC although pulled up a large area for liquid flow, the pressure was not enough to pull liquid flow without suitable directional flow channel. The experiment was a failure but the chance was used to produce a whole paint composite (paint + glass fiber, without resin).

Table 4.13 shows the processing parameters of the setup. The percentages of ez-3461s and 8989s were in weight percentage of Imron 5000. The percentages of MEKP and CONAP were in weight percentage of vinyl ester resin.

Table 4.13. Processing parameters for Case 13

Item	Description
Structure type	RIDFT IMC-3
Tube diameter to liquid inlets	0.25 in
Channel	Non-channeled FDC
Type of reinforcing fiber	7781 glass fibers
Number of layer of reinforcing fiber	6
Separation layer material	FERRO#MC08 prepak film
Surface veil	N/A
Coating material	Imron5000 50 g + 33% ez-3461s + 1.2% 8989s
Substrate material	Vinyl ester resin 150 g + 2% MEKP and 0.30% CONAP

Figure 4.13. Non-channeled FDC

4.1.14 Case 14

This setup also followed RIDFT IMC-3. A different FDC was developed, named slim-straight-strips FDC, which is shown in Figure 4.14a. The aim was to reduce dry areas after releasing FDC. The dry areas after infusion can also be seen in Figure 4.14a. There were also transverse radial cut gaps in each strip (Figure 4.14b). The aim was to correspond to the flow tendency of fluids in a closed medium. The experiment showed the infusion was better than Case 13 but worse than the one with use of traditional FDC. The flow velocity was also too slow, which took more than 5 minutes for infusion and was not able to complete the infusion. The experiment was a failure since no part was produced from this experiment.

Table 4.14 shows the processing parameters of the setup. The percentages of ez-3461s and 8989s were in weight percentage of Imron 5000. The percentages of MEKP and CONAP were in weight percentage of vinyl ester resin.

Table 4.14. Processing parameters for Case 14

Item	Description
Structure type	RIDFT IMC-3
Tube diameter to liquid inlets	0.25 in

Table 4.14 continued

Channel	Narrow-straight-strips FDC
Type of reinforcing fiber	7781 glass fibers
Number of layer of reinforcing fiber	6
Separation layer material	FERRO#MC08 prepak film
Surface veil	N/A
Coating material	Imron5000 50 g + 33% ez-3461s + 1.2% 8989s
Substrate material	Vinyl ester resin 150 g + 2% MEKP and 0.30% CONAP

Figure 4.14a. With use of narrow-straight-strips FDC, smaller dry areas were as expected shown.

Figure 4.14b. Narrow-straight-strips FDC also combine the idea of transverse radial flow, made with radial gaps cut in each strip.

4.1.15 Case 15

This setup also followed RIDFT IMC-3. A different FDC was developed, named slim-radial-strips FDC, shown in Figure 4.15c. The goal was to reduce dry areas after releasing FDC. Transverse radial cut gaps were added in each strip (Figure 4.15d). The aim was to correspond to the flow tendency of fluids in a closed medium. The experiment showed the infusion velocity was the fastest among all types of FDCs, taking less than two minutes for complete paint infusion. There were still dry areas after releasing the channel after paint infusion but since the strip had been narrowed, the paint could more easily cover the dry areas within three minutes by visual inspection. Heat was applied after paint infusion for 3 minutes for drying paint layer. Next, resin was then infused by slim-radial-strips FDC. Figures 4.15a and b show the results from this experiment. Table 4.15 shows the processing parameters of the setup. The percentages of ez-3461s and 8989s were in weight percentage of Imron 5000. The percentages of MEKP and CONAP were in weight percentage of vinyl ester resin.

Table 4.15. Processing parameters for Part 15

Item	Description
Structure type	RIDFT IMC-3
Tube diameter to liquid inlets	0.25 in
Channel	Slim-radial-strips FDC
Type of reinforcing fiber	7781 glass fibers
Number of layer of reinforcing fiber	6
Separation layer material	FERRO#MC08 prepak film
Surface veil	N/A
Coating material	Imron5000 50 g + 33% ez-3461s + 1.2% 8989s
Substrate material	Vinyl ester resin 150 g + 2% MEKP and 0.30% CONAP

Figure 4.15a shows the top side view of Part 15, revealing the glossy surface. Figure 4.15b shows the bottom side view of Part 15, revealing the paint seeping through the separation layer of two layers of FERRO#MC08 prepak film. This was despite the

attempt at drying the paint. Figure 4.15e shows the infusion situation at 100 seconds after paint infusion. Figure 4.15f shows heat was applied after paint infusion.

Figure 4.15a. Top side view of Part 15

Figure 4.15b. Bottom side view of Part 15

Figure 4.15c. Use of slim-radial-strips FDC

Figure 4.15d. A rough drawing of slim-radial-strips FDC. This type of FDC also combines the idea of transverse radial flow, made with radial gaps cut in each strip.

Figure 4.15e. 100 seconds after paint infusion

Figure 4.15f. Infrared heat lamp was applied after paint infusion

4.1.16 Case 16

This setup also followed RIDFT IMC-3. Figures 4.16 a, b show the results from this experiment. Slim-radial-strips FDC was still used.

Table 4.16 shows the processing parameters of the setup. The percentages of ez-3461s and 8989s were in weight percentage of Imron 5000. The percentages of MEKP and CONAP were in weight percentage of vinyl ester resin.

Table 4.16. Processing parameters for Part 16

Item	Description
Structure type	RIDFT IMC-3
Tube diameter to liquid inlets	0.25 in
Channel	Slim-radial-strips FDC
Type of reinforcing fiber	7781 glass fibers
Number of layer of reinforcing fiber	6

Table 4.16 continued

Separation layer material	FERRO#MC08 prepak film
Surface veil	N/A
Coating material	Imron5000 50 g + 33% ez-3461s + 1.2% 8989s
Substrate material	Vinyl ester resin 150 g + 2% MEKP and 0.30% CONAP

Figure 4.16a shows the top side view of Part 16, revealing the glossy surface with some uncured paint on the top of the picture due to too early demolding. No bubbles were produced on the surface of this part because the temperature was controlled to under 92°C. Heat was applied during paint and resin infusion processes for 10 minutes at 90°C. However, the attempt to dry the paint did not prevent paint from seeping through the separation layer. Figure 4.16b shows the bottom side view of Part 16. Figure 4.16c shows the bottoms side view during paint infusion, revealing the paint seeping through the separation layer of two layers of FERRO#MC08 prepak film.

Figure 4.16a. Top side view of Part 16

Figure 4.16b. Bottom side view of Part 16

Figure 4.16c. Bottom side view during paint infusion process

4.1.17 Case 17

This setup also followed RIDFT IMC-3. Figures 4.17a and b show the results from this experiment. The Slim-radial-strips FDC was used.

Table 4.17 shows the processing parameters of the setup. The percentages of ez-3461s and 8989s were in weight percentage of Imron 5000. The percentages of MEKP and CONAP were in weight percentage of vinyl ester resin.

Table 4.17. Processing parameters for Part 17

Item	Description
Structure type	RIDFT IMC-3
Tube diameter to liquid inlets	0.25 in
Channel	Slim-radial-strips FDC
Type of reinforcing fiber	7781 glass fibers
Number of layer of reinforcing fiber	6
Separation layer material	FERRO#MC08 prepak film
Surface veil	N/A
Coating material	Imron5000 50 g + 33% ez-3461s + 1.2% 8989s
Substrate material	Vinyl ester resin 150 g + 2% MEKP and 0.30% CONAP

Figure 4.17a shows the top side view of Part 17, revealing the glossy surface. Figure 4.17b shows the bottom side view of Part 17, revealing the paint seeping through the separation layer, one layer of FERRO#MC08 prepak film. Heat was applied during paint and resin infusion processes for 5 minutes at 90°C. This was attempted to dry the paint.

Figure 4.17a. Top side view of Part 17

Figure 4.17b. Bottom side view of Part 17

4.1.18 Case 18

This setup also followed RIDFT IMC-3. Slim-radial-strips FDC was used. Figures 4.18 a, b show the results from this experiment.

