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The Utilization of Formable Paint Films in the Implementation of in-Mold Decoration of Composites Manufactured by the Resin Infusion Between Double Flexible Tooling Process

Carlos Andres Puentes
THE UTILIZATION OF FORMABLE PAINT FILMS IN THE IMPLEMENTATION OF IN-MOLD DECORATION OF COMPOSITES MANUFACTURED BY THE RESIN INFUSION BETWEEN DOUBLE FLEXIBLE TOOLING PROCESS

By

Carlos Andres Puentes

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The members of the committee approve the thesis, by Carlos Andres Puentes, defended on November 15, 2007.

______________________________
Okenwa I. Okoli
Professor Directing Thesis

______________________________
Young-Bin Park
Committee Member

______________________________
Yaw A. Owusu
Committee Member

______________________________
Samuel A. Awoniyi
Committee Member

Approved:

______________________________
Chun Zhang, Chair, Department of Industrial Engineering

______________________________
Ching-Jen Chen, Dean, FAMU-FSU College of Engineering

The Office of Graduate Studies has verified and approved the above named committee members.
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ABSTRACT

With the rapidly increasing deployment of polymer composites as the material of choice, environmentally benign methodologies for manufacturing and coating the resulting components are imperative. Several methodologies are currently in use to manufacture composites in ‘closed’ molds; however, the implementation of coatings is still for the most part, done using methods that provide for the release of harmful, volatile organic compounds (VOC) into the environment.

The current work details the utilization of a thermo-formable polycarbonate paint film for the in-mold decoration (IMD) of composite materials manufactured using the novel Resin Infusion between Double Flexible Tooling (RIDFT) process. RIDFT is a vacuum driven process where resin infusion is performed between two reinforcement-filled flexible diaphragms. Upon completion of infusion, the flexible diaphragms are vacuum formed over a one-sided tool, providing for the rapid cost effective manufacture of composite components.

In this process, in-mold decoration is achieved by including a thermo-formable polycarbonate paint film within the flexible diaphragms, over the reinforcing fabrics (fibers), prior to infusion. After infusion, the whole assembly (paint film, fibers and resin) is vacuum formed to the desired geometry, thus achieving in-mold decoration. The inclusion of a polycarbonate film to the RIDFT process required a comprehensive analysis on forming capability vs. surface quality finish of the composite assembly. With increasing temperature, better draw ability was achieved; however, print-through of the fibers through the film occurred. Several process parameters were optimized through sequential experimentation using analysis of variance (ANOVA) in terms of print-through, as the response variable. High and low levels of five controllable factors (temperature, mold type, time, fiber reinforcement, and vacuum pull) were tested. Light scatter, caused by irregular surfaces, was quantified through the use of Matlab, allowing for precise response input values. Statistical validation proved minimal print-through at a
forming temperature of 147° C; however, at this temperature formability of the film was limited to subtle contours. At 160° C, the forming capability of the composite assembly was maximized, yet, surface finishes exhibited high print-through.

This thesis describes achievements, difficulties, and future work in the utilization of polycarbonate films for RIDFT in-mold decoration.
CHAPTER 1

INTRODUCTION

The implementation of polymer composite materials for the production of small and large-scale components is growing at fast pace with the introduction of new materials and groundbreaking technologies. Polymer composites have been presented as the material of the future due to their high strength to weight ratios, corrosion resistance, and functional integration [1]. The industry has strived over the last four decades to push faster production rates due to soaring increases in demand, nonetheless, the production economics of polymer composites tend to limit their application in the mass production sector. The lead-time for manufacturing is simply too high. Composite molders have therefore been compelled to replace hand lay-up techniques with more advanced and efficient fabrication methodologies, if possible, involving automated processes. Several production processes are available, with the liquid composite molding techniques being the most amenable to mass production. Such alternatives include resin transfer molding (RTM), vacuum assisted resin transfer molding (VARTM), structural reaction injection molding (SRIM), and resin infusion between double flexible tooling (RIDFT).

Composite components undergo a series of finishing processes to prepare the substrate for painting after de-molding. Some of the current painting methodologies are laborious, time consuming and expensive, and may result in the release of hazardous volatile organic compounds (VOC’s) that are harmful to workers and the environment. Parts that require performance and quality of finish undergo post-coating operations, which increase the cost of the part and the environmental burden.

The macroeconomic environment, the drive towards lower costs and high efficiency, technology innovation and sound environment practice, has significantly influenced the automotive coatings market [1]. 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. Seeking methodologies to reduce the costs associated with painting and diminishing the negative environmental impacts is imperative. In-mold decoration (IMD) is set to address these issues. The following paragraphs will illustrate IMD and its advantages.

The latest improvements of extruded polymer sheets used in thermoforming have replaced many composite molding applications because they provide class ‘A’ finish along with resistance to UV degrading of exterior surfaces. In-mold Decoration (IMD) for thermoplastic and thermoset applications is the process by which an injection or compression molded part is decorated during the molding cycle. IMD applications require post trimming but eliminate secondary coating operations and can produce the same class ‘A’ finish obtained with conventional painting. For many years, IMD has been successfully used in the automotive industry for exterior body panels made from compression molded Sheet Molding Compound (SMC) to improve their surface quality in terms of functional and cosmetic properties [2]. SMC however, requires the use of expensive tooling and gel coats, which entail numerous drawbacks. RIDFT technology, on the other hand, offers many advantages.

Using the RIDFT process, thermo-formable multilayer, polycarbonate films can be used to achieve decorated surfaces of composite components. RIDFT is a vacuum driven process where resin infusion is performed between two reinforcement-filled flexible diaphragms. Upon completion of infusion, the flexible diaphragms are vacuum formed over a one-sided tool, providing for the rapid, cost effective manufacture of composite components.

The process combines the forming of a high-performance thermoplastic film with a compatible thermoset resin to form a permanent solid bond. RIDFT in-mold coating, gives manufacturers the ability to infuse, form, and paint at the same time using films in an environmentally friendly procedure. The thermoplastic film achieves the desired Class ‘A’ finish without secondary coating operations and the reinforced fabrics embedded in a
thermoset matrix provide exceptional physical properties required for various applications. This process, however, presents several challenges. Temperature equilibrium in IMD is crucial to achieve optimal forming of the film, preventing undesirable wrinkles, and a class ‘A’ finish. Furthermore, the operating window of the selected resin must be wide enough to avoid premature curing before, during, and after infusion.

The following sections will summarize the problems and the research plans for proficiently resolving these issues.

**Problem Statement**

Thermo-formable polycarbonate films have the ability to provide class ‘A’ surface finishes for both thermoplastic and thermoset applications. However, as a result of several manufacturing challenges in the thermoset field, their implementation is still for the most part, very limited. The automotive industry seeks lower costs and increased efficiency through the implementation of new and innovative technologies. The latest advancements and materials development promise to gradually lower assembly paint-line emissions, eventually completely eliminating the need for paint, while improving scratch resistance and resistance to degradation caused by humidity, temperature, and exposure to sunlight.

The goal of this research is to use thermo-formable polycarbonate films with fiber reinforcements using the RIDFT process to develop IMD components with exceptional mechanical properties in one single shot. However, the implementation of in-mold decoration of composites manufactured by the RIDFT process (RIDFT-IMD) has been somewhat problematic. The process requires the heating of the polycarbonate film to enable thermoforming. Nonetheless, the applied heat accelerates curing of the resin, thus preventing forming of the fiber-resin-polycarbonate assembly. The operating window
needs to allow time to soften and form the assembly prior to resin cure. In order to effectively implement this technology two key issues must be addressed and thoroughly analyzed; (1) full control of temperature factors, before, during, and after infusion, and (2) formability assessment of the fibers and the polycarbonate film.

Control of Temperature Factors

A major challenge in implementing polycarbonate films to the RIDFT process is controlling the optimal temperature of the system. Heat is necessary to soften the thermo-formable paint films; however, heat also triggers the curing cycle of the resin. The temperature required to cure the resin, therefore, must be above the desirable forming temperature of the polycarbonate film, but close enough not to compromise the integrity of the film during curing. Extending the processing window is imperative and necessitates the delay of resin cure. This may be achieved by the use of an appropriate catalyst that will raise the curing temperature to a suitable range. Determining the appropriate resin matrix and catalyst, thus, becomes crucial. A temperature control system is also necessary in order to effectively control and stabilize the desired temperature that will ensure proper forming of the fiber-film assembly and guarantee a wide operating window to allow for resin infusion without premature curing.

Formability Assessment of the Fibers and the Polycarbonate Film

Fibers can be easily draped around tools; however, with the inclusion of the polycarbonate paint film formability of the assembly becomes a challenge. The ability of both the fibers and the film to form over a mold depends on the shape and the surface of the tool, the draping angles, and the specific characteristics of the fiber reinforcements and the film, such as type of weave for fabrics, and gage for films. Forming the fiber-film assembly effectively will depend on the ability of the RIDFT equipment to exert enough pressure to embed, hold, and lock the assembly over the mold. Several techniques are
available for modeling the forming behavior of fiber reinforcements, as well as techniques for modeling the forming behavior of polycarbonate sheets. These techniques have been proven feasible and effective and will be used to help in developing RIDFT-IMD. An analytical model used typically in sheet metal forming processes will be implemented to predict the behavior of the forming process of the fiber/film assembly taking into consideration all the material properties that control drapability. This model is known as cup drawing and it is relatively simple compared to other sheet forming models. The RIDFT equipment will be able to simulate the punch and die system used in conventional cup drawing sheet molding processes and will be able to predict the forming behavior of the IMD assembly.

**Research Objectives**

The objective of this research is to develop an innovative process to efficiently utilize thermo-formable polycarbonate paint films for the in-mold decoration (IMD) of composite materials manufactured using the Resin Infusion between Double Flexible Tooling (RIDFT) process. Additionally, this research demands an analytical analysis to evaluate the thermoforming process of a resin/fiber-polycarbonate composite.

Formability of the composite system is made more difficult by the inclusion of the paint film; however, several achievements have been made and major challenges identified with the implementation of this cost effective and environmentally friendly methodology. Further assessment of the rheological properties of both the fabrics and the paint films determines optimal formability temperatures and the appropriate resin catalyst system. The goal of this research is to be able to produce IMD components manufactured by the RIDFT process that are similar in mechanical and aesthetic properties to conventionally painted parts.

