ABSTRACT

In-mold coating (IMC) products have been used for many years to enhance the surface of reinforced plastics, providing a smooth, sealed surface used as a conductive or non-conductive primer for subsequent painting operations. Initially, the IMC process was successfully applied to the Sheet Molding Compound (SMC) compression molded parts. Recently a new class of coating materials has been developed and applied to thermoplastic substrates. The potential benefits of using In-Mold Coating as a topcoat for thermoplastics are large due to the fact that painting is a very costly and non-environmentally friendly operation that is sought to be replaced. However, the acceptance of IMC as a competitor to the traditional painting process will depend upon the ability of the former to deliver coated parts in short cycle times with best possible surface quality and adhesion.

The core of this research work is the development of an approach to solve cases of non-uniform heat transfer between thermoplastic and mold with emphasis on cycle time, uniformity of cure, and adhesion in the Injection Molding/In-Mold Coating (IM/IMC) process. Finite Difference Method (FDM) is first applied to solve 1-dimensional (1D) heat conduction. The model is then expanded to solve 2-dimensional (2D) heat conduction. An analytical solution available in the literature is used to verify both models. The results of the heat transfer analysis are used to predict IMC cure time, which
is a major part of the Injection Molding/In-Molding Coating cycle time. These predictions agree very well with experimental data.

Extensive experimental work has been conducted to understand how different processing conditions such as packing pressure, temperature, coating volume, and delay time between thermoplastic and coating injections affect adhesion and surface quality of the parts. Here, the Pilot Facility including 50-ton injection molding machine, in-mold coating high pressure pump, mold, temperature controllers, heaters, sensors, and data acquisition system is used to conduct experiments with three different thermoplastics: Acrylonitrile Butadiene Styrene (ABS), Polycarbonate Acrylonitrile Butadiene Styrene (PCABS), and Polyethylene Terephthalate (PET). Adhesion of the coating to the substrate has been evaluated using scratch test (ASTM D3359) and button pull test (ASTM D4541). From the results of these experiments we indicate that heat transfer between thermoplastic and mold plays an important role if one desires to achieve uniform coating cure and equal adhesion anywhere in the part.
Dedicated to my father, my mother, and my brother Dmitry
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Technology, June 2001, Vol. 5, No. 2

2. Cabrera-Rios, Zuyev, Chen, Castro, Strauss, Optimizing Injection Gate Location
and Cycle Time For The In-Mold Coating (IMC) Process, Polymer Composites

3. Zuyev, Castro, Applications of Chemo-Rheology to Develop Process Windows in
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FIELDS OF STUDY

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CHAPTER 1

INTRODUCTION

Polymers have been known to mankind for thousands of years, from natural rubber to the first synthetic polymer developed around the early 20th century and finally to the current engineering thermoplastics. The polymer industry has been growing continuously, providing alternatives to conventional materials for example wood, ceramic, or metal while creating new applications for instance wire tubing and building insulation. Because of their advantages, such as corrosion resistance, light weight, and good surface quality, thermoplastics are extensively used in the automotive industry.

Injection molded thermoplastic materials are used in a variety of applications, such as the transportation, automotive, marine, recreation, construction, office products, as well as lawn and garden equipment manufacturing industries. Their use, however, is not without problems. In many instances, molded thermoplastic parts may need to be coated to facilitate paint adhesion, or to satisfy other surface property requirements, such as appearance, durability, and weather resistance. Due to inherently low surface energy of thermoplastics, they are generally difficult to paint or coat. Moreover, in view of the variation among the surface properties of individual thermoplastics and the coating
compositions to be applied, a method that works with one specific thermoplastic may not work with another. Hence, a variety of methods have been developed to achieve adhesion of coatings to the surface of molded thermoplastics materials.

1.1. In-Mold Coating of Sheet Molding Compound.

There are known applications of In-Mold Coatings (IMC) with the objective to provide generally smooth surfaces, improve durability and other surface properties, and reduce or eliminate substrate porosity. In particular, today, IMC is considered an integral part of the molding cycle in production of compression molded Sheet Molding Compound (SMC) exterior automotive body parts [1]. Figure 1.1 depicts all stages of SMC Compression Molding/In-Mold Coating (SMC/IMC) process. The coating is a single-component reactive fluid, designed to improve the surface quality of Fiber Reinforced Plastic (FRP) moldings in functional and cosmetic properties [2]. When injected onto a cured SMC part, it cures and bonds to provide paint like coating to the part surface. Since the cured IMC is 100% solid and releases no chemicals during the molding process, it is an environmentally friendly alternative to painting. The automotive industry and environmentalists welcome IMC because painting booths are inefficient and hazardous to the environment due to the chemicals that they release to the atmosphere. To date, the most common method of applying IMC involves removing the mold clamping force at the end of the SMC curing stage and separating the mold halves by approximately 1 mm.
IMC is injected automatically into the cavity, the press is re-closed, and force is applied to spread the coating across the surface of the part. The second method involves reduction of the mold clamping force and use of the IMC injection pressure to separate the tool halves during IMC coating. The third method, at the other end of the spectrum, involves maintenance of a significant clamping force during the IMC injection process, and relies on compressibility of the SMC and the pressure of the injection system to coat the part with IMC. However, even in this approach, the mold opens up near the end of injection as demonstrated by Castro and Griffith [3]. The first method is commonly called low pressure IMC, and the latter two methods are sometimes referred to as high pressure IMC.

1.2. In-Mold Coating of Injection Molded Thermoplastic Parts.

It is desirable to have a method by which a coating could be applied to a thermoplastic part in the mold, resulting in a surface finish suitable for end use application, or one which would require less surface preparation treatment than heretofore utilized. The IMC cycle for thermoplastics is composed of three stages: filling, packing, and curing. During the filling stage, the coating flows by compressing the substrate and spreads until it reaches the mold end. In the packing stage, more coating is introduced until the volume for desired coating thickness is injected. During the curing stage, the coating solidifies by a chemical reaction. Figure 1.2 depicts all stages of Injection Molding/In-Mold Coating
(IM/IMC) process. Unlike its SMC counterparts, thermoplastic injection molds have no shear edges. Any significant opening of the mold, caused by the injection of the liquid coating, will result in the material escaping from the mold and must be avoided. As a consequence, the clamping tonnage should be high enough to prevent such mold deflection. Thus, in the ideal case for thermoplastics, the flow of the coating will be due to compression of the substrate, much like in high pressure IMC for SMC, but without any mold opening. The differences between SMC and thermoplastic IMC are contrasted in figure 1.3.

Applications of In-Mold Coating process for thermoplastic substrates include but are not limited to: automotive, marine, heavy truck, agriculture, industrial, and consumer industries. Figure 1.4 outlines some of the applications of IMC to SMC and thermoplastic parts. There are many incentives and benefits of applying IMC process to thermoplastic substrates in the automotive industry in particular. The following are some incentives that motivate automotive companies:

- IMC is an environmentally friendly process
- IMC is an alternative to very costly painting process
- Coating protects thermoplastic automotive part from outdoor exposure (UV light, oils, chemical spills)
- IMC improves thermoplastic part’s surface appearance

Following the incentives the benefits for the automotive industry are outlined below:
• Reduction in capital investments
• Reduction in floor space for painting lines
• Reduction in man power supporting painting facilities
• Reduction of emissions cost
• Lean manufacturing
• Environment protection