Table 4.18 shows the processing parameters of the setup. The percentages of ez-3461s and 8989s were in weight percentage of Imron 5000. The percentages of MEKP and CONAP were in weight percentage of vinyl ester resin.

Table 4.18. Processing parameters for Part 18

Item	Description
Structure type	RIDFT IMC-3
Tube diameter to liquid inlets	0.25 in
Channel	Slim-radial-strips FDC
Type of reinforcing fiber	7781 glass fibers
Number of layer of reinforcing fiber	6
Separation layer material	FERRO#MC08 prepak film
Surface veil	N/A
Coating material	Imron5000 50 g + 33% ez-3461s + 1.2% 8989s
Substrate material	Vinyl ester resin 150 g + 2% MEKP and 0.30% CONAP

Figure 4.18a shows the top side view of Part 18, revealing the uneven but glossy surface. FDC effect might decrease the surface finish quality. Figure 4.18b shows the bottom side view of Part 18, revealing the paint seeping through the separation layer of one layer of FERRO#MC08 prepak film. Heat was applied during paint and resin infusion processes for 10 minutes at 90°C.

Figure 4.18a. Top side view of Part 18

Figure 4.18b. Bottom side view of Part 18

4.1.19 Case 19

This setup followed RIDFT IMC-1 without using surface veil. One layer of glass fiber was used on top layer and three layers of glass fiber were used in bottom layer. The separation layer used was a release film. The coating material chosen for infusing in top layer was vinyl ester resin with one-gram red-color pigment. The infusion was applied to the top layer first. The aim was to demonstrate co-infusion again for more complete production than part 2. Slim-radial-strips FDC was used. The co-infusion is successful coming with an observation. The top layer infusion is faster than the bottom layer. The reason might be the difference in number of layers, and the reduced of FDC effect (described in section 3.2) in bottom layer. Figures 4.19 a, b show the results from this experiment.

Table 4.19 shows the processing parameters of the setup. The percentages of MEKP and CONAP were in weight percentage of vinyl ester resin.

Table 4.19. Processing parameters for Part 19

Item	Description
Structure type	RIDFT IMC-1 without surface veil
Tube diameter to liquid inlets	0.25 in
Channel	Slim-radial-strips FDC
Type of reinforcing fiber	7781 glass fibers
Number of layer of reinforcing fiber	Top 1, bottom 3
Separation layer material	Release film
Surface veil	N/A
Coating material	Vinyl ester resin 50 g + 2% MEKP and 0.30% CONAP + Imron5000 1g
Substrate material	Vinyl ester resin 150 g + 2% MEKP and 0.30% CONAP

Figure 4.19a shows the top side view of Part 19, revealing the obvious red color due to added pigment to top layer resin. Figure 4.19b shows the bottom side view of Part 19, revealing that the top layer resin did not seep through the separation layer (one layer of release film). This was a successful co-infusion experiment made with the RIDFT process. However, the fact remains that the release film is not an appropriate

separation layer since it does not bond to the resin or the paint. The top and bottom composites were separated easily from the separation layer.

Figure 4.19a. Top side view of Part 19

Figure 4.19b. Bottom side view of Part 19

4.1.20 Case 20

This setup followed RIDFT IMC-1 without using a surface veil. One layer of glass fiber was used on the top layer and three layers of glass fiber were used in bottom layer. The separation layer used was Avloy base web-film. The coating material chosen for infusing in top layer was Imron 5000 paint. The top layer was infused first. Slim-radial-strips FDC was used. The aim was to test a new separation layer, Avloy base web-film. The infusion was stopped while the paint went to the vacuum source. The top layer infusion was still faster than the bottom layer, which might be due to the difference of number of layers and the reduced effectiveness of the FDC (described in section 3.2) in bottom layer. Some paint from the top layer entered into bottom layer from the edges. After discussion, there are three items to be modified in IMC process listed in Table 4.20a. Figures 4.20 a, b show the results from this experiment.

Table 4.20a. Three modifications in IMC process

Three modifications in IMC process		The reasons to make the modifications
1	Cut a V-type impermeable layer such as release film placing at source of both infusions (Figure 4.20d, e and f)	According to Darcy's law (equation 2.8), the farther from the vacuum source the stronger the pressure gradient. Therefore, the pressure at source of both infusions is the largest among a part. The largest pressure then most easily brings the force to retrace the paint. To cut a V-type impermeable layer such as release film placing at source of both infusions is then easier to seal top and bottom frames better.
2	Place an impermeable layer in between two tail flow media (Figure 4.20e)	The two flow media are connected to the top layer and bottom layer separately. The reason to use two flow media instead of one is that once the separation layer is impermeable the air sucking force cannot reach both layers if there is only one tail flow media (Figure 4.20e). To separate the excess top/bottom fluid flowing into top/bottom tail flow media, this modification was made. The reason to separate is any one excess amount of top/bottom layer flow can flow into the other and lead to poor vacuum-sucking force at this invaded layer. Figure 4.19b shows flow without this modification, and Figure 4.20b shows flow with this modification.
3	Infuse bottom layer first	The FDC effect was found more obvious in the top layer than bottom layer because the top silicone layer has a greater resistance to the vacuum force from FDC compared to the separation layer and the bottom silicone layer. Infusing the top layer first would lead to reducing the vacuum force. To overcome slow flow in the bottom layer, infusing the bottom layer first is preferable if the separation layer is non-dissolvable to bottom layer fluid.

Table 4.20 shows the processing parameters of the setup. The percentages of ez-3461s and 8989s were in weight percentage of Imron 5000. The percentages of MEKP and CONAP were in weight percentage of vinyl ester resin.

Table 4.20b. Processing parameters for Part 20

Item	Description
Structure type	RIDFT IMC-1 without surface veil
Tube diameter to liquid inlets	0.25 in
Channel	Slim-radial-strips FDC
Type of reinforcing fiber	7781 glass fibers
Number of layer of reinforcing fiber	Top 1, bottom 3
Separation layer material	Avloy base web-film
Surface veil	N/A
Coating material	Imron5000 50 g + 33% ez-3461s + 1.2% 8989s
Substrate material	Vinyl ester resin 150 g + 2% MEKP and 0.30% CONAP

Figure 4.20a shows the top side view of Part 20, revealing a wrinkled surface due to the vacuum source being removed. Figure 4.20b shows the bottom side view of Part 20, revealing that the top layer paint did not seep though or retrace the separation layer of one layer of Avloy base web-film. The bottom flow did not reach the end by the time vacuum source was removed. This fact also explains the reason of flowing bottom layer first. Although the Avloy base web-film can prevent the paint and resin from seeping through, the separation layer could not bond the paint and resin. The top and bottom composites are easy to take off from the separation layer. Figures 4.20c and d show the V-cut effect. Figure 4.20c shows the impermeable layer without the V-cut placed at fluid infusion source, revealing the much resin/paint race tracking. Figure 4.20d shows the impermeable layer with the V-cut placed at fluid infusion source, revealing the less resin/paint retracing. Figure 4.20e shows the setup after the first two modifications in Table 4.20a.

Figure 4.20a. Top side view of Part 20

Figure 4.20b. Bottom side view of Part 20

Figure 4.20c, d. Impermeable layer without (left), with (right) V-cut located at source

Figure 4.20e. Part 21 setup shows on left hand side of the picture an impermeable layer placed in between two tail flow media. On right hand side of the picture a V-cut impermeable layer was placed at the source of infusion ports.

4.1.21 Case 21

This setup followed RIDFT IMC-1 without using surface veil. One layer of glass fiber was used on the top layer and three layers of glass fiber were used in the bottom layer. The separation layer used was prepreg film. The top and bottom infusions were simultaneous. The aim was to test a new separation layer of prepreg film. Slim-radial-strips FDC was used. The co-infusion failed because paint and resin could not be separated by the prepreg film. Figures 4.21 a and b show the results from this experiment.