The following section will review available literature on issues related to the research and development of RIDFT-IMD.
CHAPTER 2
LITERATURE SURVEY

Composite Manufacturing Processes

There are two common classifications for composite manufacturing processes. The first one is open molding, sometimes referred to as contact molding, and the second one is closed molding. In open molding, the resin and reinforcements are exposed to the atmosphere during the fabrication process. In closed molding, the composite is fabricated in a two-part mold, or in a single female mold within a vacuum bag. Open molding techniques include hand lay-up, either by manual or mechanical resin application, chopped fiber process, either by automatic spray-up or manual application, and filament winding. Closed molding techniques include compression molding, pultrusion, reaction injection molding, resin transfer molding, vacuum bag molding, vacuum infusion processing such as vacuum assisted resin transfer molding, resin infusion between double flexible tooling, centrifugal casting, and continuous lamination [3]. Composite molding manufacturing processes can be further classified or characterized according to volume fabrication requirements. Hand lay-up is used for low production volumes while chopped fiber processes and filament winding are used for medium to high production volumes. Vacuum bag molding and vacuum infusion molding, are used for low volume applications, while compression molding, resin transfer molding, pultrusion, reaction injection molding, centrifugal casting, and continuous lamination processes are used for medium to high volume production [3]. Resin infusion between double flexible tooling has not been adapted for manufacturing applications yet, but used for prototype development.

The following sections will review liquid composite molding techniques that have relevance to the implementation of IMD of composites.
Resin Transfer Molding

Resin transfer molding, sometimes referred to as liquid molding is a closed molding technique. It begins with a two-part, female and male, matched mold, typically made of metal. Dry reinforcement fabrics, characteristically pre-form or pre-shaped fibrous reinforcements, are placed into the mold and the mold is secured tightly. Resin and catalyst are mixed together in a vessel and then pumped through an injection port into the mold cavity under low pressure. In some systems, the resin and catalyst are pumped separately into the injection head and mixed while entering the mold as shown in Figure 1. RTM usually involves the use of low viscosity resins, such as polyester, vinyl-ester, and epoxy resins, in order to wet the fabric quickly and uniformly before gel time. Depending on the application, the mold or the resin, or both can be heated to high temperatures achieving perfectly even heat distributions. Parts produced by RTM do not need to be autoclaved since the clamping force between the molds produces enough pressure to control fiber volume content [4]. During infusion, the excess resin is ejected through very small openings in the mold called bleeds to eliminate voids and guarantee consistency of resin to fiber ratios, typically 60 percent fiber to 40 percent resin. Open mold techniques that do not have full pressure have to be autoclaved in order to ensure fiber-resin ratios and eliminate void content which is remarkably low in RTM parts, from 0 to 2 percent [4].
RTM is a high performance production methodology. It can produce large and complex parts that are very difficult to achieve with other production methods. The reason is that the male and female parts of the mold have very high quality surfaces within very low tolerances. RTM can produce thick parts with smooth gel coated decorated top and bottom (A and B) surfaces, eliminating most post-molding work like sanding, painting or buffing. RTM has been implemented for many years to achieve IMD surfaces of components, through the implementation of gel coats [5]. The surfaces achieved provide good cosmetic finishes; however, they do not achieve class ‘A’ surface finishes and present several drawbacks associated with the properties of gel coats.

Structural Reaction Injection Molding

In contrast to RTM, where resin and catalyst are premixed prior to injection into the mold, reaction injection molding (RIM) injects a rapid-cure polyurethane resin and a catalyst into the mold in two separate streams as shown in Figure 2; mixing and the
The mixing of the two chemicals, as they are being injected into the mold occurs at very high speed. The mixture, however, flows into the mold at relatively low temperature, pressure, and viscosity. The curing process occurs in the mold, also at relatively low temperature and pressure. The entire procedure, from mixing to de-molding, typically takes less than a minute and not only is it much faster than RTM, it also requires much less energy. Different types of RIM are usually characterized by different ways in which reinforcements are introduced into the final component. Structural reaction injection molding (SRIM), widely used in the automotive industry, incorporates a fiber mat or a pre-form as reinforcement material, providing enhanced dimensional and structural strength. The automotive industry is increasingly combining SRIM, with rapid pre-forming methods to fabricate structural parts that do not require a class ‘A’ finish [6]. For the parts that due require class ‘A’ finish the automotive industry has created a specialized form of SRIM called long fiber injection, discussed in detail in the following sections.

Figure 2: Structural Reaction Injection Molding (SRIM) [6]
Resin Infusion Between Double Flexible Tooling

The RIDFT concept developed at the High Performance Materials Institute (HPMI) differs significantly from the processing procedures of traditional Resin Transfer Molding (RTM), and structural reaction injection (SRIM). In this process, resin infusion and fiber wetting occur between two flexible tools (silicone membranes) in a two-dimensional flat shape [7]. After infusion, the wetted reinforcement and flexible tooling are drawn over a mold and vacuumed to a specific geometry. The steps of the RIDFT process are shown in Figure 3.

![Figure 3: Schematic of the RIDFT Process [7]](image)

The mold used in the RIDFT can be fabricated using non-metallic materials, since it does not need to withstand high pressures. Furthermore, the mold does not come in contact with the resin, eliminating the use of releasing agents and avoiding premature wear of the mold. Co-infusion of paint performed by Chiu and Okoli et al [1] and
implementation of acrylic sheets performed by Toro et al [8] opened a new window of possibilities for the application of IMD through RIDFT technology.

**Conventional Decoration of Composites**

Several methodologies are currently in use to manufacture composites in ‘closed’ molds; however, the implementation of coatings is still for the most part, done using methods that provide for the release of harmful, volatile organic compounds (VOC’s) to the environment. These carbon compounds can undergo an atmospheric photochemical reaction, contributing to air pollution and causing ozone depletion.

The automotive industry seeks lower costs and higher efficiency through the implementation of new and innovative technology. At the same time, reducing the environmental impact is crucial. The latest materials development in liquid composite molding promise to lower assembly paint-line emissions, eventually eliminating solvents in paint, while improving scratch resistance and resistance to degradation caused by humidity, temperature, and exposure to sunlight. Atomized paint and special gel coats, however, still present the simplest and more cost effective alternatives for mass producers.

**Spray Painting**

Spray painting is the process of spraying paint with the use of air compressors and specialized spray guns. Automobile manufacturers have improved spray paint methods and technologies over the last years in an effort to reduce occupational exposure and reduce the depletion of harmful volatile organic compounds (VOC’s) into the environment. Spray guns used in finishing and coating procedures atomize paint with compressed air and project a paint mist onto the surface of components. The mechanism
used in atomization and delivery of paint directly affects the transfer efficiency of the process. Transfer efficiency is defined as the ratio of the amount of coating solids deployed onto the surface to the total amount of coating solids that exit the spray gun nozzle [9]. The paint directed outside the main spray pattern and not deployed onto the surface of the component is referred to as overspray. Atomized paint can also bounce back, in other words, be pulled away from the surface of the component by compressed air currents deflected by the surface. Only 40 percent of the paint adheres to the surface of the finished component. The remaining 60 percent account for overspray and bounce back. Control technologies and new paint formulations have been developed to improve the efficiency of the process and reduce its environmental impact. Common effective controls include the implementation of high volume, low pressure (HVLP) spray guns, low volume, low pressure (LVLP) spray guns, electrostatic spray guns and powder coatings, and spray paint booths [10].

Conventional spray guns operate with air pressures of 30 to 90 psi at a fluid pressure of 10 to 20 psi and generate volumes of 2 to 10 cubic feet per meter (cfm). They achieve very fine atomization but their transfer efficiency is very poor, in the range of 20 to 40 percent. High volume low-pressure (HVLP) spray guns operate with air pressures between 0.1 to 10 psi at a fluid pressure of 50 psi and generate volumes of 30 to 200 cfm. The lower velocity of the atomizing air stream results in a more controlled spray pattern, less bounce back, and enhanced transfer efficiency, of at least 65 percent. In the same way, low volume, low pressure (LVLP) spray guns, atomize coatings at lower pressure, between 0.1 to 10 psi, however, they generate volumes between 50 to 60 percent smaller than HVLP spray guns [10]. Another type of spraying system, commonly used in the automotive industry, uses the electrostatic spray gun. Instead of wet paint, the electrostatic gun uses powder coating, and even though the transfer efficiency is similar to that obtained with wet paint spraying systems, powder coating can be reused, achieving utilization rates as high as 98 percent [10].
Even with the increased efficiency in spray-painting operations, spray guns inherently produce harmful emissions. Spray booths, ventilated structures enclosing a spraying operation, can confine and limit the escape of vapor and residues and safely conduct or direct overspray and volatile compounds produced to an exhaust system. In most automotive assembly plants, spray painting is done in a downdraft, paint spray booth shown in Figure 4. In this type of booth, conditioned ambient air is introduced through the roof while the paint overspray and fumes exit through the exhaust system in the floor. Another type of booth is the cross draft booth shown in Figure 5. In this type of booth, the ambient air enters through filters in the front and is exhausted through filters in the back of the booth. Both systems are widely used in the automotive industry, depending on the application, to ensure good finishes, reduce employee exposure to gases, and reduce the release of harmful volatile organic compounds. Evaluations of these controls, however, indicate that spray booths do not effectively eliminate worker exposure or VOC depletion.

Figure 4: Down Draft Spray Booth and Side-Down Draft Booth [11]
Figure 5: Cross Draft Spray Booth and Semi-Down Draft Booth [11]

Gel Coats

The term gel coat is often used generically to describe any resin-based surface coating for composites, but the term technically refers to polyester-based coats. Surface coat is a more general term which refers to either epoxy or polyester materials. Gel coats and surface coats are uniquely formulated, thickened versions of resins with added color, which can be applied to the surface of a mold to achieve either a cosmetic or a protective layer of coating [12]. Liquid gel coats, applied before laying of the fiber mats in both open and closed molding for cosmetic applications, save the step of spray painting.