1.3. Research Objectives.
There are five main research issues that arise when considering IMC process as a replacement for painting, as represented schematically in figure 1.5. The first three research issues are uniformity of cure, cycle time, and adhesion. Non-uniform coating cure, long cycle times, and bad adhesion are the results of poorly understood coating kinetics, ineffectively designed mold thermal system, and incorrectly chosen processing conditions. The fourth issue is concerned with our ability to coat a part which can be very challenging, especially if the part is large and complex. The factors that affect IMC filling are injection nozzle(s) placement, IMC rheology, and processing conditions. The final issue is dealing with coating leakage. If the processing conditions are not set up correctly, or if the clamping tonnage is not sufficient enough, the coating process will result in leakage and must be avoided. While the last two issues are beyond the scope of this study, the first three research issues and the factors affecting them are the main concern
of this dissertation. Our ability to deliver In-Mold Coated thermoplastic parts in short
cycle times with good surface quality and adhesion will help to fulfill the current need in
several industries to replace paint operations with environmentally friendly IMC process.
The structure of this dissertation is as follows: Chapter 2 deals with IMC cure kinetics. In
this chapter, Differential Scanning Calorimeter experiments are shown, kinetic model to
predict the IMC reactive behavior is derived and explained in great detail, and model
predictions are presented. Finally, one-component temperature activated reactive systems
are compared to two-component mixing activated reactive systems.
Chapter 3 describes one dimensional heat transfer modeling between mold and
thermoplastic. Heat transfer plays a critical role in the IMC process. To ensure that
coating solidifies at the same time on the surface of a thermoplastic part, the substrate
must have a uniform thermal history. For example, an automobile bumper, which has
thickness variation, should have thoroughly designed cooling system to allow for the
coated surface to be at the same temperature when IMC injection takes place. The heat
transfer, thus, has a direct influence on uniformity of the curing reaction which in turn
affects adhesion, final part appearance [4], and overall cycle time. This chapter also has a
review of Finite Difference Approximation method, which is used to solve 1D and 2D
heat transfer equations.
Chapter 4 discusses more complex, two dimensional heat transfer modeling between
thermoplastic and mold. In this chapter, the theory behind the modeling is outlined first.
Then, injection molding experiments along with infrared analysis of the parts are presented. Finally, one dimensional temperature predictions are compared with the two dimensional temperature predictions.

Chapter 5 illustrates IMC experimental work. This chapter discusses IMC Pilot Facility, shows pictures of coated ABS, PCABS, and PET parts along with the temperature and pressure data, and processing conditions used to make those parts.

Chapter 6 is dedicated to qualitative and quantitative measurements of adhesion of IMC to thermoplastic substrates. In this chapter, two methods to evaluate adhesion are used: button pull test and scratch test. The adhesion results are interpreted with the aid of the heat transfer analysis.

Chapter 7 emphasizes key research contributions, summarizes particularly important findings from previous chapters and discusses future work.
Figure 1.1. Schematic of SMC Compression Molding/In-Mold Coating (SMC/IMC) process.
Figure 1.2. Schematic of Injection Molding/In-Mold Coating (IM/IMC) process.
Figure 1.3. Key differences between SMC and thermoplastic IMC.
Figure 1.4. Applications of IMC to SMC and thermoplastic parts.
Figure 1.5. Research issues and factors affecting them.
CHAPTER 2

KINETICS

To characterize a reactive system properly, it is necessary to study its cure kinetics. In the following sections we will first discuss the use of Differential Scanning Calorimeter as a tool to obtain raw reaction data. We will then provide a background on the free radical reaction mechanism and a complete set of equations involved in describing it. We will discuss the experiments, derive the kinetic constants, and show the model predictions. Finally, we will compare temperature activated and mixing activated coating systems.

2.1. Differential Scanning Calorimeter.

Differential Scanning Calorimeter (DSC) is the most widely used of all thermal methods [5]. DSC measures temperatures and heat flows associated with thermal transitions in a material. Common usage includes investigation, selection, comparison, and end-use performance of materials in research, quality control, and production applications [6]. Properties measured include glass transitions, phase changes, melting, crystallization, and cure kinetics to name a few. This thermal technique uses the differences in heat flow as a function of temperature or time between a substance and a reference subjected to a
controlled temperature program. While other thermal techniques record the differences in temperature, DSC is distinctive in that it measures differences in energy.

Figure 2.1 is a picture of a DSC cell [6]. Small aluminum sample pans sit on raised platforms inside the dynamic sample chamber. Heat is transferred through the discs and up into the sample and reference pans. The difference in heat is monitored by the thermocouple junction formed between the platform and chrome discs attached to the underside of the platforms. When a temperature difference is detected between the sample and reference by the temperature controller, energy, in the form of current, is supplied to keep the two thermally balanced [7]. The energy input is proportional to the heat capacity of the sample. A DSC curve plots the energy input per unit time as a function of temperature [8].

DSC is used to obtain a wide variety of data. In figure 2.2, three separate thermal transitions for a typical semicrystalline polymer are shown. The first thermal transition (figure 2.2 part A) is referred to as the glass transition temperature or \( T_g \) of the material. Polymers exhibit the glass transition when a viscous or rubbery state is transformed into a hard, brittle, glass-like state [9]. In areas below the \( T_g \), the material will be hard and brittle, like a solid. In temperature ranges above the \( T_g \), the material will act more like a viscous liquid. The next thermal transition (figure 2.2 part B) is an exothermic process in which heat is given away from the sample and is called crystallization. This peak can tell
us the crystallization temperature (the temperature at the highest point) as well as the 
energy of crystallization (the area under the peak). Most importantly, this peak tells us 
that the material can, in fact, crystallize. We wouldn’t see it in an amorphous polymer. 
The third thermal transition (figure 2.2 part C) is referred to as melting. When we reach 
the polymer’s melting temperature, or \( T_m \), those polymer crystals start to melt. The 
chains come out of their ordered arrangements and start to move freely past one another. 
Again, we can obtain the melting temperature (the temperature at the lowest point) as 
well as energy of melting (the area under the peak). When the polymer crystals melt, they 
must absorb heat in order to do so. This means that when we reach the melting 
temperature, the polymer’s temperature won’t rise until all the crystals have melted. This 
also means that the furnace is going to have to put additional heat into the polymer in 
order to both melt the crystals and keep the temperature rising at the same rate as that of 
the reference pan. This extra heat flow during melting shows up as a large valley in our 
DSC plot as heat is absorbed by the polymer (figure 2.2 part C). Figure 2.3 represents all 
the parts of figure 2.2 put together.

DSC analysis for thermosets are slightly different. Usually with increasing temperature, 
molecules will solidify via a chemical reaction and crosslink into a network. In a DSC 
scan of this process a large heat evolution peak would be the heat of reaction (see figure 
2.4). This network can also display a \( T_g \) when it is fully cured, but they will not 
crystallize or melt. At high enough temperature, the thermoset will decompose.
For this research, DSC was used as a tool to obtain required information including the heat given away in both dynamic and isothermal scans. Data obtained has been analyzed and will be presented in later sections. While the DSC is a powerful tool in thermal analysis, it does have several drawbacks. The sample size of the DSC is extremely small, usually on the order of 5 to 20 milligrams. Such a small sample size leaves room for error. Another drawback is the lag time between positioning the sample in the cell and the time the unit reaches the desired temperature. This cannot be avoided as heat escapes the pre-heated cell when the sample is introduced.

2.2. Free Radical Polymerization Mechanism under Isothermal Conditions.

In-Mold Coating reaction system obeys a free radical reaction mechanism. A kinetic model has been developed to describe addition co-polymerization with initiation, inhibition, and propagation. By assuming that the termination step is negligible and the reaction rate between inhibitor and initiator’s free radicals is much faster than any other reactions, the kinetic mechanism can be simplified into a single equation. The parameters, rate constant of initiator decomposition, rate constant of propagation, activation energy of decomposition, and activation energy of propagation are estimated from the inhibition time and the time to reach the peak exotherm of isothermal DSC curves. Let’s discuss the free radical polymerization model in more detail.