Table 4.21 shows the processing parameters of the setup. The percentages of ez-3461s and 8989s were in weight percentage of Imron 5000. The percentages of MEKP and CONAP were in weight percentage of vinyl ester resin.

Table 4.21. Processing parameters for Part 21

Item	Description
Structure type	RIDFT IMC-1 without surface veil
Tube diameter to liquid inlets	0.25 in
Channel	Slim-radial-strips FDC
Type of reinforcing fiber	7781 glass fibers
Number of layer of reinforcing fiber	Top 1, bottom 3
Separation layer material	Prepreg film
Surface veil	N/A
Coating material	Imron5000 50 g + 33% ez-3461s + 1.2% 8989s
Substrate material	Vinyl ester resin 150 g + 2% MEKP and 0.30% CONAP

Figure 4.21a shows the top side view of Part 21, indicating that the paint penetrated through the separation layer. Figure 4.21b shows the bottom side view of Part 21, revealing the paint not only penetrated the separation layer but sank to the very bottom level. This may have resulted since the density of paint (1.173 gm/ml) which is larger than that of resin (1.030 gm/ml).

Figure 4.21a. Top side view of Part 21

Figure 4.21b. Bottom side view of Part 21

4.1.22 Case 22

This setup followed RIDFT IMC-3 without surface veil. The separation layer used was release film. The top and bottom were infused simultaneously. The goal was to test an impermeable layer under structure RIDFT IMC-3. Slim-radial-strips FDC was still used. The infusion process was not as smooth as co-infusion under structure RIDFT IMC-3, because paint infusion was not easy without a glass fiber as flow medium. Moreover, after demolding, the paint was found to adhere on the top silicone layer instead of on the separation layer since the release film is easier to detach than silicone layer. This impresses the importance of using a separation layer with good bonding properties. Figures 4.22 a, b show the results from this experiment.

Table 4.22 shows the processing parameters of the setup. The percentages of ez-3461s and 8989s were in weight percentage of Imron 5000. The percentages of MEKP and CONAP were in weight percentage of vinyl ester resin.

Table 4.22. Processing parameters for Part 22

Item	Description
Structure type	RIDFT IMC-3
Tube diameter to liquid inlets	0.25 in
Channel	Slim-radial-strips FDC
Type of reinforcing fiber	7781 glass fibers
Number of layer of reinforcing fiber	6
Separation layer material	Release film
Surface veil	N/A
Coating material	Imron5000 50 g + 33% ez-3461s + 1.2% 8989s
Substrate material	Vinyl ester resin 150 g + 2% MEKP and 0.30% CONAP

Figure 4.22a shows the top side view of Part 22, revealing the paint adhered on top silicone layer instead of on separation layer because the release film was easier to detach than silicone layer. Figure 4.22b shows the bottom side view of Part 22, revealing the paint did not penetrate the separation layer.

Figure 4.22a. Top side view of Part 22 Figure 4.22b. Bottom side view of Part 22

4.1.23 Case 23

This setup followed RIDFT IMC-I without a surface veil. The separation layer used was 7781 glass fibers impregnated with SC-15 epoxy resin, and cured at 142°F for 40 minutes. The aim was to test the new separation layer under structure RIDFT IMC-I. The bottom layer was infused first. The infusion was stopped because the resin penetrated the separation layer, demonstrating the failure of this separation layer. Figures 4.23 a, b show the results from this experiment.

To further describe the details in testing this separation layer, few preliminary tests were made on this SC-15 resin (Table 4.23a). The toughened-epoxy (SC-15) consisted of two components: Part A – Base resin and Part B – Catalyst. The ratio of base resin to catalyst was 100/30. The preliminary tests on SC-15 resin found that curing at 142°F for 35 minutes made it semi-solid with good formability, but paint/resin penetrable. Curing at 142°F for 40 minutes made it semi-solid with good formability but paint/resin impenetrable, and at 142°F curing for 45 minutes it became a semi-solid but with poor formability and paint/resin impenetrable. Bonding was no problem for all samples after curing. The formability was defined by “Yes” for no wrinkle after wrapping a semi-ball with diameter of 5 inches, and “No” for showing wrinkles under same ball wrapping test.

In comparing the different results of the preliminary tests (Resin/Paint impenetrable) and IMC test (Resin/Paint penetrable) of SC-15 curing for 40 minutes at 142°F, it was assumed the difference came from the pressure condition. The preliminary test was under atmosphere, and IMC was under vacuum pressure. The vacuum pressure for RIDFT process should not be changed because it will affect the infusion process. Therefore, this separation layer was found unsuitable.

Table 4.23b shows the processing parameters of the setup. The percentages of ez-3461s and 8989s were in weight percentage of Imron 5000. The percentages of MEKP and CONAP were in weight percentage of vinyl ester resin.

Table 4.23a. Tested parameters of 142°F cured SC-15 at atmosphere

Curing time	Condition	Formability	Resin/Paint Penetrability	Bond Ability to Paint/Resin
10 min	Liquid	Yes	Yes	Yes
30 min.	Semi-solid	Yes	Yes	Yes
35 min.	Semi-solid	Yes	Yes	Yes
40 min.	Semi-solid	Yes	No	Yes
45 min.	Semi-solid	No	No	Yes
60 min.	Semi-solid	No	No	Yes
120 min	Solid	No	No	Yes

Table 4.23b. Processing parameters for Part 23

Item	Description
Structure type	RIDFT IMC-1 without surface veil
Tube diameter to liquid inlets	0.25 in
Channel	Slim-radial-strips FDC
Type of reinforcing fiber	7781 glass fibers
Number of layer of reinforcing fiber	Top 1 Bottom 3
Separation layer material	7781 glass fibers impregnated with SC-15 epoxy resin, at 142°C cured for 40 minutes
Surface veil	N/A
Coating material	Imron5000 50 g + 33% ez-3461s + 1.2% 8989s
Substrate material	Vinyl ester resin 150 g + 2% MEKP and 0.30% CONAP

Figure 4.23a shows the tested separation layer (142°F cured SC-15 for 40 min.), revealing the flexibility and formability which might meet the requirement of RIDFT process. Figure 4.23b shows the process view of part 23, revealing the resin penetrated the separation layer. Figure 4.23c, d shows SC-15 cured at 142°F for 60 min., revealing the paint and resin did not penetrate and could have good bonding with the cured SC-15 layer but the condition of this layer is already close to solid without formability.

Figure 4.23a. Separation layer for part 23

Figure 4.23b. Process view of Part 23

Figure 4.23c(left), d(right). SC-15 cured at 142°F for 60 min (top view and bottom view)

4.1.24 Case 24

The aim of this case was only to test the feasibility of the water-soluble resin, polyvinyl alcohol, as a separation layer. The preliminary test shows the success of impenetrability but failed bond ability.

Figure 4.24a shows the tested separation layer, cured polyvinyl alcohol. Figure 4.24b shows few drops of both Imron5000 paint and Vinyl ester resin to try the penetrability and the bond ability. Figure 4.24c shows the bottom view of the separation layer after being dropped paint/resin, demonstrating the paint/resin would not seep

through the layer. Figure 4.24d shows poor bond ability for the cured resin, although the cured paint can bond without apparent gaps.

Figure 4.24a. Separation layer for Case 24

Figure 4.24b. Resin/Paint drop on Case 24

Figure 4.24c. Bottom view of Case 24

Figure 4.24d. Resin non-attachable

4.2 Factor Discussion

Twenty-four case studies were detailed in this chapter, following the methodologies described in Chapter 3. Several factors affected the IMC experiments listed in this section. First, the separation layer is one of the most important factors deciding of the part is successful or not. Second, the structure type also affects the fluency of the process and surface finish. Third, the FDC would change the flow velocity and distribution of infusion. Fourth, temperature is also a factor to influence curing. Fifth, the tube diameter can reduce or increase system infusion pressure. All of these factors are detailed in this section.