In a two part mold operation such as RTM, a lower female mold is coated via spray up, dry reinforcement fabrics are laid over the cured gel coat surface, and a matched male mold is drawn over the female mold and clamped under pressure. The
resin is then injected into the preform while the gel coat adheres to the composite, providing a perfect in-mold coat.

Some gel coats can achieve class ‘A’ finishes but emit harmful volatile compounds and are generally suitable for room temperature applications only. Although gel coats are standard in the industry and offer an excellent alternative to spray painting operations they have some limitations [12]. Before application of the coat an initial layer of mold release agent, regularly polyvinyl alcohol (PVA), must be applied over the mold increasing lay-up time. Proper gel coat application is difficult if the process has not been adapted for automation. Temperature variations, inadequate catalyzation, spray thickness, contaminates in the mold and handling techniques are factors that may contribute to poor surface finishes. Furthermore, gel coats are inherently susceptible to cracking, crazing, blistering, and other types of environmental damage [12].

**In-mold Decoration of Composites**

For many years, composite manufacturers have replaced gel-coats with vacuum formed, heavy-gage acrylic sheets to provide water and chemical resistant surfaces. These sheets are able to overcome the biggest disadvantages of gel coat implementation; however, they do not provide the finish and gloss achieved by a paint base coat and a clear coat. For applications requiring a class ‘A’ finish, extruders of polymer sheets developed multilayer systems for composite and thermoplastic applications that could accurately imitate clear-coated paint. These sheets are typically co-extruded with one or more thinner layers of UV-resistant plastics comprising agents that provide exceptional heat and chemical resistance [13]. For components subject to light loads the sheets can be vacuum formed and trimmed but for components subject to heavy loads the sheets must be backed up by reinforced fabrics through open or closed molding. The resulting component is decorated inside the mold, hence the term in-mold decoration.
IMD has been successfully used for exterior body panels in automobiles made from compression-molded sheet molding compound (SMC) to improve their surface quality in terms of functional and cosmetic properties [2]. When injected onto a cured SMC part, the resin cures and bonds, providing a paint-like surface. Thermoplastic films or multilayer films, however, present the newest and most promising alternative for IMD.

A number of forms of IMD have been researched, focusing primarily on ways to achieve in-mold coating by means of injection molding of plastics and thermo-formable films. Injection molding is the process by which a thermoplastic is injected at very high pressure and temperature into a mold, subsequently curing and producing an IMD part. Some thermoplastics can produce a class ‘A’ surface; however the mechanical properties of the resulting part are far less than those of a thermoset part. The issue concerning both thermoplastic and thermoset composite molders, is the inability to adapt thermoplastic resins, thermoset resins, and fiber reinforcements into one single process. McCarthy et al [14] described the effects of implementing thermoplastic paint films on different fiber structures. Castro et al [15] offered the process model for in-mold functional decoration of thermoplastic substrates. Moreover, Toro and Okoli [8] experimented on the use of thermo-formable paint films to produce in-mold decorated composite parts using the resin infusion between double flexible tooling process. In these experiments, low viscosity, vinyl-ester resin, Derekane 470-45, was used to impregnate the fibers. A thermoplastic paint film produced by Avery-Dennison was used. The results revealed substandard adhesion of the paint film, premature curing of the resin, poor surface finish, and severe print through. Further research was performed by Chiu and Okoli [1] on the use of co-infusion as means for in-mold decoration, however their work identified numerous difficulties.
Sheet Molding Compound

The sheet molding compound (SMC) process is a high temperature process consisting of a set of matched metal molds heated to temperatures typically in the range of 138° C to 177° C [13]. A premixed mixture of resin, catalyst, mineral fillers, and reinforcement fabrics, compounded into sheet form is laid over the heated female mold and compressed by a matched, heated male mold. When the molds are cooled down, the part is de-molded, and typically, spray painted on automated conveyer lines, using paint robots and continuous flow ovens. Even though post-mold coating on SMC components guarantees a class ‘A’ surface finish it adds an additional production step and allows for the harmful release of volatile organic compounds.

Thermoformable sheets for IMD were considered as an alternative to SMC post-coating; however, the films had to be inserted into the mold cavity preheated to temperatures well above the temperature desired for maintaining their dimensional stability. Moreover, the large differences in coefficients of thermal expansion (CTEs) between highly filled SMC and the polymer films created large stresses on the interface as the molded parts cooled down to room temperature, causing the films to delaminate.

Injection Molding

In-mold decoration by means of injection molding has gained considerable popularity for applications that require class ‘A’ finishes and do not require high strength to weight ratios [16]. In injection molding, IMD takes place simultaneously during the molding process. A thermoplastic film is placed over the mold cavity before the mold is closed. A hot molten polymer resin is injected under pressure in such a way that the heat transfer softens the film, reducing its stiffness. The heat generation and the force generated by the injection of the resin make the film adhere to the inner walls of the mold.
cavity. After the resin and the film solidify, the mold is opened and the finished IMD part is removed. Figure 6 shows a schematic of the injection molding process. The process can be summarized in four stages:

1) Thermoforming of the film into a preform
2) Trimming of the edges
3) Placement of the preform into the injection press
4) Injection of substrate into the mold

Figure 6: Injection Molding [17]

The elongation of the thermoplastic film is a function of temperature, the higher the temperature, the larger the percentage of elongation. Too high temperatures, however, may compromise the mechanical integrity of the material causing thermal degradation and tackiness [16]. It is therefore crucial to maintain a stable temperature during the forming process. The optimal temperatures vary according to material specifications.
Long Fiber Injection

Long fiber injection (LFI) is a form of structural reaction injection molding (SRIM) and one of the fastest growing fabrication techniques in the past five years [18]. It differs from SRIM because instead of using a fiber mat it uses chopped long fibers. Long fiber-reinforced composites achieve the same performance as continuous fiber reinforced composites, and present higher production speeds and manufacturing accuracy through automation, accredited to chopped fiber-spray up robots. Long fiber-reinforced thermoplastics (LFRT) have replaced metals and other composite molding techniques in a number of applications [19]. Long fiber technologies have also been developed for thermoset applications, particularly long fiber injection of polyurethanes.

In LFI, a fast curing two-part polyurethane is mixed with chopped fibers and delivered into the mold cavity in a continuous process. The fibers, cut to a specific length, depending on the geometry and complexity of the mold, are delivered into a mixing head. At the same time, the polyurethane components, polyol and isocyanate, enter the mixing head, wetting the chopped fiber. A robot directs the mixing head over the mold as the mixture is poured into the cavity, as shown in Figure 7. Once the delivery of the mixture is complete, the mold is closed and sealed under pressure. After curing the part is demolded and little or no secondary work is done to it. The IMD procedure for LFI is very similar to the injection molding process, given that a preform is placed inside the mold to back mold the substrate. The LFI process, however, requires far less pressure than injection molding, allowing for the use of less costly tooling materials such as aluminum [18].
LFI presents a smart alternative to SMC as well. Even though lots of work has been done to improve upon the surfaces of compression molded composite exterior automotive body panels, LFI processes can achieve class ‘A’ finishes through the incorporation of thermoplastic film technology.

Resin Infusion Between Double Flexible Tooling  IMD

Thermo-formable multilayer, polycarbonate films have been used to achieve decorated surfaces of composite components by the RIDFT process. In-mold decoration is achieved by including the thermo-formable paint film within the flexible silicone membranes, over the reinforcing fabrics, prior to infusion. After infusion, the whole assembly (paint film, fibers and resin) is brought to a high temperature through the use of heat lamps and subsequently vacuum formed to the desired geometry, thus achieving IMD. Figure 8 shows the RIDFT equipment currently used for IMD applications.
Toro and Okoli [8] performed preliminary studies of RIDFT-IMD. The results demonstrated the feasibility of the methodology. However, the paint films used were not adequate for proper adhesion, and the resin-matrix system accounted for a very narrow operating window, leading to premature curing, wrinkling of the films, and poor surface finishes.

The current work details the utilization of the GE SLX Lexan films. These high performance polycarbonate films offer good heat resistance, superior dimensional strength, high gloss surface finish, and UV stability.
Given that only a one-sided mold is used to produce any particular part, and because it is relatively inexpensive to print ink on a plastic film, manufacturers can fabricate products with various applications and tailor them to the exact specifications and needs of different target markets at a very low cost. RIDFT in-mold coating, gives manufacturers the ability to infuse, form, and paint at the same time using films in an environmentally friendly procedure. The thermoplastic film achieves the desired Class ‘A’ finish without secondary coating operations and the reinforced fabrics embedded in a thermoset matrix provide exceptional physical properties required for various applications.

**Modeling IMD Composite Forming**

Fibers can be easily draped around tools. The ability to form over a mold, however, depends on the shape and surface of the tool, the draping angles, and the specific characteristics of the fiber reinforcement. Modeling techniques allow composite molders to make critical decisions based on pre-production information. The earliest and the simplest of techniques for composite reinforcement forming are the mapping approaches, which only take into account the fiber mat dimensions, fiber geometry, and tool profile [21]. The other techniques for composite forming are the mechanics approaches, which, as opposed to the mapping approaches, are far more intricate and require numerous calculations during the course of forming.

Due to the wide spectrum of flow conditions, a mechanics cup drawing approach was used to model RIDFT IMD components. This simplified the intrinsic complexity of the fiber-film assembly and determined the major process conditions that control formability.
Cup Drawing

Sheet forming processes, generally classified as deep drawing or compression operations, represent a complex range of flow conditions. Cup drawing represents radial drawing, in which one of the principal strains in the plane of the sheet is positive and the other is negative and the change in thickness of the sheet is very small [22]. Formability depends upon tooling as well as material properties. Failure occurs due to plastic instability in tension rather than fracture.