In the initiation step an initiator molecule decomposes to give two free radicals:
\[ I \rightarrow 2R \cdot \]

Those free radicals react with molecules of inhibitor present in the system:

\[ R + Z \rightarrow RZ \cdot \]

In the propagation step, free radicals react with molecules of monomer:

\[ R \cdot +M \rightarrow RM \cdot \]

Here, we use the free radical kinetic model originally developed by Stevenson [10] and used by Lee [11], as well as Castro and Lee [12] to represent the curing reaction of the IMC. The assumptions for this model are as follows:

1. A single initiator and inhibitor are used
2. No monomer reacts until the number of initiator’s free radicals is equal to the effective number of inhibitor molecules initially present
3. Free radical termination is negligible

Based on these assumptions the equations representing the model using the following notation are given next:

- \( c_{i0} \) : Initial concentration of initiator
- \( c_{z0} \) : Initial concentration of inhibitor
- \( c_{m0} \) : Initial concentration of monomer
- \( c_i \) : Concentration of initiator at a given time
- \( c_z \) : Concentration of inhibitor at a given time
\( c_M \) : Concentration of monomer at a given time

\( t_Z \) : The time when all the inhibitor is consumed (inhibition time)

\( t_m \) : The time at which peak exotherm occurs

\( t \) : Time

\( q \) : Inhibitor efficiency

\( f \) : Initiator efficiency

\( k_{d0} \) : Frequency factor for decomposition

\( k_d \) : Kinetic rate constant for decomposition at a given temperature

\( k_{p0} \) : Frequency factor for propagation

\( k_p \) : Kinetic rate constant for propagation at a given temperature

\( E_d \) : Activation energy of decomposition

\( E_p \) : Activation energy of propagation

\( R \) : Ideal gas constant

\( T \) : Temperature

For \( t < t_Z \)  
\[-\frac{dc_i}{dt} = k_d c_i \]  \hspace{1cm} (2.1)

where \( k_d \) and \( k_p \) are represented with an Arrhenius type equation:

\[ k_d = k_{d0} e^{-\frac{E_d}{RT}} \quad k_p = k_{p0} e^{-\frac{E_p}{RT}} \]  \hspace{1cm} (2.2)
For isothermal conditions, we can integrate equation 2.1 to get the following:

\[ c_i = c_{i0}e^{-k_it} \]  
\[ (2.3) \]

Therefore, the concentration of free radicals in the initiation step is equal to twice the initial concentration of initiator minus the concentration of initiator at a particular time step. Mathematically, it can be expressed:

\[ c_{R*} = 2fc_{i0}(1 - e^{-k_it}) \]  
\[ (2.4) \]

Note that initiator and inhibitor efficiencies, \( f \) and \( q \), are introduced in this model because of the following reasons:

1. Not every molecule of initiator produces a free radical
2. Not every molecule of inhibitor can react with a free radical

The values of \( f \) and \( q \) are between zero and one.

For \( t = t_z \)

\[ qc_{Z0} = 2fc_{i0}(1 - e^{-k_it_z}) \]  
\[ (2.5) \]

Equation 2.5 means that at the time when all inhibitor is consumed the initial concentration of inhibitor is equal to twice the initial concentration of initiator minus the concentration of initiator at time \( t_z \). Let’s use equation 2.5 to find inhibition time \( t_z \).

\[ t_z = -\frac{1}{k_{d0}}\ln(1 - \frac{qc_{Z0}}{2fc_{i0}})e^{\frac{\varepsilon_z}{RT}} \]  
\[ (2.6) \]

For \( t > t_z \)

\[ \frac{dc_m}{dt} = -k_pc_me_{R*} \]  
\[ (2.7) \]
The concentration of free radicals at a particular time step in the propagation stage is equal to twice the initial concentration of initiator minus the concentration of initiator at that time step minus the initial concentration of inhibitor. Mathematically, it can be expressed in the following way:

\[ c_{R*} = 2f c_{10}(1 - e^{-k_d t}) - q c_{Z0} \]  

(2.8)

Using equation 2.5, equation 2.8 transforms into:

\[ c_{R*} = 2f c_{10}(e^{-k_d t} - e^{-k_d t}) \]  

(2.9)

Let’s substitute equation 2.9 into equation 2.7 and solve it in terms of \( c_m \):

\[ \frac{dc_m}{dt} = -k p_0 e^{\frac{-E_p}{RT}} c_m 2f c_{10}e^{-k_d t} (1 - e^{-k_d t}) \]  

(2.10)

Let \( A_i = 2k p_0 f c_{10} e^{-k_d t} \). Rewriting equation 2.10 yields:

\[ \frac{dc_m}{dt} = -A_i e^{\frac{-E_p}{RT}} c_m(1 - e^{-k_d (t-t_0)}) \]  

(2.11)

Let’s introduce a new term called conversion, \( c^* \), which indicates the extent of chemical reaction. Mathematically, conversion can be expressed by the following equation:

\[ c^* = \frac{c_{m0} - c_m}{c_{m0}} \]

\[ c_m = c_{m0}(1 - c^*) \]  

(2.12)

Let’s substitute equation 2.12 back into equation 2.11.
It is important to note that at the time when peak exotherm occurs, since the reaction rate is the maximum, the second derivative of conversion is zero, e.g. \( \frac{d^2 c^*}{dt^2} = 0 \). Taking another derivative of equation 2.13 yields:

\[
\frac{d}{dt}\left( \frac{dc^*}{dt} \right) = A_1 e^{-\frac{E_1}{RT}} \left[ (1-c^*)(-k_d e^{-k_d(t-t_2)}) + A_1 e^{-\frac{E_1}{RT}} (1-e^{-k_d(t-t_2)})^2 (1-c^*)(-1) \right] = 0,
\]

\[
A_1 e^{-\frac{E_1}{RT}} = \frac{k_d e^{-k_d(t-t_2)}}{(1-e^{-k_d(t-t_2)})^2} = C
\]

We are going to use equations 2.6 and 2.14 later for deriving the kinetic constants.

2.3. Free Radical Polymerization Mechanism under Non-Isothermal Conditions.

Derivation of free radical model equations under non-isothermal conditions is a more challenging task since temperature is no longer constant. Therefore, we cannot simply integrate equations 2.1 and 2.7 the way we did it in the previous section.

Let’s start with the initiation stage:

For \( t < t_2 \) \( \frac{-dc_i}{dt} = k_d c_i \) \( \frac{c_i^*}{c_{i10}} = \frac{c_{i10} - c_i(t)}{c_{i10}} \) \( 21 \)
Rearranging equation 2.16 yields:

\[ c_i(t) = c_{i0}(1 - c_i^*(t)) \]  
(2.17)

Substituting equation 2.17 back into the first order kinetic model (equation 2.15) results:

\[ -\frac{dc_{i0}(1 - c_i^*(t))}{dt} = k_d c_{i0}(1 - c_i^*(t)) \]  
(2.18)

Equation 2.18 can be manipulated to get the following:

\[ \frac{dc_i^*(t)}{dt} = k_d (1 - c_i^*(t)) \]  
(2.19)

Concentration of the free radicals in the initiation step is equal to twice the initial concentration of initiator minus the concentration of initiator at a particular time step.

\[ c_{R*} = 2 f (c_{i0} - c_i(t)) \]  

Substituting equation 2.17 into the above equation yields:

\[ c_{R*} = 2 f c_{i0} c_i^* \]  
(2.20)

For \( t = t_Z \) \( q c_{Z0} = 2 f (c_{i0} - c_i(t_Z)) \)  
(2.21)

\[ c_i^*(t_Z) = \frac{c_{i0} - c_i(t_Z)}{c_{i0}} \]  
(2.22)

Rearranging equation 2.22 results:

\[ c_i(t_Z) = c_{i0}(1 - c_i^*(t_Z)) \]  
(2.23)

Let substitute equation 2.23 back into equation 2.21:
\[
\frac{qc_{z_0}}{2fc_{t_0}} = c_i^*(t_z) \tag{2.24}
\]

Let’s consider propagation stage:

For \( t > t_z \) \[
\frac{dc_m}{dt} = -k_p c_m c_{R*} \tag{2.25}
\]

Equation 2.25 cannot be integrated due to the temperature being non-isothermal. The concentration of free radicals at a particular time step in the propagation stage is equal to twice the initial concentration of initiator minus the concentration of initiator at that time step minus the initial concentration of inhibitor.

\[
c_{R*} = 2f(c_{i0} - c_i(t)) - qc_{z0} \tag{2.26}
\]

Let’s take equation 2.21 and plug it into equation 2.26:

\[
c_{R*} = 2f(c_i(t_z) - c_i(t)) \tag{2.27}
\]

Let’s substitute equations 2.12 and 2.27 into equation 2.25:

\[
\frac{dc^*}{dt} = k_p 2f (1 - c^*)(c_i(t_z) - c_i(t)) \tag{2.28}
\]

Let’s substitute equations 2.17 and 2.23 into equation 2.28:

\[
\frac{dc^*}{dt} = k_p 2f (1 - c^*)c_{i0}(c_i^*(t) - c_i^*(t_z)) \tag{2.29}
\]

To calculate conversion of the coating in non-isothermal conditions, equations 2.19, 2.24, and 2.29 have to be solved simultaneously.
2.4. Differential Scanning Calorimeter Results, Constants Derivation, and Model Predictions.