4.2.1 Separation Layer Discussion

The separation layer to meet IMC requirements should have features of impenetrability and bond ability to the infused liquids. The RIDFT process is a two-step process, infusion and forming; therefore, formability is a requirement in selecting an appropriate separation layer. Polysulfone film was used as the separation layer in the work of Gillio *et al* [3]. It was however unsuitable for the RIDFT process because of its poor formability. Several specimens were tested and listed below.

Table 4.24. Parameters for all separation layers

P/N	Description	Formability	Impermeability	Bond ability
Reference	Polysulfone film	No	Yes	Yes
Part 2	Vacuum bagging film	Yes	Yes	No
Part 6	Copy paper	Yes	No	Yes
Part 7~18	FERRO#MC08 prepak film	Yes	Yes/No	Yes
Part 19, 22	Release film	Yes	Yes	No
Part 20	Avloy base web-film	Yes	Yes	No
Part 21	Prepreg composite	Yes	No	Yes

Table 4.24 continued

Part 23	SC-15 impregnated fibers	Yes/No	Yes/No	Yes
Part 24	Water soluble resin, polyvinyl alcohol	Yes	Yes	Yes/No

The condition of impermeability for FERRO#MC08 prepak film and SC-15 impregnated fibers and condition of bond ability for water-soluble resin, polyvinyl alcohol are not certain. FERRO#MC08 prepak film may be dissolved in organic chemical ingredients. The vinyl ester resin contains styrene that dissolves the separation layer, FERRO#MC08 prepak film. The Imron5000 paint contains organic constituents such as acetone. This allows it to attack the FERRO#MC08 prepak film. However, a paint that will not attack the Ferro prepak film may be formulated in future. Moreover, FERRO#MC08 prepak film has the property of dissolvability in resin and would help build a thin surface coating (painting). Therefore, further IMC experiments should be conducted. As for SC-15 impregnated fibers, there are different reactions for impermeability and formability shown in Table 4.23a. Regarding water-soluble resin, polyvinyl alcohol, the bond ability was positive for the paint and negative for resin as described in section 4.1.24. The recommendation for this separation layer is to conduct further investigations once the corresponding formulation of the coating material is available.

4.2.2 Structure Type Discussion

Three types of structures in IMC experimentation was described in Chapter 3, RIDFT IMC-1, RIDFT IMC-2 and RIDFT IMC-3. All structure types consist of separation layers and bottom reinforcing fiber layers. The main difference is in the top layer. RIDFT IMC-1 consists of reinforcing fiber layers and/or a surface veil, RIDFT IMC-2 consists of only surface veil and RIDFT IMC-3 consists of nothing on the top layer. The effects for each one can be listed in the following table:

Table 4.25. Parameters for all structure types

Structure Type	Description	Infusion fluency while using slim-radial-strips FDC	Surface finish
RIDFT IMC-1	Top layer: Reinforcing fiber layers and/or surface veil. Middle: Separation layer Bottom layer: Reinforcing fiber layers	Fast (about 5~20 inches per minute)	1. Coarse finish for with surface veil. 2. Fiber sink through for without surface veil
RIDFT IMC-2	Top layer: Surface veil. Middle: Separation layer Bottom layer: Reinforcing fiber layers	Fast (about 5~20 inches per minute)	Rough/Coarse
RIDFT IMC-3	Top layer: None Middle: Separation layer Bottom layer: Reinforcing fiber layers	Slow (about 0.5~10 inches per minute)	1. Glossy 2. Case 22 phenomenon might happen

The conclusion for this factor was drawn as the RIDFT IMC-1 and -2 demonstrated faster infusion process. RIDFT IMC-3 has better surface finish. RIDFT IMC-2 was eliminated from experimentation because of bad surface finish.

4.2.3 Flow Distribution Channel Discussion

Four types of FDCs in IMC experimentation were described in Table 4.26. Traditional FDC has properties of large dry uncoated regions left behind, and requiring a secondary process to spread the coating. A FDC yielding as little dry area as possible was required to make. FDC type 2, non-channeled FDC, was intended to lift up a large area of the top silicone layer to avoid dry areas after paint infusion. However, with this FDC, race tracking of paint resulted since the top and bottom silicone layer were pulled up together, creating a flow path at the sides. FDC type 3, narrow-straight-strips with

radial cut gaps FDC, was then made to create less size dry areas. The dry areas were formed because of the strips made of black foam (Figure 4.10c). Reducing the size of the foams can decrease the size of dry areas after infusion. FDC type 3 resulted in increased infusion speed compared with type 2. Narrow dry areas were presented after infusion. The flow speed was quite different in all directions in the experiments. For example, flow speed at the right hand side of the channel is much faster than that at the left hand side of the channel. Another fact was that the farther from the source of fluid, the slower the flow because of the pressure gradient as mentioned in Darcy's law (Equation 2.8). Therefore, the best distance of foam strip to foam strip was defined to use the fastest flow speed among those of FDC type 3. Also, the strips' directions were defined to line as radial ways sourced at infusion inlet to even the distance from the source of fluid. FDC type 4, slim-radial-strips with radial cut gaps FDC, was made to meet the above designs, better distance (about 3/4 inches) of foam strip to foam strip and directions of strips lined as radial ways sourced at paint infusion inlet. The experiments showed good infusion speed and thin dry areas after infusion. The conclusion for this factor was drawn as the FDC type 4 has the best effect on IMC experimentation.

Table 4.26. Parameters for all FDCs

FDC type #	Description	Schematics shown in Figure #	Properties in IMC experimentation
1	Traditional	4.10c	Large dry uncoated regions are left behind, requiring a secondary process to spread coating
2	Non-channeled	4.13	1.) Intended to lift up large area of top silicone layer 2.) Race tracking of paint resulted
3	Narrow-straight-strips with radial cut gaps	4.14a,b	1.) Infusion speed better than type 2 2.) Narrow dry areas after infusion
4	Slim-radial-strips with radial cut gaps	4.15c,d	1.) Good infusion speed 2.) Thin dry areas after infusion

4.2.4 Temperature Discussion

Temperature was found to be a major factor that affects time of curing and liquid viscosity. Experimental results are shown in Table 4.27. A higher temperature (200°F) was determined to have properties of less curing time and lower viscosity, effective on both the Imron5000 paint and Vinyl ester resin. The lower viscosity also resulted in faster infusion speed.

Table 4.27. Parameters for time of curing and viscosity at different temperatures

Temperature	Means	Time of curing (min.)		Viscosity (cp)	
		Imron5000+ 33% ez-3461s + 1.2% 8989s	Vinyl ester+ 2% MEKP and 0.30% CONAP	Imron5000+ 33% ez-3461s + 1.2% 8989s	Vinyl ester+ 2% MEKP and 0.30% CONAP
30°C(86°F)	Room	120±20	30±5	1500±300	75±15
93°C(200°F)	Heat lamp	20±5	10±5	500±100	25±5

4.2.5 Tube Diameter Discussion

The smaller tube inner diameter can increase system infusion pressure demonstrated in Cases 1 and 2. The original tube inner diameter 0.5 inches was designed to fit one liquid inlet port. When the number of liquid inlet ports were increased to two, to fit the IMC design, the infusion pressure was obviously not enough, as demonstrated in Case 1. Decreasing the tube diameter to half of the original, 0.25 inches, would increase the infusion pressure sufficient for simultaneous infusion as demonstrated in Case 2.

4.3 Factor Table for Each Case

Table 4.28 lists the major factors for each case from Part 1 to 24, in which the characters A~H denote as follows:

A: Structure type (RIDFT IMC-#)

B: Tube diameter (in.)