Deep drawing of cylindrical flat-bottom cups, sometimes referred to as cupping or Swift cup testing, is a relatively simple process to model sheet forming behavior. This process is very similar in nature to RIDFT-IMD. In this process, improper process parameters can cause wrinkling, as shown in Figure 9. Figure 10, further defines the coordinate system $x$, $y$, and $z$ and shows two important regions: the flange, where most of the deformation occurs, and the wall, which must support force to cause the deformation in the flange. The formability of a sheet may be expressed as a limiting drawing ratio (LDR) which is the largest ratio of sheet-to-cavity diameter, $(d_2/d_1)$ that may be drawn or pulled successfully into the mold cavity. In sheet molding processes, as well as in the RIDFT process, determining the exact size of the blank, is crucial, for obtaining optimal forming parameters. The maximum limiting drawing ratio is 2.7. This means that the size of the sheet must not exceed 2.7 times the size of the mold cavity. Determining the exact ratio can successfully eliminate wrinkles produced during forming.
The work of Whiteley et al [23] shows that the LDR depends upon the average strain ratio, $\bar{R}$. Figure 11 illustrates a schematic of a partially drawn cup in sheet metal forming, with its coordinate system. This diagram can closely represent a simple mold used in RIDFT-IMD. Some assumptions are made to simplify the model:
1) The flow in the flange is characterized by plane strain, \( \varepsilon_z = 0 \), so the wall thickness of the part will be the same as that of the starting sheet. Stress will be present in the \( z \) direction but there will be no deformation. In the RIDFT process, this means that the thickness of the starting polycarbonate film will be the same thickness following vacuum forming.

2) Angular variations of \( R \) can be handled by using the average-strain ratio,

\[
\bar{R} = \left( R_0 + 2R_{45} + R_{90} \right)/4
\]

3) The material properties are rotationally symmetric, so that there is “planar isotropy” and “normal anisotropy.” Planar isotropy means that the surface of the sheet is the same in physical properties along the plane axes. Normal anisotropy means that the sheet does not have the same physical properties in the \( z \) axis.

The deformation of the flange, shown in Figure 11, assumes that the rate of change of the strain is zero \( (d\varepsilon_z = 0) \), indicating that the total surface area remains unchanged. In such a way, the area inside any element (a polycarbonate film in RIDFT-IMD), initially at a distance \( \rho_0 \) from the center, is constant. Therefore, the rate of change of the distance from the center is defined as:

![Figure 11: Schematic Illustration of Partially Drawn Cup [22]](image)
\[ dp = \frac{-r_i dh}{\rho} \]  

(1)

where, \( r_i \) is the punch radius and \( dh \) is the incremental distance moved by the punch. In the RIDFT process, a silicone sheet, as opposed to conventional metal punches, represents the punch, and vacuum pressure draws the polycarbonate sheet into the mold cavity. The incremental work done on the element is equal to the volume of the element times the incremental work per volume. Since \( d\varepsilon_z = 0, \ d\varepsilon_x = -d\varepsilon_y \), the work per volume is \( (\sigma_x - \sigma) d\varepsilon_y \), so the work on the element is \( dW = 2\pi r t \rho dp(\sigma_x - \sigma) r_i dh / \rho^2 \). The total work on all elements per increment of punch travel is given as:

\[ \frac{dW}{dh} = 2\pi t \sigma_f \ln \left( \frac{r}{r_i} \right) \]  

(2)

where, \( \sigma_f \), is \( (\sigma_x - \sigma) \).

The drawing force, \( F_d \), which must equal \( \frac{dW}{dh} \), will have its largest value at the beginning of the draw when \( r = r_o \), so

\[ F_{d_{\text{max}}} = 2\pi t \sigma_f \ln \left( \frac{r_o}{r_i} \right) = 2\pi t \sigma_f \ln \left( \frac{d_o}{d_i} \right) \]  

(3)
where, $d_o$ and $d_1$ are the blank and punch diameters, respectively.

In the cup wall, which must carry the force $F_{d_{\text{max}}}$, the axial stress, 

$$\sigma_x = \frac{F_{d_{\text{max}}}}{2\pi r t},$$

is

$$\sigma_x = \sigma_f \ln\left(\frac{d_o}{d_1}\right) \quad (4)$$

The drawing limit will be reached when this stress reaches the flow strength of the wall, $\sigma_w$, when,

$$\sigma_w = \sigma_f \ln\left(\frac{d_o}{d_1}\right) \quad (5)$$

or,

$$\ln(LDR) = \ln\left(\frac{d_o}{d_1}\right) = \frac{\sigma_w}{\sigma_f} \quad (6)$$

Modeling of the IMD assembly using the limiting drawing ratio depends greatly on the material properties of the resin, the fibers, and the film. Tooling also plays an important role since the work utilized to form the sheet as it flows over the die cavity.
increases with the ratio of the sheet thickness to radius of the curvature of the die lip, causing higher drawing force and lower limiting drawing ratio.
CHAPTER 3
PRELIMINARY RESULTS

Several achievements were made and a few problems identified with the implementation of standard RIDFT-IMD. Assessment of the rheological properties of the paint film determined radical improvements of formability at temperatures over 140°C; however, resin cure issues were prevalent well below the prescribed film forming temperature. Studies were conducted to ascertain the appropriate resin-catalyst system to delay curing, extending the operating window, until complete forming of the polycarbonate film. The following sections outline the preliminary experimental procedures and the results attained.

Initial Approach to RIDFT-IMD

The work details the utilization of GE’s Lexan SLX multilayer films for in-mold decoration (IMD) of composite materials. These high performance polycarbonate films offer good heat resistance, superior dimensional strength, high gloss surface finish, and UV stability.

GE’s Lexan SLX Polycarbonate Films

The Lexan film presents an excellent profile to meet the different performance requirements of several users. Its high quality and strength enhance the use of color with no loss of brightness. It is durable and easy to decorate, offering remarkable ink adhesion without pre-treatment. Furthermore, the film is available in a wide assortment of standard and high-performance grades with a variety of surface finishes and textures. RIDFT-IMD involves the use of a one-side hard-coated high performance film, which offers a gloss
level of 92 (glass-like). It provides exceptional scratch resistance, formability, impact resistance, and dimensional stability. Furthermore, it provides anti-static embossability and thinning in 3D forming applications of up to 30 percent.

**Initial Experimentation Procedure**

RIDFT-IMD prototypes were successfully produced using Lexan SLX films; however, further improvements had to be made in order to achieve consistency in attaining high quality Class ‘A’ surface finishes. To clearly address the issues related to the process, a detailed description of the pilot manufacturing procedure is critical. Figure 12 displays the first RIDFT machine. This vacuum driven equipment has the capability of producing parts up to 61cm in length by 30.5cm in width.

The bottom silicone frame is carefully placed on top of the vacuum chamber of the RIDFT machine over the mold. The reinforcing fabrics (fibers) and the Lexan film are then centered on top of the silicone sheet. Once the fibers are in place two flow channels are used at opposite ends to aid resin flow. Two polyethylene tubes are inserted through lateral holes on the bottom frame, one as a vacuum port and the other as an infusion port as shown in Figure 13. The top silicone membrane is placed over the bottom membrane and vacuumed together. The infusion process and the distribution of the resin are aided with a temporary flow distribution channel.
Operating Window

Crucial to the RIDFT-IMD process is the operating window. Since the application of heat is necessary to soften the thermoformable paint films, the resin curing trigger temperature needs to be above the forming temperature of the paint film. If this is not the case, premature gelling of the resin will prevent appropriate forming of the RIDFT-IMD assembly. Extending the processing window necessitates the delay of resin cure. This may be achieved by the use of an appropriate catalyst that will raise the curing temperature to a suitable range.
Initial tests involved the use of Trigonox C; however, the resin cured too rapidly, starting its gelling sequence as the temperature approached 113°C. Figure 14 shows the exothermal DSC test for Hetron 922L and Trigonox C. At 113°C, the high performance polycarbonate film was soft but not formable so the surfaces of the prototypes produced exhibited wrinkles and certain surface irregularities as shown in Figure 15. In order to determine the temperature that would create the best surface finish several tests were performed by heating and forming Lexan films alone. Assessment of the tests determined a radical improvement of formability at temperatures over 140°C. Trigonox C failed to delay the curing of the resin upon a temperature increase. As such, it was replaced with Trigonox K-90, a curing agent that was able to delay curing. Like Trigonox C, Trigonox K-90 is an initiator for the co-polymerization of styrene, butadiene, acrylonitrile, vinylacetate, acrylates, and methacrylates, and it is commonly used for the cure of promoted unsaturated polyester and vinyl ester resins, such as Hetron 922L.

Figure 14: DSC test for Hetron 922L with Trigonox C
Trigonox K-90 was able to raise the curing temperature of the resin to approximately 140°C. Several tests were performed using Trigonox K-90, marking a significant improvement. DSC analysis was performed on the resin, using Trigonox K-90 as the catalyst, and keeping the same concentrations of 0.3 percent and 1 percent, for cobalt and Trigonox, respectively. The graph in Figure 16 shows the DSC curve for the corresponding resin-catalyst system.

As shown by the curve, at 140°C the resin exhibited its highest exothermic reaction. From that point, on it began its transition into a solid state. Given that the Lexan film must reach that same temperature, it was still difficult to expose the film to the specified temperature without curing the resin. All prototypes produced using Trigonox K-90 formed well in areas of the film that attained temperatures of 140°C or above; however, because exposure to heat had to be limited to avoid premature curing of the resin, some areas did not reach adequate temperatures, causing those areas to wrinkle following forming. Simple geometries such as a car hood were formed well (Figure 17), albeit with some noticeable wrinkles and surface roughness.
Furthermore, the heat lamps first implemented to generate heat over the surface of the RIDFT machine produced temperature gradients across the surface of the Lexan film. Some areas achieved optimal temperatures while others fell below 140°C and tended to wrinkle upon forming. In addition, areas reaching temperatures above 200°C presented a problem as well. Excess heat burned the film’s protective layer and caused shrinkage, degrading the film’s surface finish and compromising its dimensional stability. Figure 18 shows high heat concentration areas in which the protective layer of the Lexan film was completely disintegrated. In order to achieve a Class ‘A’ surface finish, the protective layer must be intact following the opening of the mold.
Important progress was made with the inclusion of Trigonox K-90, however, the operating window was not good enough. Further investigation was conducted to address
the preliminary issues associated with RIDFT-IMD. The following section identifies the initial problems encountered with this technology and determines the focus of this research.