In this section several isothermal experiments with Stylecoat (coating for thermoplastics) are shown, then the process of evaluating kinetic constants is described, and finally model predictions are discussed.

Isothermal DSC runs have been performed for Stylecoat with different catalyst levels (Tetra Butyl Perbenzoate (TBPB)): 0.5, 1.0, 1.5, and 2.5% at different temperatures: 90, 100, 110, 120, 130, and 140 degree Celsius. Non-isothermal scans for Stylecoat have also been performed for all catalyst levels. For a complete set of DSC experiments, please refer to Zuyev’s MS Thesis [7]. Figures 2.5 and 2.6 show selected isothermal scans for two catalyst levels: 1.5% and 2.5% respectively. From the figures it can be noted that the higher the catalyst level and the higher the temperature, the faster the reaction. From the DSC data we get two important values, inhibition time – the time when reaction starts ($t_z$) and the time of the peak exotherm ($t_m$). In the free radical polymerization mechanism, those two values are used to derive kinetic parameters. For instance, let’s further evaluate equation 2.6 that contains inhibition time $t_z$. If we take a natural logarithm of equation 2.6, we get:

$$\ln t_z = \ln\left(-\frac{1}{k_{f0}}\ln(1 - \frac{q c_{Z0}}{2f c_{f0}}) + \frac{E_d}{RT}\right)$$

(2.30)
Since we know the inhibition times from the experiments, we can plot \( \ln t_z \) versus \( \frac{1}{T} \) to get a line which can be fitted to a linear equation, as shown in figure 2.7. From the slope of the above equation we can get the value for \( E_d \). From the intercept we can get the value for \( k_{z0} \). Note that the ratio \( \frac{q c_{z0}}{2 f c_{i0}} \) is usually unknown simply because it is difficult to keep track of the initial concentration of inhibitor added to the system; coating manufacturers usually do not include the value for \( c_{z0} \) into material data sheets. Thus we can try several values of the ratio \( \frac{q c_{z0}}{2 f c_{i0}} \) and choose the one that improves the straight line fit. Lee and co-workers [11] have found that \( \frac{q c_{z0}}{2 f c_{i0}} = 0.01 \) is usually a good compromise. To evaluate \( f k_{p0} \) and \( E_p \), we take the maximum reaction rate from the DSC experiments, which we know occurs at a point where time is equal to the time of peak exotherm. Let’s further evaluate equation 2.14. If we take a natural logarithm of equation 2.14, the following equation is obtained:

\[
\ln C = \ln(A_i e^{E_p / RT}) = \ln A_i - \frac{E_p}{RT}
\]  

(2.31)

By plotting \( \ln C \) versus \( \frac{1}{T} \) we get a line which can be fitted to a linear equation, as shown in figure 2.8. Similarly, \( E_p \) can be obtained from the slope of the above equation.
and \( f_k p_0 \) can be evaluated from the intercept of that equation. Table 2.1 shows the values for \( E_d, k_{d0}, E_p, \) and \( f_k p_0 \) for all catalyst levels. For more detailed information on constant derivation, please refer to Zuyev’s MS Thesis [7].

Two cases of free radical polymerization (isothermal and non-isothermal) have been coded using C++. The following are the two sets of equations for both cases.

Isothermal case:
We use equation 2.13 to calculate conversion as a function of time. By applying Finite Difference Approximation method [13], we can approximate equation 2.13 to get:

\[
c_{k+1} = c_k + dt \left( A e^{E_d} e^{-k e (1-c_k)(1-e^{-k_d (t-t)})} \right) \tag{2.32}
\]

Note that subscript \( k \) in equation 2.32 represents time increment.

Non-isothermal case:
We use equations 2.19, 2.24, and 2.29 to calculate conversion as a function of time. Again, by applying Finite Difference Approximation method, we can rewrite equations 2.19 and 2.29 to get:

\[
c_{i+1}^{**} = c_{i}^{**} + dt \left( k_{i} (1-c_{i}) \right) \tag{2.33}
\]

\[
c_{k+1}^{**} = c_{k}^{**} + dt \left( 2 f_k p (1-c_{k}) c_{10} (c_{i}^{**} - c_{i1}^{**}) \right) \tag{2.34}
\]

The code that calculates the cure time in isothermal reactions is shown in Appendix A along with a flow chart. The code that calculates the cure time in non-isothermal
reactions is included as a part of the 1D heat transfer code and is shown in Appendix B along with a flow chart. Figure 2.9 displays the cure time predictions for the selected isothermal DSC experiments using the C++ code.

2.5. Mixing Activated Versus Temperature Activated Coating Systems.

Typical SMC mold temperature is approximately 300°F (149°C) or higher, and at this temperature the coating cures very quickly. For comparison, the mold temperatures for thermoplastics commonly used in the automotive industry are 257°F (125°C) for Polyethylene Terephthalate (PET), 190°F (88°C) for Polycarbonate Acrylonitrile Butadiene Styrene (PCABS), 136°F (58°C) for Acrylonitrile Butadiene Styrene (ABS), and 113°F (45°C) for Thermoplastic Polyolefin (TPO). Under these temperatures, the same IMC coating used in SMC would not be able to cure as fast. To prove this, we calculated inhibition and cure times of the IMC coating exposed to the recommended mold temperatures of SMC, PET, PCABS, and ABS. Table 2.2 shows the inhibition and cure time values. As can be seen, the lower the mold temperature, the higher the cure time values. For instance, cure time values larger than 350 seconds may not be acceptable in the production environment. Therefore, to find a suitable IMC coating for Injection Molding, experimenting with different coating systems is inevitable. When a new coating system is introduced to the IMC process, there is always a risk that it might not behave as expected. One common example is that it might not cure completely, leaving glue-like
substance between the mold and the thermoplastic substrate. Even if the coating cures completely, it may not release properly from the mold making ejection of the part a very difficult task.

Stylecoat is a coating provided by Omnova Solution, Inc. (Akron, Ohio). The exact composition is confidential. However, the main components of this coating are known: unsaturated polyester, styrene, inhibitor, and initiator. Normally, Tetra Butyl Perbenzoate (TBPB) is used as an initiator for Stylecoat. The minimum recommended temperature to achieve reasonable cure times is 90°C. We have successfully used Stylecoat to coat PET and PCABS thermoplastics. To coat low temperature thermoplastics, such as ABS and TPO, Cobalt Octoate (CoOct), 2,4-Pentanedione (2,4-P), and Methyl Ethyl Ketone Peroxide (MEKP) were used as initiators since they activate chemical reaction at lower temperatures. Several combinations of those chemicals were tested by Xia Cao, a graduate student from Chemical Engineering department at the Ohio State University, to find a suitable catalyst for Stylecoat. Shelf life and cure time were measured for each catalyst combination (see table 2.3). Shelf life is the time it takes for the coating to solidify at room temperature after the catalyst is added. Cure time was measured under the isothermal conditions at 70°C for the coating to reach 60% and 70% conversion which were considered to be safe for demolding. The combination of 4.5% MEKP, 1.5% CoOct, and 0.5% 2,4-P was eventually chosen as a catalyst for Stylecoat due to its cure time (12.4 min to reach 70% conversion) and reasonable shelf life (3 hours). This coating
system was tried in our IMC Pilot Facility to coat ABS and TPO parts and plugged up the machine in a relatively short time due to the short shelf life.