C: FDC type- (#1: Traditional; #2: Non-channeled; #3: Narrow-straight-strips; #4: Slim-radial-strips)

D: Number of fiber layer

E: Material of separation layer

F: Surface veil

G: Heating time (minute) at 90°C

H: Number of separation layer

Table 4.28. Major factors for Parts 1~24

P/N	A	B	C	D	E	F	G	H
1	N/A	0.5	N/A	6	N/A	No	N/A	N/A
2	1	0.25	N/A	6 (Top 3, Bottom 3)	Vacuum bagging film	Yes	N/A	1
3	2	0.25	N/A	6	N/A	Yes	N/A	N/A
4	2	0.25	N/A	6	N/A	Yes	N/A	N/A
5	3	0.25	N/A	6	N/A	No	N/A	N/A
6	1	0.25	N/A	6 (Top 3, Bottom 3)	Copy paper	No	N/A	1
7	2	0.25	N/A	6	Ferro prepak film	Yes	N/A	1
8	1	0.25	#1	6	Ferro prepak film	No	N/A	1
9	2	0.25	#1	8 (Top 3, Bottom 5)	Ferro prepak film	Yes	N/A	1
10	3	0.25	#1	6	Ferro prepak film	No	N/A	1
11	3	0.25	#1	6	Ferro prepak film	No	N/A	1
12	3	0.25	#1	6	Ferro prepak film	No	N/A	1
13	3	0.25	#2	6	Ferro prepak film	No	N/A	1
14	3	0.25	#3	6	Ferro prepak film	No	N/A	1
15	3	0.25	#4	6	Ferro prepak film	No	5	2
16	3	0.25	#4	6	Ferro prepak film	No	10	2
17	3	0.25	#4	6	Ferro prepak film	No	5	1
18	3	0.25	#4	6	Ferro prepak film	No	10	1

Table 4.28 continued

19	1	0.25	#4	4 (Top 1, Bottom 3)	Release film	No	N/A	1
20	1	0.25	#4	4 (Top 1, Bottom 3)	Avloy base web-film	No	N/A	1
21	1	0.25	#4	4 (Top 1, Bottom 3)	Prepreg film	No	N/A	1
22	3	0.25	#4	6	Release film	No	N/A	1
23	1	0.25	#4	4 (Top 1, Bottom 3)	SC-15 impregnated fibers	No	N/A	1
24	N/A	N/A	N/A	N/A	Polyvinyl alcohol	N/A	N/A	N/A

To summarize, Parts 1~18 were work-in-process experiments and the findings and improvements were discussed in each case in Section 4.1. The experimental analysis will be addressed in Chapter 5. Parts 19~24 were mainly testing several different materials of separation layers. The results and discussions were listed in Section 4.1.

4.4 Case Study Summary

In summary, the important detected factors in accordance to each experiment in this thesis are listed in Table 4.29. More detailed descriptions can be found in Section 4.1.

Table 4.29. Summary for Parts 1~24

Part #	Detected factor	Aim	Finding
1	Initial rough run	Test co-infusion	The tube pressure was not enough
2	1.) Smaller diameter tubes 2.) The use of an impermeable vacuum-bagging film as separation layer	1.) Use smaller diameter tubes to increase vacuum pressure 2.) Demonstrate co-infusion	1.) Successful infusion 2.) Successful infusion
3	The use of bleeder layer as flow media	Test bleeder layer as paint flow media	Soft surface Zoning effect
4	Simultaneous infusion	Evaluate the potential for the coating material (paint) to flow over the resin	Zoning effect
5	Reversing infusion inlet ports	Investigate the effect of having the coating material flow beneath the resin during simultaneous infusion	Zoning effect
6	The use of Copy Paper as separation layer	Evaluate the importance of a separation layer to the IMC setup during simultaneous infusion	The need of an impermeable separation layer
7	The use of a new separation layer FERRO#MC08 prepak film	Determine the separation layer	The resin can soon dissolve the separation layer
8	Infusing paint before resin.	Test the effect	The paint dissolved the separation layer slowly

Table 4.29 continued

9	1.) Traditional FDC 2.) RIDFT IMC-2	1.) Accelerate flow speed 2.) Test RIDFT IMC-2	1.) The flow was successful accelerated with large dry areas left 2.) The surface finish was coarse because of the surface veil
10	1.) Resin infusion was initiated one second after paint infusion was initiated 2.) RIDFT IMC-3	1.) Test the effect 2.) Test RIDFT IMC-3	1.) Zoning effect indicates that the infusion differential time was too short 2.) Dry areas by traditional FDC were noticeable
11	1.) Resin infusion was initiated two minutes after paint infusion began 2.) Heat was applied for two minutes	1.) Test the effect 2.) Gel the paint	1.) Better infusion than Case 10 2.) Despite the attempt at drying the paint, paint still seeped through separation layer
12	1.) Resin and paint inlet ports were both centrally overlapping located with an impermeable layer in between. 2.) Two layers of separation layer.	1.) To offer better resistance to paint seeping through 2.) To see if thicker separation layer would affect the paint to prevent from seeping.	1.) It did offer better resistance only at the infusion ports 2.) Paint still seeped through

Table 4.29 continued

13	Non-channeled FDC	Pull up a large area from upper silicone membrane and avoid dry areas	Failure
14	Narrow-straight-strip s FDC	Reduce dry areas	Failure
15	Slim-radial-strips FDC	Reduce dry areas and the clearances between any two strips. Also, make the flow channel as radial distribution.	The paint infusion was the best so far.
16	Repeat of Case 15	Repeat of Case 15	Description in chapter 5
17	Repeat of Case 15	Repeat of Case 15	Description in chapter 5
18	Repeat of Case 15	Repeat of Case 15	Description in chapter 5
19	1.) RIDFT IMC-1 without surface veil. The use of separation layer of release film 2.) Change coating material to 50g resin + 1g paint	1.) Demonstrate Co-infusion 2.) Distinguish top layer different from bottom layer by color	1.) Top layer infusion is faster than bottom layer. Postulation: Number of layers difference. FDC effect weak in bottom layer 2.) Good effect
20	1.) RIDFT IMC-1 without surface veil. 2.) Separation layer of Avloy base web-film	1.) Study RIDFT IMC-1 2.) Try the separation layer of Avloy base web-film	1.) Find three major improvements to do 2.) The separation layer can not bond to liquids

Table 4.29 continued

21	Separation layer of prepreg composite	Try the separation layer	The separation layer can not stop paint and resin seeping
22	1.) RIDFT IMC-3. 2.) Separation layer of release film	1.) Test the separation layer by RIDFT IMC-3 2.) Demonstrate Co-infusion by RIDFT IMC-3	1.) Flow slowly. Postulation: Top layer had no flow media and FDC effect was insufficient 2.) The paint adhered on top silicone layer instead of separation layer
23	Separation layer of SC-15 curing at 142°F	Try the separation layer	Failure
24	Separation layer of water soluble resin, polyvinyl alcohol	Try the separation layer	Failure

CHAPTER 5

EXPERIMENTAL ANALYSIS

5.1 Basis for Experimentation Tests

The components manufactured and discussed in the preceding chapter were analyzed to ascertain the effects of the production parameters on their mechanical and rheological properties. The goal of these tests was to determine how changes within the manufacturing process affected the physical properties of the finished parts. Physical properties of the non-coated and the in-mold coated parts manufactured with the RIDFT process were tested and analyzed.

5.2 Differential Scanning Calorimetry (DSC)

The methodology followed in this section was in accordance with the DSC methodology discussed in Chapter 3. The goal of DSC is to get the curing temperature or time for the measured materials. Comparing the heat flow of the paint and the resin alone shows that the fluids are not completely miscible (Figure 5.1, 5.2) because the peaks are not similar. Since the resin curing peak temperature (186.27°C, Table 5.1) is higher than the paint (145.25°C, Table 5.2), the resin will still be in the liquid state after the paint has started curing. However, the paint consists of many ingredients that may have different curing properties. In reality, the paint has longer solidifying time than the

resin due to its complicated composition. Thermogravimetric Analysis (TGA) was used to measure the weight change of the paint.