**Identification of Problems**

i) The first and most fundamental problem was the inability of the system to maintain vacuum equilibrium due to leak points in the screws, across the surface of the frames. Without vacuum equilibrium, it is impossible to shut the vacuum after infusions. Since the vent had to be kept open until curing, consistency of resin to fiber ratios was hard to achieve. Resin was invariably pulled out of the part after complete wetting of the fibers. This ceased only upon increased resin viscosity at the onset of gelling.

ii) The preliminary RIDFT-IMD process demonstrated important progress with the inclusion of Trigonox K-90 as the curing agent; however, it is imperative that the curing of the resin occurs at a temperature above 140°C, which is the optimal forming temperature of the Lexan film.

iii) Due to the rectangular shape of the frames and the distance between the two silicone membranes, uniform pull (forming stress distribution) was difficult to achieve because of the four corner angles in the rectangular frames and the distance that each silicone sheet had to stretch to seal against the other. This propagated wrinkles in the Lexan film.

iv) The prediction of the forming behavior of the IMD assembly was necessary to determine suitability of the RIDFT-IMD to differing geometrical configurations. This was addressed by utilizing a limiting drawing ratio (LDR) analytical approach, commonly used in cup drawing.
v) Uneven heat distribution during the forming stage of the film was found to be a significant problem. This may be addressed by the development of an internal heating system that could potentially eliminate temperature gradients and uneven distribution of heat. Maintaining uniform temperature throughout the system and undertaking several problems associated with the equipment is crucial for RIDFT-IMD.

Redesigning the RIDFT equipment to eliminate setbacks was essential to the development of the RIDFT IMD methodology and the completion of this thesis work. The development of a new, redesigned RIDFT radically reduced the problems encountered with the first equipment and was capable of maintaining uniform temperatures of up to 195° C. The new machine was able to produce prototypes with improved properties; far exceeding the ones produced using the old equipment. Some challenges, however, were encountered.
CHAPTER 4
METHODOLOGY

Trouble-shooting issues related to the first RIDFT equipment called for a reverse engineering approach in which every single component of the machine was broken down and re-engineered. The main key issues that were addressed were the inability of the equipment to maintain constant vacuum (an ideal seal, zero leaks) and the inability of the system to provide a controllable heat source. The previous methodology neglected the importance of controlling fundamental factors, and for that reason, the prototypes manufactured exhibited numerous irregularities. All the modifications and add-ons to the RIDFT-IMD concept contributed significantly to improving the overall process.

Round RIDFT Design

The previous RIDFT machine had a rectangular chamber and rectangular frames. Each frame consisted of two independent frames that clamped the silicone sheet through a series of screws distributed across the surface of the frame as seen in Figure 19. This two-part frame design presented numerous minute leak points that added up resulted in significant vacuum loss. Their rectangular shape also created a non-uniform draping of the silicone, creating voids in all four corners of the frame. In addition, the distance between both silicone membranes was too large, making it difficult for the sheets to drape over each other achieving their maximum potential silicone to silicone surface area contact.
Circular Frames

The first step was to switch from a rectangular shape to a circular shape, in order to achieve uniform draping of the silicone sheets. The frames were redesigned to consist of single aluminum rings. The bottom ring was made with a thickness of 0.25 inches, the smallest possible thickness that allowed the ring to maintain its rigidity and still be fairly light for handling. The top frame was made with a thickness of 0.375 inches, slightly thicker than the bottom frame. A 0.3125-inch groove, one inch in width, was machined around it using a five axis CNC routing machine. From the opposite side of the groove a 0.25-inch NPT fitting was placed to pull vacuum from the groove. Two, 0.3125-inch, in width and a 0.25-inch in depth, grooves at opposite sides of the ring and perpendicular to the vacuum groove were machined, as channels for Teflon tubing, for infusion and vacuum. Teflon tubing was able to stand higher temperatures than regular polyethylene. In both the top and the bottom frames a 0.030-inch gage silicone circular sheet was glued on to their surface. In the top frame the sheet had to be carefully draped over the groove to avoid the creation of voids. The new design allowed the two frames to be vacuumed together with full silicone to silicone contact as shown in Figure 20.
Redefined Vacuum Chamber

The re-engineering of the frames required a new design for the vacuum chamber. The quickest method to manufacture a round chamber to fit the new frames that would be capable of withstanding vacuum pressure was vacuum infusion process (VIP). A plaster mold was made using a conventional inflatable exercise ball. Ten layers of fiberglass were draped in the inside of the mold and infused with a mix of polyester and vinyl-ester resin as shown in Figure 21.
This procedure generated a second mold which was gel coated and draped on the outside with seventeen layers of structural glass and two layers of carbon fiber. Following the placement of the fibers the mold was infused in the exact same manner as the first mold. The third part made, produced a structural vacuum chamber with a completely coated inside as seen in Figure 22. In the center of the chamber a hole was drilled out for the placement of a pneumatic cylinder that attached to a base disc in the inside of the chamber as shown in Figure 23. The shaft’s up and down motion provided the ability to adapt the base of the chamber for different size molds.

![Figure 22: Vacuum chamber](image)

Furthermore, the manifolds controlling the vacuum ports and the main chamber vacuum were simplified into one single manifold shown in Figure 24, further reducing potential leak points. The redefined RIDFT chamber was subject to rigorous testing involving vacuum integrity. The new machine held a constant 25 inches of mercury for a period of twenty-four hours, never possible when utilizing the old equipment. Having overcome vacuum leaks, the next step was to device a way to maintain constant and controllable heat. The first approach was the implementation of a heat dome, which was manufactured in the same way as the main vacuum chamber, however, only utilizing three layers of structural fiberglass.
Heat System

The heat dome was equipped with a set of two 500W quartz light bulbs connected to a thermo-controller as shown in Figure 25. A thermocouple was able to provide a precise reading of the temperature between the surface of the top silicone frame and the tightly sealed dome. The space between the bottom silicone sheet and the vacuum chamber, however, was cold. To overcome this problem, a heating
element was placed inside and connected to the same thermo-controller connected to the heat dome. The final assembly, referred to as RIDFT 4-1, shown in Figure 26, was able to provide uniform top and bottom surface heat of up to 195° C, making a vast improvement in the manufacturability of IMD components.

Figure 25: Heat Dome

Figure 26: Final assembly RIDFT 4-1
RIDFT 4-1 Process Control

Several process parameters (temperature, vacuum, and resin to catalyst ratios) were different from the initial methodology; however, the type of film used was exactly the same (Lexan SLX, 0.020-inch gage). Vacuum was held constant at twenty five inches of mercury and temperature was fully controlled at varying set points. The resin, Hetron 922L was catalyzed without the aid of cobalt and only with a 1% concentration of Trigono K-90. This resulted in a significant delay of resin cure leading to a wider operating window.

The RIDFT-IMD process with the incorporation of the new concept equipment was broken down into six main stages: loading, sealing, infusion, heating, forming, and demolding. Figures 27 through 29 present a clear schematic of the process.

![Diagram of the loading and sealing stages](image)

Figure 27: Loading and Sealing

In the loading stage, the fibers and the Lexan film are placed on the bottom silicon membrane (fibers over the film). In the sealing stage, the two membranes are sealed by means of a vacuum and locked securely into a two dimensional flat arrangement. In the infusion stage, resin is driven into the part by means of vacuum, until the fibers are completely wet out. In the heating stage, a combination of radiant, resistive, and convection heat raises the temperature to proper forming temperature of the Lexan film.
Once the specified temperature is attained, the assembly is drawn over a mold by means of a vacuum, in the forming stage. Finally the part is de-molded and trimmed.

The fully reengineered machine produced improvements in the prototypes made, especially with the inclusion of the radiant heat dome. Determining the exact process parameters for the process, however, still presented a challenge. Exact temperature, exposure time, blank size, mold type, and vacuum pull, had to be determined in order to achieve consistency in delivering exceptional prototypes.
Recognition of Problems

Repetitive testing using the new equipment was conducted to determine precise process parameters that would ascertain quality parts. During testing, different ambient temperatures, ranging from 140° C to 195° C, were tested, while interchanging female and male molds of varying geometries. Higher temperature runs with female molds resulted in the best prototypes, exhibiting high gloss and exceptional stability; however, there was a big tradeoff between wrinkles and surface smoothness. High temperatures during forming eliminated wrinkles previously obtained with the old methodology but produced print through of the fibers. Several other issues involving the machine itself arose too, despite a fully proactive approach of re-engineering every flawed aspect of the first machine. One issue was the inability of the fiber structured vacuum dome to resist heat. The polyester vinyl-ester resin that was used to infuse the chamber was a high temperature resistant resin; however, post-curing of the resin in an oven was not performed. Upon a sudden increase in temperature in the inside of the dome, resin post-cured cracking the vacuum chamber in half. Another issue, causing difficulties was predicting forming through the use of irregular molds (simple but irregular contours). The final issue, and the most important of all, was the inability of the machine to control high temperature in the bottom, between the bottom silicon membrane and the vacuum chamber. Temperature rose to quickly making it difficult to oscillate with the thermocontroller. The processing window was hence, significantly reduced. In order to tackle the new problems, the RIDFT 4-1, had to be modified.
CHAPTER 5
TROUBLESHOOTING AND FINAL RIDFT-IMD DESIGN

Continuous testing of the RIDFT 4-1 equipment identified several problems related to the RIDFT-IMD process and to the machine itself. Several preliminary findings were made with this machine marking significant progress, such as a proper temperature range, mold type, and infusion parameters. However, the new machine had room for improvements leading way to its successor, the RIDFT 4-2 prototype machine.

RIDFT 4-1 Achievements

One the factors determined with the utilization of the RIDFT 4-1 prototype machine was mold type. Experiments were conducted with two identical molds, one male and one female mold. Figure 30 shows a prototype built with a female mold and one made with a male mold. Results with the female mold were predicted to be superior because with the female mold the silicone draped over a solid surface. After experimentation, it was proven that the composites manufactured with the female mold had better contour and finish, as predicted.

Another crucial factor that was determined with the use of the RIDFT 4-1 equipment was the temperature range suitable for proper forming and complete elimination of wrinkles. The ambient temperature range was determined between 175° C to 205° C, however testing exact temperatures became difficult as the temperature in the vacuum chamber rose to quickly. This range provided, however, a very useful guide for future experimentation. Vacuum control (fast or quick opening of the valve) was established too, even though logical assumptions had already concluded that a faster pull would produce better results. Blank size of the the Lexan film was not determined because the molds utilized were not uniform around, therefore, the limiting drawing ratio
approach did not apply. The new redesigned RIDFT 4-2 incorporated a uniform cup mold, in addition to variations that provided ground for substantial experimentation and optimization of process parameters.