Another way to coat low temperature thermoplastics is to use Stylecoat initiated by TBPB and use higher than recommended mold temperature. As mentioned before, Stylecoat coating catalyzed by TBPB initiator requires minimum temperatures of 90°C to cure. Coating lower temperature thermoplastics such as ABS and TPO would require the thermoplastics to be exposed to a much higher temperature than their recommended mold temperature. Forcing the thermoplastics to these extreme conditions will result in part defects (for parts pictures and explanation of the defects refer to Chapter 5).

Mixing activated system is sought of as a suitable solution for coating low temperature thermoplastics. Two-component systems are based on the concept of Reaction Injection Molding (RIM). The center of the RIM process is the chemical reaction between two components (for example, isocyanate and polyol) that are kept in temperature-controlled tanks, as shown in figure 2.10. From these tanks, both, isocyanate and polyol are delivered through supply lines to metering equipment responsible for precise metering and transport of both components into a mix head under a high pressure (between 1500 and 3000 PSI). Because the two reactants are separated into their respected containers, they do not react until they are mixed; the concern for shelf life is virtually eliminated.

As for the mixing methods there are generally three viable options: static, dynamic, and impingement mixing. In static mixing, the two reactants are carefully metered and mixed
in a helical shaped mixing pipe (Kenics mixer, figure 2.11) which will direct the flow of material radially toward the pipe walls and back to the center to achieve a uniform mixture. This type of mixer works well for conventional ratio (i.e. 10:3 or 10:1) between the two reactants, but would not be able to achieve an acceptable mix when there is a large discrepancy in the ratio (i.e. 10:0.1). Solvent must be used in between shots to clean the mixing head after each shot. This is considered to be impractical and has become a major reason why the static mixer is viewed as unattractive for high volume production environments.

In dynamic mixing (figure 2.12), the two reactants are mixed in a dynamic mixer tank where the mixing will be driven by a motor rotating impeller. Unlike static mixing, dynamic mixing is capable of producing uniform mixture for practically any given ratio between the two reactants. However, the use of solvent is also a requirement for dynamic mixing.

The third option is impingement mixing. In impingement mixing the two streams are metered and then impinged at a high velocity before entering the mold. Within the impingement mixing, there are several types of mix heads available: T-shape mix head and L-shape mix head. T-shape mix head (figure 2.13) is the common type used in RIM. When the piston in the T-shape mix head is retracted, the reactants can flow into the mixing chamber and, subsequently, into the mold under pressure. When the piston moves forward, the flow of the reactants is interrupted. L-shape mix head (see figure
2.14) has one additional piston. The piston at the first mixing chamber pushes the
ing material to the second chamber, allowing the piston in the second chamber to
push the material into the mold. We believe that the L-shape mix head has a great
potential to work for the IMC process of thermoplastic substrates due to the high pressure
injection capability. More research is needed to prove this concept.
Table 2.1. Summary of activation energies of decomposition and propagation, and rate constants for decomposition and propagation for all catalyst levels. Stylecoat.

<table>
<thead>
<tr>
<th>Catalyst level</th>
<th>$E_d$</th>
<th>$k_{d0}$</th>
<th>$E_p$</th>
<th>$f_k_{P0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>29568.74</td>
<td>1.1184</td>
<td>118000.602</td>
<td>1.662e18</td>
</tr>
<tr>
<td>1.0</td>
<td>29795.71</td>
<td>1.642</td>
<td>130155.67</td>
<td>9.1697e19</td>
</tr>
<tr>
<td>1.5</td>
<td>31446.87</td>
<td>2.9809</td>
<td>127611.58</td>
<td>5.29e19</td>
</tr>
<tr>
<td>2.5</td>
<td>30997.92</td>
<td>3.206</td>
<td>152345.736</td>
<td>1.43e23</td>
</tr>
</tbody>
</table>
Table 2.2. Inhibition and cure times as a function of temperature. Stylecoat.

<table>
<thead>
<tr>
<th>Material / Parameters</th>
<th>ABS</th>
<th>PCABS</th>
<th>PET</th>
<th>SMC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mold Temperature, degree C</td>
<td>58</td>
<td>88</td>
<td>125</td>
<td>149</td>
</tr>
<tr>
<td>Catalyst Level, % TBPB</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Inhibition time, seconds</td>
<td>196.6</td>
<td>77.2</td>
<td>29.6</td>
<td>17.3</td>
</tr>
<tr>
<td>Cure time, seconds</td>
<td>4426.2</td>
<td>336.9</td>
<td>44.7</td>
<td>24.9</td>
</tr>
</tbody>
</table>

Table 2.2. Inhibition and cure times as a function of temperature. Stylecoat.
Table 2.3. Shelf life and cure times for different levels of initiators. Stylecoat.

<table>
<thead>
<tr>
<th>Sample</th>
<th>MEKP</th>
<th>CoOct</th>
<th>2,4-P</th>
<th>Shelf Life @ 26°C (min)</th>
<th>t_{60}% (min)</th>
<th>t_{70}% (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.5</td>
<td>0.5</td>
<td></td>
<td>530</td>
<td>77.3</td>
<td>96.7</td>
</tr>
<tr>
<td>2</td>
<td>1.5</td>
<td>0.5</td>
<td>0.05</td>
<td>-</td>
<td>41.7</td>
<td>47.4</td>
</tr>
<tr>
<td>3</td>
<td>1.5</td>
<td>0.5</td>
<td>0.15</td>
<td>380</td>
<td>25.4</td>
<td>29.1</td>
</tr>
<tr>
<td>4</td>
<td>1.5</td>
<td>0.5</td>
<td>0.5</td>
<td>350</td>
<td>18.5</td>
<td>21.4</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>0.5</td>
<td>0.5</td>
<td>-</td>
<td>13.5</td>
<td>15.8</td>
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<tr>
<td>6</td>
<td>1.5</td>
<td>1.5</td>
<td>0.5</td>
<td>-</td>
<td>33.2</td>
<td>38.3</td>
</tr>
<tr>
<td>7</td>
<td>4.5</td>
<td>1.5</td>
<td>0.5</td>
<td>180</td>
<td>10.6</td>
<td>12.4</td>
</tr>
</tbody>
</table>
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$y = 3794.3x - 5.7908$

$R^2 = 0.9219$
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The equation of the line is $y = -13763x + 37.974$ with $R^2 = 0.8703$. 

$\ln(C) = -13763 \times \frac{1}{T} + 37.974$
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CHAPTER 3

ONE DIMENSIONAL HEAT TRANSFER ANALYSIS

Mathematical models of physical or natural processes inevitably contain some inherent errors [13]. These errors result from incomplete understanding of natural phenomena, the stochastic or random nature of many processes, and uncertainties in experimental measurements. Often, a model includes only the most relevant features of the physical process and is deliberately stripped of details related to second-level effects. Even if an error-free mathematical model could be developed, it could not, in general, be solved exactly on a computer. All computers have finite memories and computational registers; only a discrete subset of the real, rational numbers may be generated, manipulated, and stored. Thus, it is impossible to represent infinitely small or infinitely large quantities or even a continuum of the real numbers on a finite interval.

Algorithms that use only arithmetic operations and certain logical operations such as algebraic comparison are called numerical methods. The error introduced in approximating the solution of a mathematical problem by a numerical method is usually termed the truncation error of the method. When a numerical method is actually run on a computer after transcription to computer program form, another kind of error, termed
round-off error, is introduced. Round-off errors are caused by the rounding of results from individual arithmetic operations because only a finite number of digits can be retained after each operation, and will differ from computer to computer, even when the same numerical method is being used.