Figure 5.1. DSC diagram of Derakane 470-45 vinyl ester resin

Figure 5.2. DSC diagram of Imron5000 paint

Table 5.1. DSC data for Derakane 470-45 vinyl ester resin

P/N	Curing temperature (°C)	Curing time (min.)
RESIN 1	206.90	20.7
RESIN 2	192.80	19.3
RESIN 3	197.78	19.8
RESIN 4	147.60	14.8
Average	186.27	18.65

Table 5.2. DSC data for Imron5000 paint

P/N	Curing temperature (°C)	Crystalline temperature (°C)
Paint022404	146.35	306.84
Paint022504_1	136.40	309.75
Paint022504_2	152.99	307.67
Average	145.25	308.09

TGA of Imron5000 paint (Figure 5.3) shows that it starts to lose weight from around 148°C with a considerable drop in weight from around 304°C. The percentage of weight loss is, 11.23% from 148°C to 304°C, 12.45% from 304°C to 368°C, 52% from 368°C to 415°C, 6.77% from 415°C to 457°C, and 21.86% from 457°C to 476°C. The heat flow of the three curves in Figure 5.2 show certain difference that was due to the error of weight measurement.

Figure 5.3. Imron5000 paint TGA

The temperature coincidence of DSC and DMA of Imron5000 happens at around 145°C, which validates the curing temperature of some thermosetting ingredients in paint. Some ingredients in paint were greatly vaporized at temperature above 304°C (Figure 5.3) that meets the crystalline point 308°C in Figure 5.2. It was not necessary to analyze the properties and constituent materials of the paint in this thesis.

The resin isothermal DSC at room temperature (Figure 5.4) shows curing peak time occurred at 10~15 minutes; plus the prior work time 10 minutes, the actual curing peak time should be around 20~25 minutes that meets the specification of this resin formulation (97.7% vinyl ester resin + 2% MEKP and 0.30% CONAP, percentage by weight). The isothermal testing was based on the resin (Derakane 470-45 vinyl ester) curing temperature of 25 ° C. The aim was to test the real curing time of this resin. With reference to previous temperature dependable DSC of the resin (Figure 5.1), all experiments curing time were between 10 and 30 minutes in spite of temperature change.

Figure 5.4. DSC diagram of Derakane 470-45 vinyl ester resin isothermal

In Table 5.1, the curing times for temperature-raising DSC were all between 10~30 minutes (ramping temperature was 10 °C/min) that is the same as curing time at room temperature (Figure 5.4). The discrepancies in curing temperature might be due to the impurity of the resin sample. Since the maximum operating temperature for Imron 5000 paint is 92 °C while all curing temperature for vinyl ester resin in Figure 5.1 are above 92 °C, curing temperature is not under discussion here.

5.2.1 Summary

This section analyzed the results of DSC for the Dupont Imron5000 paint and Derakane 470-45 vinyl ester resin. The paint is a material containing a variety of chemicals and displayed diverse properties in DSC diagram. Since the maximum service temperature for this paint is 92 °C [25] and DSC showed that the curing peaks of the resin and the paint both occurred above this temperature, the curing temperature is not under discussion in this thesis. Curing would happen with time elongation [28]. The curing time for the resin at room temperature (25 °C), 10~30 minutes, is validated in DSC diagram, Figure 5.4. The curing time for the paint at room temperature with adequately mixed with catalyst is 0.5~1 hour [25]. Therefore, the time limitations at room temperature for resin and paint infusion are 10 minutes and 30 minutes, respectively.

5.3 Dynamic Mechanical Analysis (DMA)

The methodology followed in this section was in accordance with the DMA methodology in Chapter 3. Figure 5.5 shows DMA of Derakane 470-45 vinyl ester resin. Two samples were tested. The average storage modulus is 2671.5 MPa, and Tg 161.74°C (Table 5.3).

Figure 5.5. DMA diagram of Derakane 470-45 vinyl ester resin

Table 5.3. DMA data for Derakane 470-45 vinyl ester resin

P/N	Storage Modulus (GPa)	Tg (°C)
Neat resin A2	2.601	161.11
Neat resin B2	2.742	162.37
Average	2.671	161.74

Figure 5.6 shows DMA of non-coated RIDFTed composites. Two specimens were tested. The average storage modulus was 13.185 GPa, and Tg 157.48°C (Table 5.4). These test values are considered as baselines.

Figure 5.6. DMA diagram of non-coated RIDFTed composite

Table 5.4. DMA data for non-coated RIDFTed composite

P/N	Storage Modulus (GPa)	Tg (°C)
Non Coat S11	12.902	153.22
Non Coat S22	13.468	161.74
Average	13.185	157.48

Figures 5.7~5.16 show DMA of Parts 8~18. Twelve parts cut into twenty-four samples were tested, two specimens from each part. One additional sample was made for each of Parts 10 and 11 to demonstrate the extent of the property variation observed in the IMC. The discrepancies in storage modulus and Tg in the three samples are more than 10% in Part 10. The tan delta has more than 10% difference among the three samples in Part 11. The resulting noise indicates the properties are not repeatable. This problem was attributed to the fact that the paint dissolves the separation layer and seeps through. The paint then disturbs the flow of the resin beneath the separation layer. Figure 3.9 shows the specimen cut-out locations for DMA test from Parts 10 and 11. Figure 3.10 shows the specimen cut-out locations for DMA test from Parts 8, 9, 12, 13, 15~18. The average storage modulus and Tg are shown in Table 5.5. Moreover, Table 5.5 makes DMA comparisons for Parts 8~18 with non-coated RIDFTed composites.

Figure 5.7 shows that the storage moduli of the two specimens of Part 8 are 9.456 GPa and 8.576 GPa, and Tg are 111.97° C and 111.59° C. A comparison of the average values of both coated and non-coated parts is given in Table 5.5.

Figure 5.8 shows that the storage moduli of the two specimens of Part 9 are 8.262 GPa and 7.936 GPa, and Tg are 110.46° C and 110.84° C. A comparison of the average values of both coated and non-coated parts is given in Table 5.5.

Figure 5.7. DMA diagram of Part 8

Figure 5.8. DMA diagram of Part 9

Figure 5.9 shows that the storage moduli of the two specimens of Part 10 are 10.448 GPa, 8.328 GPa and 8.061 GPa, and T_g are 105.92° C, 102.77° C and 119.48° C. The average values with comparison to non-coated composite are shown in Table 5.5.

Figure 5.10 shows that the storage moduli of the two specimens of Part 11 are 12.809 GPa, 12.448 GPa and 11.123 GPa, and T_g are 105.29 °C, 103.40 °C and 103.08 °C. The average values with comparison to non-coated composite are shown in Table 5.5.

Figure 5.11 shows that the storage moduli of the two specimens of Part 12 are 10.255 GPa and 8.741 GPa, and T_g are 95.2° C and 108.76° C. A comparison of the average values of both coated and non-coated parts is given in Table 5.5.

Figure 5.9. DMA diagram of Part 10

Figure 5.10. DMA diagram of Part 11

Figure 5.11. DMA diagram of Part 12

Table 5.5 shows the comparison of DAM data of coated and noncoated RIDFTed composites. The data of storage modulus and Tg of the coated laminates are less than noncoated ones. This may be because the paint seeping phenomenon occurred (Figure 4.16c).

Figure 5.12 shows that the storage moduli of the two specimens of Part 13 are 13.871 GPa and 13.130 GPa, and Tg are 71.97 ° C and 69.47 ° C. Part 13 is a composite made of Dupont Imron 5000 paint and glass fiber. Table 5.5 shows that Part 13 has larger storage modulus than the noncoated laminate, which might be because of the microstructural difference that will be further described in section 5.5.