Figure 30: Female and Male Molds

Development of RIDFT 4-2

The purpose of the creating a third prototype machine, was to fully control factors that could potentially lead to an exact definition of process parameters. Attaining consistent production of IMD components became imperative. Redefinition of the RIDFT 4-1 equipment included a steel vacuum chamber, capable of withstanding very high temperatures, the inclusion of a convection heating system to achieve better control, and the implementation of a uniform cup mold capable of predicting forming behavior of the composite assembly.

Figure 31 shows the cracked fiber vacuum chamber of the RIDFT 4-1 machine and the new steel chamber for the RIDFT 4-2. In order to achieve complete insulation of the steel chamber, mineral wool, capable of withstanding up to 500° C, was placed around it. The wool was then covered with aluminum sheet metal for further insulation.
In order to achieve good heat circulation and attain the ability to control different temperatures a convection heating system was designed for the vacuum chamber. Since the convection fan had to be in complete isolation from the vacuum system a separate heating chamber had to be designed, from which a fan would push the hot air into the vacuum chamber and recirculate it back and forth between both chambers. A set of two one inch and a half pipes allowed the flow of heat into the main chamber. The convection heating system designed, shown in Figure 32, however, represented a high risk of leak points. Two holes were carved into the lateral wall of the steel chamber and precise welding was performed to attach the pipes. A system of unions and bronze ball valves was incorporated to have the ability to isolate the heating system upon forming. Minor leaks were present but eliminated through weld build-up.

The final assembly of the RIDFT 4-2 equipment is shown in Figure 33. The new convection heating system, in combination with the heat dome was linked to the thermo-controller. This allowed stabilizing high temperatures, opening a path towards precise determination of the most influential process parameters for the RIDFT-IMD process.
Figure 32: Convection Heating System

Figure 33: RIDFT 4-2
Incorporation of Cup Mold

Utilizing a uniform, simple cup mold (Figure 34) was key to determining key parameters in RIDFT-IMD. Forming of Lexan films alone (no fibers or resin) had to be conducted in order to determine the blank size that would produce the best results. Initial experimentation indicated that there was a reduction in thickness of the film during drawing. By observing the movement of the Lexan film into the mold cavity, it was noted that the material was not capable of undergoing a reduction in diameter while resisting thinning under the longitudinal tensile stresses in the mold. Thinning of up to 16% was observed.

Figure 34: Cup Mold
Conclusions

Stabilizing temperature by the addition of a convection heating system was key to improving the RIDFT-IMD process. The inclusion of the cup mold for modeling forming was also key to determine the mechanical behavior of the Lexan film while being drawn into the mold. Initial experimentation identified several control factors that were analyzed to optimize results. Many experiments were conducted with the new RIDFT 4-2, providing new guidelines for the continuous improvement of the RIDFT-IMD process.
A mechanical, experimental approach was used to model forming of the Lexan films. An analysis involving deep drawability or limiting drawing ratio (LDR) was performed on cup prototypes of moderate depth (1.75 inches). Deep drawing is a process used to predict the forming behavior of sheet metal, therefore several assumptions had to be made to investigate Lexan films. Once the blank size of the film was determined, tests were conducted with fibers and resin, fibers without resin, and varying molds, to determine several other process parameters. Experimental runs producing IMD prototypes led to a clearer understanding of the most influential control factors.

**Determining Blank Size**

In the RIDFT process, a blank (Lexan film) was held in place with a silicone sheet, representing the blankholder in conventional sheet forming operations. The punch, was assumed to be the portion of the silicone sheet, which moved downward into the mold cavity forming the cup. Therefore, the punch diameter was equal to the diameter of the mold cavity (7.75 inches) and the punch angle equal to the radius of the corners in the mold. Figure 35 explains normal deep drawing. The blank holders hold the blank in place while a punch forces the material into the mold cavity. The force of the blank holders is enough to hold and allow restrained sliding.
In most deep drawing processes, in which the limiting drawing ratio (LDR) is calculated, failure of the blank occurs by thinning in the cup wall under high longitudinal tensile stresses. In the case of the Lexan film (under high temperature), the blank was subject to a reduction in width (being reduced in diameter) but was not able to resist thinning under the longitudinal tensile stresses in the cup wall. When evaluating the cup drawing of several Lexan films, an average thickness change of approximately 16% of the sheet was estimated. Furthermore, an average percentage change in length of 18.9% of the blanks was calculated. The ratio of width strain to thickness strain, $R$, was modified, to avoid errors in measurements of small thicknesses. Because the Lexan films are thin compared to their surface area the strain ratio was based on volume constancy, given by,

$$
R = \frac{\ln\left(\frac{w_o}{w_f}\right)}{\ln\left(\frac{w_o \ell_f}{w'_o \ell'_o}\right)},
$$

(7)
where \( \ell \) is refers to the gage length of the sheet specimen. To estimate the limiting drawing ratio (LDR) of Lexan sheets stretched by 18.9% in length and with a decrease in thickness of 16%, a volume constancy approach was used; therefore,

\[
\frac{w_f t_f l_f}{w_o t_o l_o} = 1.
\]  

(8)

From the percentages obtained, through the testing of specimens, the following was obtained,

\[
\frac{\ell_f - \ell_o}{\ell_o} = 0.189 \quad \text{or} \quad \frac{\ell_f}{\ell_o} = 1.189,
\]

and

\[
\frac{t_f - t_o}{t_o} = -0.16 \quad \text{or} \quad \frac{t_f}{t_o} = 0.84
\]

Therefore,

\[
\frac{w_f}{w_o} = 0.978
\]

From Equation 7 we obtain,

\[
R = \frac{\ln\left(\frac{w_o}{w_f}\right)}{\ln\left(\frac{w_o}{w_f} \frac{\ell_f}{\ell_o}\right)} = \frac{\ln\left(\frac{w_o}{w_f}\right)}{\ln\left(\frac{t_o}{t_f}\right)} = \frac{\ln(1.022)}{\ln(1.369)} = 0.314
\]
Following the assumptions stated in the Cup Drawing section in Chapter 2, the Lexan sheet is assumed to have planar isotropy and normal anisotropy. Therefore, a standard table of $\bar{R}$, a typical range of average normal anisotropy ratios can be used to determine the limiting drawing ratio (LDR) for the Lexan films. The R value obtained, 0.314, is below most sheet metals, and from a standard graph the LDR was calculated at 1.8. Given that the cup mold in the RIDFT process is 7.75 inches in diameter and equal to the punch diameter, then the maximum blank size can be calculated from the following,

$$d_{o,\text{max}} = LDR \cdot d_i = 1.8 \cdot 7.75 = 13.95 \text{ inches}$$

Experimentation with different blank sizes below the maximum LDR value were tested with the inclusion of fibers and resin. These experiments helped identify one of the most delicate and hard to control issues in this research: print-through of the fibers through a soft formable film. Experimentation was hence focused on optimizing parameters to eliminate print-through while achieving successful drawing.

**Determining the Response Variable**

One of the most crucial factors in RIDFT-IMD is surface finish and gloss; however, at high temperatures, suitable for forming the Lexan films, it became quite challenging to avoid print-through of the fibers through the film. A model was generated to conclude the parameters that were significant to the process while optimizing these parameters to avoid print-through. Experiments were conducted without the inclusion of resin to obtain more accurate results.

The texture and gloss of any material may be measured by visual inspection or computerized methods. Visual inspection is useful for quick assessment of gloss levels and surface smoothness and it is performed by comparing the sample to different
reference materials with varying gloss and texture levels. However, it was essential to this experiment to achieve exact values. In order to achieve good accuracy and precision repeatability an algorithm, created by Myungsoo Kim [24], was implemented to measure the percentage of light scatter produced by irregular surface finish. Using Matlab each sample prototype was imaged as a black and white image and the number of white pixels and black pixels was calculated. The white pixels indicated the amount of light scattered which was selected as the response for the experiment. It was initially proven by visual inspection, that the best surface finishes produced the least amount of white pixels. All pictures of each experimental run were taken in an enclosed box, sequentially, to avoid errors caused by variations in external light sources.

Response variable \((P) = \) Print-through (measured in number of white pixels)

**Choice of Factors, Levels, and Ranges**

Five controllable factors in the RIDFT process were chosen to conduct the experiment: temperature, type of mold, fiber reinforcement, time, and vacuum pull. The experiment incorporated two types of cup molds (a deep mold and a shallow mold) to form Lexan films at two different temperatures, a low temperature of 140° C and a high temperature of 160° C. The time of temperature exposure was varied, between 0 minutes to 1 minute and the fiber reinforcements used included plain weave carbon fiber and carbon fiber with the inclusion of fiberglass veil, material designed to eliminate print-through. The vacuum pull in this experiment, was either a sudden, fast pull or a gradual, slow pull. Table 1 summarizes the factors and factor levels of the experiment.
Table 1: Factor and Factor Level Combinations

<table>
<thead>
<tr>
<th>Factor A</th>
<th>Factor B</th>
<th>Factor C</th>
<th>Factor D</th>
<th>Factor 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>Mold type</td>
<td>Fiber reinforcement</td>
<td>Exposure</td>
<td>Vacuum Pull</td>
</tr>
<tr>
<td>140° C</td>
<td>Shallow (S)</td>
<td>Carbon (C)</td>
<td>0 min</td>
<td>Slow pull</td>
</tr>
<tr>
<td>160° C</td>
<td>Deep (D)</td>
<td>Carbon-Veil (CV)</td>
<td>1 min</td>
<td>Fast pull</td>
</tr>
</tbody>
</table>

**Choice of Experimental Design**

Given that the experiment consisted of five factors, the design used was a $2^{5-1}$ fractional factorial design. The fractional factorial design chosen was able to reduce the number of runs by ½, making it possible to work within the time frame and available resources.

An analysis of cost and effect variables was performed.

*Measurement* – A Matlab algorithm was used to transform pictures of experimental runs into black and white images. The amount of white pixels revealed the amount of light scattered and hence produced an accurate measure of print-through. The accuracy of the algorithm had a positive effect on the outcome of the experiment.