Linear partial differential equations (PDEs) of the second order are frequently referred to as being of the elliptic, hyperbolic, or parabolic type [13]. Such a classification is possible if the equation has been reduced, by a suitable transformation of the independent variables, to the form

\[ \sum_{i=1}^{n} A_i \frac{\partial^2 u}{\partial x_i^2} + \sum_{i=1}^{n} B_i \frac{\partial u}{\partial x_i} + Cu + D = 0 \]

(3.1)

in which the coefficients \(A_i\), evaluated at the point \((x_1, x_2, \ldots, x_n)\), may be 1, -1, or 0.

Here, \(u\) is the dependent variable, and the \(x_i\) are the independent variables. The following are the main possibilities of interest:

1. If all the \(A_i\) are nonzero and have the same sign, the PDE is of elliptic type

2. If all the \(A_i\) are nonzero and have, with one exception, the same sign, the PDE is of hyperbolic type
3. If one $A_i$ is zero ($A_i$ for instance) and the remaining $A_i$ are nonzero and of the same sign, and if the coefficient $B_k$ of $\frac{\partial u}{\partial x_k}$ is nonzero, the PDE is of parabolic type

Since the coefficients $A_i$, $B_i$, $C$, and $D$ are functions of the independent variables $x_1, x_2, \ldots, x_n$, the classification of a PDE may vary according to the particular point being considered in the $(x_1, x_2, \ldots, x_n)$ space. Very frequently, one of the independent variables will be time $t$ and the remainder (for our purpose up to three in number) will be distance coordinates $x, y$, and $z$. The following PDEs:

$$\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} = 0, \quad \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial t^2} = \frac{\partial^2 u}{\partial x^2}, \text{ and } \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} = \frac{\partial u}{\partial t}$$

are respectively of elliptic, hyperbolic, and parabolic type. Further details of the classification of PDEs are given by Petrovsky [14]. Parabolic PDEs are frequently regarded as equations of a time-dependent nature, requiring both an initial condition and subsequent time-dependent boundary conditions for their solutions. When using a finite-difference technique to solve a PDE (plus associated boundary and initial conditions), a network of grid points is first established throughout the region of interest occupied by the independent variables. Suppose, for example, we have two distant coordinates $x$ and $y$, and time $t$ as independent variables, and that the respective grid spacings are $\Delta x$, $\Delta y$, and $\Delta t$. Subscripts $i, j, n$ may then be used to denote that space point having
coordinates \( i\Delta x, j\Delta y, n\Delta t \), also called the grid-point \((i, j, n)\). Let the exact solution to the PDE be \( u = u(x, y, t) \), and let its approximation, to be determined at each grid point by the method of finite differences, be \( v_{i,j,n} \). We also use \( u_{i,j,n} \) to denote the exact solution \( u(i\Delta x, j\Delta y, n\Delta t) \) at a particular grid-point \((i, j, n)\).

The partial derivatives of the original PDE are then approximated by suitable finite-difference expressions involving \( \Delta x, \Delta y, \Delta t \), and the \( v_{i,j,n} \). This procedure leads to a set of algebraic equations in the \( v_{i,j,n} \), whose values may then be determined. By making the grid spacings sufficiently small, it is hoped that \( v_{i,j,n} \) will become a sufficiently close approximation to \( u_{i,j,n} \) at any grid-point \((i, j, n)\).

An example of partial differential equation could be the unsteady heat conduction equation \( \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right) = \rho c_p \frac{\partial T}{\partial t} \), where \( T \) denoted temperature, and \( k, \rho, c_p \) are the thermal conductivity, density, and heat capacity of any material. If \( k \) is constant, the equation may be rewritten in the following way \( \alpha \frac{\partial^2 T}{\partial x^2} = \frac{\partial T}{\partial t} \) in which \( \alpha = \frac{k}{\rho c_p} \) is the thermal diffusivity.
3.1.1. Approximation of Derivatives by Finite Difference.

Here, suppose for simplicity that \( u = u(x, y) \). Assuming that \( u \) possesses a sufficient number of partial derivatives, the values of \( u \) at the two points \( (x, y) \) and \( (x+h, y+k) \) are related by the Taylor’s expansion:

\[
u(x + h, y + k) = u(x, y) + \left( h \frac{\partial}{\partial x} + k \frac{\partial}{\partial y} \right) u(x, y) + \frac{1}{2!} \left( h \frac{\partial}{\partial x} + k \frac{\partial}{\partial y} \right)^2 u(x, y) + \ldots + \]

\[
\frac{1}{(n-1)!} \left( h \frac{\partial}{\partial x} + k \frac{\partial}{\partial y} \right)^{n-1} u(x, y) + R_n
\]

where the remainder term is given by

\[
R_n = \frac{1}{n!} \left( h \frac{\partial}{\partial x} + k \frac{\partial}{\partial y} \right)^n u(x + \xi h, y + \xi k), 0 < \xi < 1
\]  

(3.3)

The space point \( (i\Delta x, j\Delta y) \), also called the grid-point \( (i, j) \), is surrounded by the neighboring grid points shown in figure 3.1. Expanding in Taylor’s series for \( u_{i-1,j} \) and \( u_{i+1,j} \) about the central value \( u_{i,j} \), we obtain

\[
u_{i-1,j} = u_{i,j} - \Delta xu_{x} + \frac{(\Delta x)^2}{2!} u_{xx} - \frac{(\Delta x)^3}{3!} u_{xxx} + \frac{(\Delta x)^4}{4!} u_{xxxx}
\]  

(3.5)

\[
u_{i+1,j} = u_{i,j} + \Delta xu_{x} + \frac{(\Delta x)^2}{2!} u_{xx} + \frac{(\Delta x)^3}{3!} u_{xxx} + \frac{(\Delta x)^4}{4!} u_{xxxx}
\]  

(3.6)
Here, \( u_x = \frac{\partial u}{\partial x} \), \( u_{xx} = \frac{\partial^2 u}{\partial x^2} \), etc., and all derivatives are evaluated at the grid-point \((i, j)\).

By taking these equations singly, and by adding or subtracting one from the other, we obtain the following finite-difference formulas for the first- and second-order derivatives at \((i, j)\):

\[
\frac{\partial u}{\partial x} = \frac{u_{i+1,j} - u_{i,j}}{\Delta x} + O(\Delta x) \tag{3.7}
\]

\[
\frac{\partial u}{\partial x} = \frac{u_{i,j} - u_{i-1,j}}{\Delta x} + O(\Delta x) \tag{3.8}
\]

\[
\frac{\partial u}{\partial x} = \frac{u_{i+1,j} - u_{i-1,j}}{2\Delta x} + O(\Delta x^2) \tag{3.9}
\]

\[
\frac{\partial^2 u}{\partial x^2} = \frac{u_{i-1,j} - 2u_{i,j} + u_{i+1,j}}{(\Delta x)^2} + O(\Delta x^2) \tag{3.10}
\]

Formulas 3.7, 3.8, and 3.9 are known as the forward, backward, and central difference forms respectively. Similar forms exist for \( \frac{\partial u}{\partial y} \) and \( \frac{\partial^2 u}{\partial y^2} \). By taking more and more neighboring points, an unlimited number of other approximations can be obtained, but the above forms are the most compact.
3.1.2. The Explicit and Implicit Forms of the Difference Equation.