Table 5.5. Comparison of DMA values of coated and noncoated RIDFTed composites

P/N	Set up	Avg. Storage modulus (GPa)	Avg. Tg (°C)	Avg. Storage modulus reduction (%)	Avg. Tg reduction (°C) (%)
<i>Non-coated average</i>		13.185	157.48	<i>Baseline</i>	<i>Baseline</i>
8 average	1	9.016	111.78	31.62	29.02
9 average	2	8.099	110.65	38.57	29.74
10 average	3	8.227	104.67	37.60	33.53
11 average	3	10.702	97.89	18.83	37.84
12 average	3	9.498	101.98	27.96	35.24
13 average	3	13.500	70.72	-2.39	55.09
15 REPLICATE 1 avg.	3	7.086	47.27	46.26	69.98
16 REPLICATE 1 avg.	3	7.264	68.40	44.91	56.57
17 REPLICATE 1 avg.	3	11.403	122.32	13.52	22.33
18 REPLICATE 1 avg.	3	4.952	127.37	62.44	19.12
15 REPLICATE 2 avg.	3	8.983	51.69	31.87	67.18
16 REPLICATE 2 avg.	3	11.139	57.68	15.52	63.37
17 REPLICATE 2 avg.	3	13.768	123.90	-4.42	21.32
18 REPLICATE 2 avg.	3	11.958	126.11	9.31	19.92

DMA

Figure 5.12. DMA diagram of Pat 13

Figure 5.13 shows that the storage moduli of the two specimens of Part 15 replicate one are 7.727 GPa and 6.446 GPa, and T_g are 52.00 ° C and 42.54 ° C; the storage moduli of the two specimens of Part 15 replicate two are 11.419 GPa and 6.546 GPa, and T_g are 52.32 ° C and 51.06 ° C. A comparison of the average values of both coated and non-coated parts was given in Table 5.5.

Figure 5.14 shows that the storage moduli of the two specimens of Part 16 replicate one are 9.380 GPa and 5.149 GPa, and T_g are 67.14 ° C and 69.66 ° C; the storage moduli of the two specimens of Part 15 replicate two are 14.328 GPa and 7.950 GPa, and T_g are 62.72 ° C and 52.63 ° C. A comparison of the average values of both coated and non-coated parts was given in Table 5.5.

Figure 5.13. DMA diagram of Part 15

Figure 5.14. DMA diagram of Part 16

Figure 5.15 shows that the storage moduli of the two specimens of Part 17 replicate one are 12.157 GPa and 10.649 GPa, and T_g are 136.82 ° C and 107.81 ° C; the storage moduli of the two specimens of Part 17 replicate two are 13.636 GPa and 13.900 GPa, and T_g are 122.64 ° C and 125.16 ° C. A comparison of the average values of both coated and non-coated parts was given in Table 5.5.

Figure 5.16 shows that the storage moduli of the two specimens of Part 18 replicate one are 5.253 GPa and 4.652 GPa, and T_g are 127.05 ° C and 127.68 ° C; the storage moduli of the two specimens of Part 18 replicate two are 10.447 GPa and 13.469 GPa, and T_g are 124.53 ° C and 127.68 ° C. A comparison of the average values of both coated and non-coated parts was given in Table 5.5.

Figure 5.15. DMA diagram of Part 17

Figure 5.16. DMA diagram of Part 18

From Table 5.5, obvious reductions of storage modulus and Tg indicate there may be a structural problem with the IMC parts. Since the difference between the coated and non-coated parts is the paint, it is postulated that the paint may be interfering with the fiber-matrix interface after paint seeping through the separation layer. The storage modulus of Part 13 having higher value than non-coated part showed the paint-fiber composites might have better matrix-fiber interfacial bonding than resin-fiber composites that will also be validated by ESEM in Section 5.5. The setup type in column two of the table cannot show any obvious and systematical affection on the physical properties.

5.3.1 Summary

The discrepancies in storage modulus and Tg in Part 10 and Part 11 stem from large property variations obtained with the IMC parts. The resulting noise indicates the properties are not repeatable. This problem was attributed to the fact that the paint dissolves the separation layer and seeps through. The paint then disturbs the flow of the resin beneath the separation layer. Part 13 exhibited a higher storage modulus than the non-coated parts. This may indicate that the paint-fiber composites might have better fiber-matrix interfacial bonding than resin-fiber composites. This will be investigated further using the ESEM micrographs presented in Section 5.5.

5.4 Tensile Tests

The testing method was in accordance with the ASTM D 3039 standards [27]. Tensile tests were performed on the laminates, to determine their tensile properties.

Specimens for the tensile test were created by cutting and grinding laminate strips to 200 mm $\times$ 25 mm. The specimen thicknesses are shown in Table 5.7. Three specimens were cut from each laminate. Aluminum end tabs 3.2 mm thick and measuring 50 mm $\times$ 25mm were locally bonded onto both ends of the specimens, using Epon 562 resin in conjunction with a 105 hardener. This resulted in a gage section of 100 mm. The tensile tests were carried out at a crosshead separation rate of 2 mm per minute. Figure 5.17 shows samples of IMC tensile strength test specimens. Table 5.6 shows the fiber volume fraction of each part. Figure 3.11 shows the cutting location of tensile test samples from Parts 13, 15~18.

Figure 5.17. Tensile test specimen sample

From Table 5.6, fiber volume fractions of the non-coated parts (Non coat B and S) are generally greater than IMC parts (Part 8~18). Part 13 was a paint-fiber composite and has slightly less fiber volume fraction than other components. This is because the paint density (1.17gm/ml) is greater than the resin density (1.03gm/ml). The differences of fiber volume fractions among these laminates are not obvious. The average fiber volume fraction of non-coated laminates is 41%. The average fiber volume fraction of IMC laminates is 37%. The fiber volume fraction of paint-fiber laminates is 35%.

Table 5.6. Data for fiber volume fraction

P/N	Fiber Layers	Fiber Weight (g)	Laminate Weight (g)	Fiber Weight Fraction	Fiber Volume Fraction
Non coat B	6	110.25	177.35	0.62	0.40
Non coat S	6	112.31	174.99	0.64	0.42
8	8	90.32	159.53	0.57	0.36

Table 5.6 continued

9	6	75.43	131.23	0.57	0.37
10	6	80.34	138.94	0.58	0.37
11	6	108.74	192.84	0.56	0.36
12	6	109.89	190.32	0.58	0.37
13	6	107.38	199.48	0.54	0.35
15 REPLICATE 1	6	110.81	188.50	0.59	0.38
16 REPLICATE 1	6	104.58	178.23	0.59	0.38
17 REPLICATE 1	6	109.35	193.72	0.56	0.36
18 REPLICATE 1	6	109.48	190.57	0.56	0.37
15 REPLICATE 2	6	108.32	190.53	0.57	0.36
16 REPLICATE 2	6	107.50	188.25	0.57	0.37
17 REPLICATE 2	6	110.42	186.48	0.59	0.39
18 REPLICATE 2	6	108.41	188.63	0.57	0.37

Table 5.7 shows the tensile test results of all comparative laminates and the average values are presented in Table 5.8. The tensile strength and Young's modulus are higher in non-coated laminates than in coated laminates.

Table 5.7. Data for tensile test specimens

P/N	Fractural Force (KN)	Strain (mm/mm)	Dimension Width (mm)	Dimension Thickness (mm)	Tensile Strength (MPa)	Young's Modulus (GPa)
Non coat B1	13.18	0.0183	25.49	1.55	334.89	37.10
B2	14.24	0.0201	25.38	1.52	368.76	34.80
B3	13.30	0.0194	25.25	1.56	337.61	33.20
Non coat S1	14.36	0.0191	25.43	1.54	366.58	35.40