*Method* - The ability of the experimenter in operating the equipment and his knowledge about the process influenced the response.

*Mother Nature* – The amount of humidity in the air could have affected the integrity of the film; however, negligible.
Performing the Experiment

The experiments were conducted with the RIDFT 4-2 prototype equipment under low humidity levels. The experimental procedure consisted of vacuum forming Lexan films with dry reinforcements. The film and fibers were vacuumed between two flexible silicone membranes, brought to a specified temperature and then formed over a mold. The infusion step was excluded from the experiment for it was determined that inclusion of resin had no effect on the response variable. Furthermore, inclusion of the resin would lead to increased downtime between runs and could cause unwanted variations on stable experimental conditions.
Sixteen runs were performed while varying temperature, mold, reinforcements, time, and vacuum pull, which generated sixteen prototypes exhibiting different surface finishes and gloss levels. In order to quantify the results digital pictures of each prototype were taken in an enclosed compartment utilizing the camera’s flash as the only source of light. The images were transformed using Matlab into black and white images and the number of black and white pixels calculated. A control prototype, consisting of a single vacuum formed Lexan film with exceptional surface finish, was used as a reference point. Table 2 summarizes the experimental runs.

### Table 2: Experimental Runs

<table>
<thead>
<tr>
<th>Run</th>
<th>Desired Temp °C</th>
<th>Actual Temp (°C)</th>
<th>Ambient Temp °C</th>
<th>Mold/Draw</th>
<th>Fiber Reinforcement</th>
<th>Time to Temp (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>140</td>
<td>143</td>
<td>188</td>
<td>S</td>
<td>C</td>
<td>1:00</td>
</tr>
<tr>
<td>2</td>
<td>160</td>
<td>160</td>
<td>210</td>
<td>D</td>
<td>VC</td>
<td>0:00</td>
</tr>
<tr>
<td>3</td>
<td>160</td>
<td>163</td>
<td>220</td>
<td>S</td>
<td>VC</td>
<td>0:00</td>
</tr>
<tr>
<td>4</td>
<td>140</td>
<td>141</td>
<td>194</td>
<td>D</td>
<td>C</td>
<td>0:00</td>
</tr>
<tr>
<td>5</td>
<td>160</td>
<td>163</td>
<td>218</td>
<td>S</td>
<td>C</td>
<td>0:00</td>
</tr>
<tr>
<td>6</td>
<td>140</td>
<td>142</td>
<td>196</td>
<td>D</td>
<td>C</td>
<td>0:00</td>
</tr>
<tr>
<td>7</td>
<td>160</td>
<td>161</td>
<td>209</td>
<td>D</td>
<td>C</td>
<td>0:00</td>
</tr>
<tr>
<td>8</td>
<td>140</td>
<td>140</td>
<td>186</td>
<td>D</td>
<td>VC</td>
<td>0:00</td>
</tr>
<tr>
<td>9</td>
<td>160</td>
<td>162</td>
<td>221</td>
<td>S</td>
<td>C</td>
<td>0:00</td>
</tr>
<tr>
<td>10</td>
<td>140</td>
<td>142</td>
<td>190</td>
<td>S</td>
<td>VC</td>
<td>0:00</td>
</tr>
<tr>
<td>11</td>
<td>140</td>
<td>140</td>
<td>197</td>
<td>S</td>
<td>VC</td>
<td>0:00</td>
</tr>
<tr>
<td>12</td>
<td>160</td>
<td>160</td>
<td>199</td>
<td>S</td>
<td>VC</td>
<td>0:00</td>
</tr>
<tr>
<td>13</td>
<td>140</td>
<td>141</td>
<td>203</td>
<td>S</td>
<td>C</td>
<td>0:00</td>
</tr>
<tr>
<td>14</td>
<td>160</td>
<td>162</td>
<td>220</td>
<td>D</td>
<td>VC</td>
<td>0:00</td>
</tr>
<tr>
<td>15</td>
<td>140</td>
<td>143</td>
<td>190</td>
<td>D</td>
<td>VC</td>
<td>0:00</td>
</tr>
<tr>
<td>16</td>
<td>160</td>
<td>160</td>
<td>210</td>
<td>D</td>
<td>C</td>
<td>1:00</td>
</tr>
</tbody>
</table>

The highlighted runs indicate the prototypes with the least amount of white pixels, consequently, the prototypes with the best surface finishes. Table 3 shows the results obtained using Matlab, used to determine the prototypes with the best surface. Furthermore, the graph in Figure 37, provides a more clear representation of the data obtained from each run.
Table 3: Matlab Results

<table>
<thead>
<tr>
<th>Run</th>
<th>Object Rate</th>
<th>White Rate</th>
<th>Percentage Object Rate (%)</th>
<th>Percentage White Rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0.9999</td>
<td>8.4300E-05</td>
<td>99.990%</td>
<td>0.008%</td>
</tr>
<tr>
<td>Run1</td>
<td>0.9472</td>
<td>5.2800E-02</td>
<td>94.720%</td>
<td>5.280%</td>
</tr>
<tr>
<td>Run2</td>
<td>0.9978</td>
<td>2.2000E-03</td>
<td>99.780%</td>
<td>0.220%</td>
</tr>
<tr>
<td>Run3</td>
<td>0.9426</td>
<td>5.7400E-02</td>
<td>94.260%</td>
<td>5.740%</td>
</tr>
<tr>
<td>Run4</td>
<td>0.9999</td>
<td>8.4771E-05</td>
<td>99.990%</td>
<td>0.008%</td>
</tr>
<tr>
<td>Run5</td>
<td>0.9698</td>
<td>3.0200E-02</td>
<td>96.980%</td>
<td>3.020%</td>
</tr>
<tr>
<td>Run6</td>
<td>0.9998</td>
<td>2.4257E-04</td>
<td>99.980%</td>
<td>0.024%</td>
</tr>
<tr>
<td>Run7</td>
<td>0.9967</td>
<td>3.3000E-03</td>
<td>99.670%</td>
<td>0.330%</td>
</tr>
<tr>
<td>Run8</td>
<td>0.9999</td>
<td>1.2207E-04</td>
<td>99.990%</td>
<td>0.012%</td>
</tr>
<tr>
<td>Run9</td>
<td>0.9716</td>
<td>2.8400E-02</td>
<td>97.160%</td>
<td>2.840%</td>
</tr>
<tr>
<td>Run10</td>
<td>0.9959</td>
<td>4.1000E-03</td>
<td>99.590%</td>
<td>0.410%</td>
</tr>
<tr>
<td>Run11</td>
<td>0.9887</td>
<td>1.1300E-02</td>
<td>98.870%</td>
<td>1.130%</td>
</tr>
<tr>
<td>Run12</td>
<td>0.9764</td>
<td>2.3600E-02</td>
<td>97.640%</td>
<td>2.360%</td>
</tr>
<tr>
<td>Run13</td>
<td>0.9909</td>
<td>9.1000E-03</td>
<td>99.090%</td>
<td>0.910%</td>
</tr>
<tr>
<td>Run14</td>
<td>0.9957</td>
<td>4.3000E-03</td>
<td>99.570%</td>
<td>0.430%</td>
</tr>
<tr>
<td>Run15</td>
<td>0.9998</td>
<td>2.0015E-04</td>
<td>99.980%</td>
<td>0.020%</td>
</tr>
<tr>
<td>Run16</td>
<td>0.9911</td>
<td>8.9000E-03</td>
<td>99.110%</td>
<td>0.890%</td>
</tr>
</tbody>
</table>

Figure 37: White Percentage Rate on Experimental Runs

The control prototype exhibited the least amount of white pixels as shown in Figure 38. Runs 4, 6, 8, and 15 exhibited very low print-through as shown in Figure 39;
however, they failed to form properly over the mold. This trend revealed that there is a very fine line between eliminating print-through and achieving good forming. Several other runs such as run 2, 7, 10, and 14, shown in Figure 40, formed properly and achieved acceptable surfaces exhibiting low levels of print-through; nonetheless, greater than the print-through of those that did not achieve forming due to lower temperatures. Runs 1, 3, 5, 9, 11, 12, 13, and 16 exhibited exceptional forming, however, with high levels of print-through, as shown in Figures 41 and 42.

Control

Figure 38: Control Prototype
Figure 39: Prototypes 4, 6, 8, 15
Figure 40: Prototypes 2, 7, 10, 14
Figure 41: Prototypes 1,3,5 and 9
Figure 42: Prototypes 11, 12, 13, and 16
In order to optimize and determine the significant controllable parameters that affect print-through it was necessary to input the response values for each run into Design Expert software.

**Statistical Analysis of Data**

The initial results determined that the print-through level of the films varied with temperature variation, mold type, exposure time and rate of vacuum pull. The half-normal probability plot demonstrated that factor A (temperature), factor B (mold type), factor D (exposure time), factor E (vacuum pull), and the interaction BE were significant. From the ANOVA table obtained, the p-value for the model was extremely small, which indicated the significance of the model. However, the Predicted R-squared value of 0.4762 was not as close to the Adjusted R-squared value of 0.6931 as normally expected. This indicated a large block effect or a possible problem with the model or data. To overcome this problem a response transformation had to be performed.