Let’s consider a simple partial differential equation along with initial and boundary conditions. The distribution \( u(x,t) \) at any \( t > 0 \) may be found by defining suitable dimensionless variables and by assuming that the physical properties are constant.

\[
\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial x^2}, \text{ for } 0 < x < 1, \ 0 < t < T \tag{3.11}
\]

\[
u(x,0) = f(x), 0 \leq x \leq 1
\]
\[
u(0,t) = g_0(t), 0 < t \leq T
\]
\[
u(1,t) = g_1(t), 0 < t \leq T \tag{3.12}
\]

Here, \( f(x) \) is the initial condition, and \( g_0(t) \) and \( g_1(t) \) are the boundary conditions. In order to approximate the solution of equations 3.11 and 3.12, a network of grid points is first established throughout the region \( 0 \leq x \leq 1, \ 0 \leq t \leq T \) with grid spacings

\[
\Delta x = \frac{1}{M}, \Delta t = \frac{T}{N}, \text{ where } M \text{ and } N \text{ are arbitrary integers. For any grid-point } \left( i, n \right) \text{ that}
\]

do not have \( i = 0, i = M, \text{ or } n = 0, \) the derivatives of equation 3.11 are now replaced by the finite-difference forms suggested by equations 3.7 and 3.10:

\[
\frac{v_{i,n+1} - v_{i,n}}{\Delta t} = \frac{v_{i-1,n} - 2v_{i,n} + v_{i+1,n}}{(\Delta x)^2}
\]

or, defining

\[
\lambda = \frac{\Delta t}{(\Delta x)^2} \tag{3.13}
\]
then

\[ v_{i,n+1} = \lambda v_{i-1,n} + (1 - 2\lambda)v_{i,n} + \lambda v_{i+1,n} \]  

(3.14)

If all the \( v_{i,n} \) are known at any time level \( t_n \), equation 3.14 enables \( v_{i,n+1} \) to be calculated directly (that is, explicitly) at any time level \( t_{n+1} \) for \( 1 \leq i \leq M - 1 \). For the boundary points \( i = 0, i = M \), we have

\[ v_{0,n+1} = g_0(t_{n+1}) \]

\[ v_{M,n+1} = g_1(t_{n+1}) \]  

(3.15)

Since the initial values of \( v \) are prescribed at \( t = 0 \) by

\[ v_{i,0} = f(x_i) \]  

(3.16)

the values of \( v \) can evidently be obtained at all the grid points by repeated application of equations 3.14 and 3.15; we must calculate all values of \( v \) at any one time level before advancing to the next time-step.

Having constructed a plausible procedure for obtaining the values of \( v \), we must now consider the important question of whether these values actually represent a good approximation to the solution of the original PDE (equation 3.11) at the grid points. The departure of the finite-difference approximation from the solution of the PDE at any grid point is known as the local discretization error \( w \). That is,

\[ w = u - v \]  

(3.17)
The finite-difference method is said to converge if \( w \to 0 \) as the grid spacings \( \Delta x \) and \( \Delta t \) tend to zero. Please, note that a sufficient condition for convergence of the explicit method is that \( 0 < \lambda \leq \frac{1}{2} \). The computational procedure is assumed to be capable of an exact representation of the solution of the finite-difference equation. This is not quite true in practice, since only a finite number of digits can be retained by the computer and the phenomenon of round-off error is introduced.

The implicit method, on the other hand, consists of representing a PDE by a finite-difference form evaluated at the advanced point of time \( t_{n+1} \), instead of at \( t_n \) as in the explicit method. Referring again to the problem of equations 3.11 and 3.12 the difference equation becomes:

\[
\frac{v_{i,n+1} - v_{i,n}}{\Delta t} = \frac{v_{i-1,n+1} - 2v_{i,n+1} + v_{i+1,n+1}}{(\Delta x)^2} \quad (3.18)
\]

Or, using equation 3.13, yields

\[-\lambda v_{i-1,n+1} + (1 + 2\lambda)v_{i,n+1} - \lambda v_{i+1,n+1} = v_{i,n} \quad (3.19)\]

The boundary and initial conditions of the explicit method still hold here:

\[
\begin{align*}
v_{0,n+1} &= g_0(t_{n+1}) \\
v_{M,n+1} &= g_1(t_{n+1}) \\
v_{i,0} &= f(x_i)
\end{align*}
\]
The implicit method converges to the solution of the PDE as $\Delta t \to 0$ and $\Delta x \to 0$, regardless of the value of the ratio $\lambda = \frac{\Delta t}{(\Delta x)^2}$. In this respect, the implicit method has an advantage over the explicit method at the expense of a more complicated computational procedure.


It has been shown in the previous section that, under certain conditions, the explicit and implicit finite difference forms are convergent. The term convergent is understood to mean that the exact solution of the finite difference problem (in the absence of round-off error) tends to the solution of the PDE as the grid spacings in time and distance tend to zero. There are two important concepts closely associated with the convergence of a particular finite difference procedure, namely, those of consistency and stability [13]. Richtmyer [15] presented a theorem which demonstrates for linear PDE that, provided that a consistency criterion is satisfied, stability is both a necessary and sufficient condition for convergence.

Referring to a certain computational procedure, the term stability denotes a property of the particular finite difference equation used as the time increment is made very small. It means that there is an upper limit (as $\Delta t \to 0$) to the extent to which any piece of information, whether present in the initial conditions, or brought via the boundary
conditions, or arising from any sort of error in the calculations, can be amplified in the computations. For the explicit method, \( \lambda = \frac{\Delta t}{(\Delta x)^2} \leq \frac{1}{2} \) is a necessary and sufficient condition for stability. The implicit method, on the other hand, is unconditionally stable for all \( \lambda \).

The term consistency, applied to a certain finite difference procedure, means that the procedure may in fact approximate the solution of the PDE under study, and not the solution of some other PDE. For example, consider the explicit approximation,

\[
\frac{v_{i,n+1} - v_{i,n}}{\Delta t} = \frac{v_{i-1,n} - 2v_{i,n} + v_{i+1,n}}{(\Delta x)^2}
\]

of the one-dimensional heat conduction equation (equation 3.11).

\[
\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial x^2}
\]

The truncation error of the approximation is defined as the difference between the finite differences and the derivatives they are intended to represent. It can be readily shown with the aid of Taylor’s expansion \([13]\) that the truncation error is equal to \( O(\Delta t + [(\Delta x)^2]) \). Since the truncation error tends to zero as \( \Delta t \to 0 \) and \( \Delta x \to 0 \), the explicit representation is consistent with the original PDE. There are cases when the explicit approximation of one PDE is in fact consistent with an entirely different PDE. For more information and examples, refer to \([13]\).
3.1.4. Finite-Difference Approximations at the Interface between Two Different Media.

Let’s consider a one-dimensional unsteady-state heat-conduction problem involving two different substances A and B in contact as shown in figure 3.2. The objective is to derive the relevant finite-difference approximation for the temperature \( T_i \) at point \( i \) on the interface between A and B. The following procedure is based on heat flux at the interface. Let A and B have thermal diffusivities \( \alpha_A \) and \( \alpha_B \), and thermal conductivities \( k_A \) and \( k_B \), and let the grid spacing be \( \Delta x \) in both media. Suppose that the new temperature \( T'_i \), after a time increment \( \Delta t \), is to be calculated using an explicit representation.

Medium A. From Taylor’s expansion \[13\], we have, approximately,

\[
T_{i-1} = T_i - \Delta x \left( \frac{\partial T}{\partial x} \right)_{iA} + \frac{(\Delta x)^2}{2} \left( \frac{\partial^2 T}{\partial x^2} \right)_{iA}
\]

(3.20)

where the subscript \( iA \) denotes the derivative in medium A at the interface. Rearranging equation 3.20 yields:

\[
\left( \frac{\partial^2 T}{\partial x^2} \right)_{iA} = \frac{2}{(\Delta x)^2} \left[ T_{i-1} - T_i + \Delta x \left( \frac{\partial T}{\partial x} \right)_{iA} \right]
\]

(3.21)

Also, the time derivative is approximated by

\[
\left( \frac{\partial T}{\partial t} \right)_{iA} = \frac{T'_i - T_i}{\Delta t}
\]

(3.22)
The substitution of equations 3.21 and 3.22 into the unsteady-state heat-conduction equation \( \alpha \frac{\partial^2 T}{\partial x^2} = \frac{\partial T}{\partial t} \) gives:

\[
\frac{2\alpha_A}{(\Delta x)^2} \left[ T_{i-1} - T_i + \Delta x \left( \frac{\partial T}{\partial x} \right) \right] = \frac{T_i - T_{i+1}}{\Delta t}
\]

or rearranging the above equation gives:

\[
\Delta t \left( \frac{\partial T}{\partial x} \right) = \frac{(T_i - T_{i+1} + (T_i - T_{i-1})}{2\lambda \alpha_A}
\]  

where \( \lambda = \frac{\Delta t}{(\Delta x)^2} \).