Table 5.7 continued

S2	13.31	0.0199	25.52	1.56	334.32	33.20
S3	13.22	0.0189	25.51	1.53	338.69	30.10
13A	5.80	0.0082	27.27	1.43	148.81	18.10
13B	4.21	0.0056	24.70	1.30	131.04	23.60
13C	4.79	0.0068	25.01	1.37	139.78	20.61
15 R1 A	3.33	0.0103	25.18	1.62	93.25	9.10
15 R1 B	3.39	0.0129	25.03	1.60	96.61	7.46
15 R1C	3.10	0.0093	25.09	1.64	85.94	9.26
16 R1 A	5.87	0.0100	25.54	1.69	154.21	15.4
16 R1 B	6.25	0.0127	25.19	1.83	135.48	10.7
16 R1 C	6.04	0.0119	24.52	1.66	148.35	12.43
17 R1 A	3.93	0.0097	25.55	1.50	94.44	9.7
17 R1 B	3.68	0.0086	24.66	1.58	94.33	10.9
17 R1 C	4.14	0.0074	25.30	1.56	98.69	13.30
18 R1 A	3.20	0.0045	25.29	1.52	83.21	18.70
18 R1 B	3.33	0.0074	25.19	1.52	86.99	11.70
18 R1 C	3.25	0.0062	25.20	1.53	84.41	13.51
15 R2 A	3.42	0.0111	25.23	1.67	132.42	11.06
15 R2 B	3.54	0.0103	25.73	1.61	124.53	9.12
15 R2 C	3.10	0.0093	25.05	1.65	117.30	9.94
16 R2 A	5.87	0.0103	25.32	1.64	142.53	13.89
16 R2 B	5.23	0.0111	25.20	1.72	120.57	14.88
16 R2 C	6.04	0.0172	24.92	1.76	137.85	13.74
17 R2 A	4.05	0.0110	25.13	1.53	83.74	10.67
17 R2 B	3.85	0.0091	24.96	1.52	79.42	9.24
17 R2 C	3.96	0.0082	24.88	1.54	79.00	10.03
18 R1 A	3.21	0.0045	25.01	1.52	100.73	11.10
18 R1 B	3.13	0.0086	25.14	1.57	94.2	10.94
18 R1 C	3.46	0.0065	25.10	1.53	123.7	13.78

Table 5.8. Data for average values of tensile tests

P/N	V_f	Tensile Strength (MPa)	Young's Modulus (GPa)
Non coat B	0.40	347.09	32.23
Non coat S	0.42	346.53	32.90
13	0.35	139.88	20.77
15	0.38	91.93	8.61
16	0.38	146.01	12.84
17	0.36	95.82	11.30
18	0.37	84.87	14.64
152	0.36	124.75	10.04
162	0.37	133.65	14.17
172	0.39	80.72	9.98
182	0.37	106.21	11.94

5.4.1 Summary

The tensile strength and Young's modulus are higher in non-coated laminates than in coated laminates. This may be due to the initial interaction between the paint and the fibers, prior to the resin infusion. This may have resulted in poor resin impregnation of the fibers with the resultant infusion properties.

5.5 Microstructural Evaluation

In addition to mechanical and material property tests, an Environmental Scanning Electron Microscope (ESEM) assessment was carried out on the non-coated and IMC laminates. The goal was to verify if proper adhesion and fiber wet out occurred in each of the laminates.

In part 3, a bleeder was used to assess the effects on surface finish. Voids are visible in this part, (Figure 5.18) which may have resulted from the bleeder absorbing too much of the coating material. The bleeder did not improve the surface finish.

Figure 5.18. ESEM of Part 3

Figure 5.19 shows the fractured surface of fibers close to the resin side (bottom side of Part 9). It shows extensive fiber pullout, which is indicative of a poor fiber-matrix bond. This poor interfacial bond may have resulted in the radical difference in storage moduli observed in the non-coated and coated parts (Table 5.5).

Figure 5.19. ESEM of Part 9

Figure 5.20 (ESEM of Part 13) shows the fracture surface of Part 13. Part 13 is a laminate made of paint and fibers only, without resin. Good bonding between the fibers and paint can be observed. This may have resulted in the rather high storage modulus observed (Table 5.5). Figure 5.21 on the other hand, shows the failed surface on a non-coated specimen, indicative of matrix catastrophic failure. This may have resulted in the much higher tensile properties observed, when compared with Part 13.

Figure 5.22 shows the fracture surface of the resin side (bottom side of the Part 14). Figure 5.23 shows the fracture surface of the paint side (top side of the Part 14). The comparison indicates that the paint may have adhered better to the fibers than the resin did. This may be attributed to the paint having arrived at the fibers earlier, (since it is infused first and seeps through the separation layer), resulting in the resin's inability to adhere fully to the fibers. Nonetheless, more work needs to be done to ascertain the validity of this postulation.

Figure 5.20. ESEM of Part 13

Figure 5.21. ESEM of non-coated part

Figure 5.22. ESEM of Part 14 (Resin side).

Figure 5.23. ESEM of Part 14 (Paint side)

Figure 5.24 shows microstructure of non-coated part surface that exhibits fiber print-through. Figure 5.25 shows microstructure of IMC part surface that exhibits a smoother surface.

Figure 5.24. ESEM of non-coated part surface. Figure 5.25. ESEM of IMC part surface

5.5.1 Summary

The microstructures of failed coated and non-coated parts were assessed. It was observed that the paint might have adhered better to the fibers than the resin did. This may be attributed to the paint having arrived at the fibers earlier, (since it is infused first and seeps through the separation layer), resulting in the resin's inability to adhere fully to the fibers. The failed surface on a non-coated specimen was indicative of matrix catastrophic failure. This may have resulted in the much higher tensile properties observed, when compared with Part 13. Nonetheless, more work needs to be done to ascertain the validity of this postulation. The microstructure of a coated surface demonstrated that the IMC part surface finish was better than the non-coated part.

CHAPTER 6

CONCLUSION

The primary advantages of the RIDFT process over other conventional closed mold processes such as RTM and SCRIMP is the much lower costs involved and a reduced production cycle time. The RIDFTed IMC process leads to further reduction in production cycle time by combining both the composite manufacturing and painting process into a one-step process. This invariably translates into further savings in time and cost as well as a significant reduction in the VOC emission typically associated with the conventional spar-painting process for manufactured composite parts. The primary objective of this thesis was to determine the feasibility of incorporating an In-Mold Coating technique through co-infusion into the RIDFT process and develop a methodology that would lead to the production of fully painted RIDFTed composite laminates in one-step. The summary, conclusion, future work and possible research extension are outlined in the following sections.

6.1 Summary

As stated earlier, the objective of this thesis was to determine the feasibility as well as develop a methodology for incorporating the in-mold coating technique into the RIDFT process. This research was carried out in a series of steps to determine the materials that are most compatible with the process, which would invariably lead to the

production of painted composite laminates with good material and mechanical properties as well as surface finish. A compressive experimental approach resulting in twenty-four case studies was undertaken.

6.1.1 IMC

The RIDFT IMC setups were developed for the experiments based on the work of CIRTM [3]. It was found that co-infusion of two fluids is achievable with the RIDFT process. However, the ability to in-mold paint the resulting components depended greatly on the ability of the coating material to flow over the separation layer without mixing with the resin.

A material study was carried out to ascertain the qualities of a suitable separation layer. It was found that formability, impermeability and bond-ability are important. However, for the separation layer to perform satisfactorily, it must be able to keep the two fluids apart until infusion is complete. The Ferro prepak film material was found to perform best with the IMC experiments. It had the added benefit of dissolving in the resin with eliminates the problem of formability. Nonetheless, the coating material used in this study (Dupont Imron 5000) was able to dissolve the separation layer during infusion resulting in unsatisfactory components. It is however believed that with the use of a coating material that will not adversely affect the separation layer, successful IMC may be achieved.

6.1.2 FDC

A study was also undertaken to improve the flow of the co-infused materials by improving the flow distribution channel. Four configurations were assessed. It was found that Slim-radial-strips FDC was the best configuration.

6.2 Future Work

Further work for the further development of the IMC process should be centered largely on material selection that would entail the selection of a separation medium that would not decompose when in contact with the paint. To develop a more comprehensive and robust manufacturing process for the IMC technique the following areas has been suggested for further study.

- In-depth material study to determine the separation medium that would be most compatible with both the resin and the paint
- Liaise with different paint manufacturers to formulate a paint that contains chemical constituents that would not interact with the material being used as the separation medium
- Study of the mechanics of fluid flow during co-infusion to achieve better flow
- Study on the control of coating thickness and the resultant surface finish

All of these should lead to the development of an IMC RIDFT manufacturing process that is repeatable, efficient, robust, and leads to the production of composite laminates that have good material and mechanical properties as well as excellent surface finish quality.

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BIOGRAPHICAL SKETCH

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