A square root transformation yielded a Predicted R-squared value of 0.8081 which was in reasonable agreement with the Adjusted R-squared value of 0.8988. Furthermore the R-squared value of 0.9393 specified that more than 93 percent of variability in the response was explained by the model. It was determined that the print-through level of the prototypes varied with temperature (A), mold type (B), time (D), pull (E), and the interactions between B and E, BE, and D and E, DE, as shown by the Half Normal Probability plot in Figure 43.
The model equations are the following:

Final equation in terms of coded factors:

\[
\text{Sqrt(Print-through)} = + 0.097 + 0.028 \times A - 0.057 \times B \\
+ 0.015 \times D - 0.018 \times E + 0.0 \\
16 \times B \times E - 0.015 \times D \times E
\]  
(9)

Final equation in terms of actual factors:

Mold S  
Pull S  
\[
\text{Sqrt(Print-through)} = - 0.26874 + 2.83930 \times 10^{-3} \times \text{Temp} + 0.060415 \times \text{Time}  
\]  
(10)

Mold D  
Pull S  
\[
\text{Sqrt(Print-through)} = - 0.41495 + 2.83930 \times 10^{-3} \times \text{Temp} + 0.060415 \times \text{Time}  
\]  
(11)

Mold S  
Pull F  
\[
\text{Sqrt(Print-through)} = - 0.30503 + 2.83930 \times 10^{-3} \times \text{Temp} - 9.51927 \times 10^{-4} \times \text{Time}  
\]  
(12)

Mold D  
Pull F  
\[
\text{Sqrt(Print-through)} = - 0.38801 + 2.83930 \times 10^{-3} \times \text{Temp} - 9.51927 \times 10^{-4} \times \text{Time}  
\]  
(13)
Figure 43: Half Normal Plot

The Normal Plot of Residuals in Figure 44 is approximately linear, virtually many of the design points fall on the straight line, which indicates that the assumption of normality has not been violated. The plot of Residuals vs. Predicted in Figure 45 indicates that the assumption of constant variance has not been violated because the plot does not show any pattern or structure. Furthermore, the plot of Residuals vs. Run in Figure 46 indicates that the assumption of independence has not been violated because the data points are randomly scattered through out the plot.
Figure 44: Normal Plot of Residuals

Figure 45: Residuals vs. Predicted.
The interaction graph of mold type and vacuum pull, shown in Figure 47, indicates that utilizing a deep mold and pulling the vacuum in a fast, sudden manner, gives a lower print-through level in the polycarbonate film. The interaction graph of exposure time and vacuum pull in Figure 48 indicates that a fast pull with minimal exposure time will result in the least amount of print-through. Moreover, the graphs of Residuals vs. Factor in Figures 49 through 52, reveal that the variability between the high and low levels for all factors is not high, thus there is no dispersion effect.
Figure 47: BE Interaction

Figure 48: DE Interaction
Figure 49: Residuals vs. Temperature

Figure 50: Residuals vs. Mold
Figures 51 and 52: Residuals vs. Time and Residuals vs. Pull, respectively.
The process was statistically optimized to determine the best combination of factor levels that would provide the lowest possible print-through level. The following results were obtained:

Temperature = 147.84° C  
Mold type = Deep mold  
Fiber reinforcement = Carbon (negligible factor)  
Time = .03 min  
Vacuum pull = Slow

A validation run, shown in Figure 53, was performed using the optimized parameters suggested to reaffirm the relevance of the experiment. The amount of white pixels calculated for the validation run was 0.0015. This value fell within the confidence intervals of the predicted response as shown in Table 4.

Validation Run

Figure 53: Validation Run
Table 4: Response Prediction Interval

<table>
<thead>
<tr>
<th>Factor</th>
<th>Name</th>
<th>Level</th>
<th>Low Level</th>
<th>High Level</th>
<th>Std. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Temp</td>
<td>147.8</td>
<td>140</td>
<td>160</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>Mold</td>
<td>D</td>
<td>D</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Reinforcements</td>
<td>C</td>
<td>C</td>
<td>VC</td>
<td>N/A</td>
</tr>
<tr>
<td>D</td>
<td>Time</td>
<td>0.03</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>E</td>
<td>Pull</td>
<td>S</td>
<td>S</td>
<td>F</td>
<td>N/A</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Prediction</th>
<th>SE</th>
<th>95% CI</th>
<th>95% CI</th>
<th>SE</th>
<th>95% PI</th>
<th>95% PI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Print-through</td>
<td>4.31E-05</td>
<td>0.4</td>
<td>1.57E-03</td>
<td>3.30E-03</td>
<td>0.3</td>
<td>4.98E-03</td>
</tr>
</tbody>
</table>

The validation run was implemented to check only for the response variable (print-through) and the resulting prototype was not intended to produce the best forming scenario. As seen in Figure 53, wrinkles were present in the cup prototype. A clear trade-off between low print-through and good formability was recognized.

**Determining the Operating Window**

Having optimized the temperature and determining minimum and maximum ranges it was imperative to adjust the operating window for resin infusion. An unpromoted vinyl-ester resin, Hetron 922INF, was implemented and catalyzed with a concentration of 1 percent Trigonox K-90, successfully achieving delay of cure upon a temperature increase (up to 160° C). The resulting, operating window allowed the composite assembly (resin, fibers, and film) to form. Issues predicted by the previous experiment prevailed in prototypes formed with parameters to minimize the amount of print-through and prototypes formed with parameters to maximize forming capability. The operating window difficulty, encountered at the beginning of this project was overcome; however, issues concerning surface finish must be addressed in future research.
A set of prototypes, both reinforced with carbon fiber, are shown in Figures 54 and 55. The first prototype was produced following the optimized parameters for minimized print-through. The second prototype was produced using the optimized parameters for maximized print-through. The first prototype exhibited better surface finish as predicted, but wrinkling occurred at the edges of a relatively simple mold (car hood mold). The second prototype formed well over the mold, however, a considerable amount of print-through was observed.

Figure 54: Minimizing print-through

Figure 55: Maximizing print-through
By optimizing RIDFT-IMD parameters in terms of surface response, the temperature for the operating window was determined and the adjustment of curing agents made. Un-promoted vinyl-ester resin and Trigonal K-90 were able to delay cure within a temperature range of 140° C to 160° C making the forming of the composite assembly possible, prior to the start of the resin cure cycle. Surface irregularities were improved; however, glass surface finish has not yet been attained.

Initial efforts to achieve better surface consisted of utilizing double layers of Lexan films to simulate a gage increase. Theoretically, the fibers would in-bed in the first layer without reaching the second layer, affecting surface finish. The forming temperature utilized for these experiments was 160° C but due to the increase in gage, more time was required for the films to reach that temperature. Forming of the composite assembly was successful, however print-through was observed. When the films detached a subtle difference was recognized between the first film and the second film, indicating that varying gage may represent an additional controllable parameter requiring further investigation. Figure 56 shows the differences from layer to layer.

![Figure 56: Differences in Stacked Layers](image-url)
CHAPTER 7
CONCLUDING REMARKS

The primary objective of this research was to develop an innovative and effective process to utilize thermo-formable polycarbonate films for the in-mold decoration (IMD) of composites manufactured using the Resin Infusion between Double Flexible Tooling (RIDFT) process. Process development for this technology required a clear understanding of all the controllable parameters in the RIDFT process that were influential in the production of successful prototypes. The project demanded an analytical and systematic approach to modeling and predicting forming and response behavior of a resin/fiber-polycarbonate composite. Initial results identified several difficulties in forming and preserving the integrity of the composite assembly. To validate the process, experimentation was performed by simplifying process parameters to identify the most crucial controllable factors that could potentially be optimized to achieve improved results.

The primary goal of this research was to produce in-mold decorated components manufactured by the RIDFT process that could match conventionally painted parts. Significant progress was attained yet several issues concerning surface finish must be addressed and further research conducted.

Formability of Assembly

Sequential experimentation with statistical validation proved good formability of the composite assembly at 160° C; however, surface finishes exhibited high print-through of the fibers into the film. Optimization software determined that the best possible scenario for minimal print-through was forming close to 147° C; however, at this temperature formability of the film was limited to very subtle contours, such as the car hood pattern utilized for the final validation runs. With a controllable environment the prototypes were able to exhibit uniform trends across the surface. With the optimized
parameters, the limitations of the film were identified and the surface finish was significantly improved from previous results.

Operating Window

Knowing the temperature range and the behavior of the assembly at different temperatures within this range was crucial to determining the necessary delay of resin cure required to avoid premature curing. A change was made from a promoted vinyl-ester resin to an un-promoted vinyl-ester resin (Hetron 922 INF) that was catalized with curing agent, Trigonox K-90. This catalyst had the capability to maintain the resin stable for approximately six minutes at a temperature of 170°C before starting its curing sequence. The problems encountered with premature resin cure at the beginning of this project were surmounted.

Surface Finish

From previous results, surface finish was considerably improved. Quantifying results based on light reflection was significant; however further experimentation must be conducted. The prototypes exhibiting the least amount of light scatter, and hence, the least amount of print-through still exhibited certain undesirable irregularities by industry standards. These irregularities could have various root causes, ranging from mold finish, to silicon finish, to fiber reinforcements, to gage length of the film. Each possible root cause must be isolated and statistically analyze to identify its potential significance. Moreover, a more precise method of analyzing surface finish must be implemented to test and quantify results. A surface profilometer can distinguish surface smoothness and identify variations more precisely than white pixel imaging, method implemented for the purposes of this research.
Future Work

Future work on the development of a valuable RIDFT-IMD process should be concentrated on isolating possible root causes of surface irregularities. Developing a detailed understanding of all potential factors that could have an effect on surface finish that were not addressed in this research, such as silicone surface or surface finish of mold is crucial. A comprehensive approach will entail the following:

1) Investigate the influence of the silicone surface interface on print-through and work with various silicone manufacturers to identify the best possible characteristics in terms of a perfectly homogenous surface.

2) Conduct statistical experimentation on a variety of molds with different surface finishes, identifying a print-through threshold.

3) Investigate in detail the interaction between the silicone and the mold (the silicone-mold interface)

4) Conduct comparative testing by isolating the potential factors influencing surface irregularities.

5) Incorporate substrate layers to eliminate print-through at higher forming temperatures and conduct statistical testing based on statistical tests performed in this study.

6) Increase the gage of the film and evaluate print-through outcome vs. forming ability.

7) Implement the use of a surface profilometer to quantify surface finish

8) Develop a full understanding of the effect of resin inclusion on the outcome of each experiment through the utilization of finite element modeling.

These recommendations can potentially lead to the creation of a significant model explaining every single variable associated with the RIDFT-IMD process. Ongoing work will show continuous progress towards the development of a viable process that can measure up to the standards of class ‘A’ surface quality finish in the industry.
REFERENCES

BIOGRAPHICAL SKETCH

Carlos Andres Puentes was born in Cali, Colombia on August 28, 1982. He earned his bachelor’s degree in Industrial and Manufacturing Engineering from Florida State University in the fall of 2005. He continued with Florida State University working in composites manufacturing with the High Performance Materials Institute (HPMI), while pursuing his master’s degree in Industrial and Manufacturing Engineering. Over the course of two years, he managed to improve upon the Resin Infusion between Double Flexible Tooling Process, and provided valuable guidelines for future experimentation.