Medium B. It may similarly be shown that

\[
-\Delta x \left( \frac{\partial T}{\partial x} \right) = \frac{(T_i - T_{i-1})}{2\lambda \alpha_B}
\]

(3.23)

The unwanted derivatives \( \left( \frac{\partial T}{\partial x} \right)_{\partial A} \) and \( \left( \frac{\partial T}{\partial x} \right)_{\partial B} \) may now be eliminated by observing that the heat flux must be continuous at the interface, so that

\[
k_A \left( \frac{\partial T}{\partial x} \right) = k_B \left( \frac{\partial T}{\partial x} \right)
\]

(3.25)

Then, from equations 3.23, 3.24, and 3.25, it follows after a certain amount of simplification that [13]:

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\[ T_i' = T_i + \left[ \frac{2\alpha_A}{\alpha_A + k_A} \right] T_{i+1} \left[ 1 + \frac{k_A}{k_B} \right] T_i + \frac{k_A}{k_B} T_{i-1} \] (3.26)

which is required explicit finite-difference representation. Note that for \( \alpha_A = \alpha_B \) and \( k_A = k_B \), equation 3.26 reduces to the familiar form

\[ T_i' = \alpha_A \lambda T_{i+1} + (1 - 2\alpha_A \lambda) T_i + \alpha_A \lambda T_{i-1} \] (3.27)

Also, we can use equation 3.25 to obtain an alternative solution for the temperature at the interface between two media. Let’s assume that the distance between the nodes for media A and B is different to make the problem a bit more complex.

Using equation 3.7 and 3.8, we can write:

\[ k_A \frac{T_i - T_{i-1}}{\Delta x_A} = k_B \frac{T_{i+1} - T_i}{\Delta x_B} \] (3.28)

Rearranging equation 3.28 yields:

\[ T_i (k_A \Delta x_B + k_B \Delta x_A) = k_B \Delta x_A T_{i+1} + k_A \Delta x_B T_{i-1}, \]

then, the temperature of the interface can be represented by the following equation:

\[ T_i = \frac{k_B \Delta x_A T_{i+1} + k_A \Delta x_B T_{i-1}}{k_A \Delta x_B + k_B \Delta x_A} \] (3.29)

Equation 3.29 can be used as an alternative to the equation 3.26 to calculate the temperature at the boundary. The major difference between them is that equation 3.26 is time dependent and equation 3.29 is not. On the other hand, equation 3.29 contains terms
\(T_{t+1}\) and \(T_{t-1}\) which are time dependent. We used both equations in our computer code and observed no difference as far as the results are concerned. We, therefore, decided to use equation 3.29 to calculate temperatures at the interface between two media.

3.2. Injection Molding Background.

Since we have a fair number of both injection molding and In-Mold Coating experiments in this dissertation, it is beneficial to the reader to learn some basic information on injection molding process. For more detailed information, please refer to Injection Molding Handbook [16]. Figure 3.3 shows a picture of injection molding machine similar to the one we used in our experiments. The main components of any modern injection molding machine are: clamping unit, mold, injection unit, and computer control. Figure 3.4 shows a typical injection molding cycle with the following stages: mold closing, filling, packing, cooling, mold opening, and ejection. The sequence of events during the injection molding of a plastic part, as shown in figure 3.4, is called the injection molding cycle. The cycle begins when the mold closes, followed by the injection of the polymer into the mold cavity. Once the cavity is filled, a packing pressure is maintained to compensate for material shrinkage. In the next step, the screw turns, feeding the next shot to the front of the screw. This causes the screw to retract as the next shot is prepared. During this time, the part cools down in the cavity of the mold. Once the part is sufficiently cool, the mold opens and the part is ejected. Figure 3.5 shows a typical
pressure profile for injection molding. In this example, the cycle time is 35 seconds. A slight pressure increase occurs when the mold is closed. Filling raises the pressure; during packing the melt is held at this pressure. When gate freeze off occurs, melt can no longer be forced into the cavity and the pressure drops. When part cools below its glass transition temperature, the mold can be opened and the part can be ejected. At this stage, the pressure drops to the ambient level. Figure 3.6 shows a typical temperature profile for injection molding. The temperature is first constant when the mold is closing. During the filling stage we see a sharp temperature increase. During the cooling stage temperature decreases exponentially as the melt is cooling down.

3.3. IMC Cure Cycle Modeling.

To predict the IMC cure cycle, we assume that its presence does not affect the heat transfer in the thermoplastic substrate. The coating layer is very thin, usually on the order of 1-3 thousands of an inch. Due to such thin coating layer, we do not observe a temperature increase during chemical reaction, as represented in figure 5.3. Thus, we model the heat transfer in the thermoplastic and use the calculated surface temperature as a function of time to predict the cure time in the IMC reaction model. Figure 3.7 shows a schematic of one dimensional mold with appropriate initial and boundary conditions. Equation 3.30 represents the 1D heat transfer model for either the thermoplastic or the
steel mold. Note that the difference in the material is accounted in the thermal diffusivity \( \alpha \).

\[
\frac{\partial T}{\partial t} = \alpha \left[ \frac{\partial^2 T}{\partial x^2} \right]
\]  

(3.30)

This equation needs to be solved numerically, so we use Explicit Finite Difference Approximation method that allows us to assign nodes and calculate temperature in the nodes using equation 3.31 for the steel material and equation 3.32 for the thermoplastic.

\[
T_{i,k+1} = T_{i,k} + \alpha \Delta t \left[ \frac{T_{i+1,k} - 2T_{i,k} + T_{i-1,k}}{(\Delta x)^2} \right]
\]  

(3.31)

\[
T_{i,k+1} = T_{i,k} + \alpha_{TP} \Delta t \left[ \frac{T_{i+1,k} - 2T_{i,k} + T_{i-1,k}}{(\Delta x_{TP})^2} \right]
\]  

(3.32)

where \( i,k \) are x-coordinate and time; \( \Delta x \) is distance between nodes in x direction; \( \Delta t \) is a time increment; \( \alpha \) is a thermal diffusivity; \( k \) is thermal conductivity; and S and TP are subscripts for steel and thermoplastic respectively. The temperature at the interface between steel and thermoplastic can be calculated using equation 3.33. This equation is derived from the principle of equal heat flux at the interface and is equivalent to the equation 3.26 as far as the results are concerned.

\[
T_{i,k} = \frac{k_{TP} \Delta x_{TP} T_{i+1,k} + k_s \Delta x_{s} T_{i-1,k}}{k_s \Delta x_{TP} + k_{TP} \Delta x_{s}}
\]  

(3.33)
The temperature of the thermoplastic influences the coating process in two different aspects. First, it affects the curing reaction of the coating. Thus, if the cooling circuits in the mold are not properly designed, thinner sections will cool faster than thicker sections. The second aspect when the thermoplastic temperature affects the coating is during flow. The flow of the coating is constrained by the thermoplastic compressibility, which can be evaluated from the Pressure-Volume-Temperature (PVT) relationship.

Figures 3.8 and 3.9 show thermal images of Honda Civic’s bumper an instant after ejection from a mold. As can be noted from these two pictures, the temperature difference between cold and hot areas of the part can be as large as 30 degrees Fahrenheit. If we were to In-Mold Coat this bumper, the temperature difference would result in non-uniform cure of the coating and, presumably, poor adhesion and surface quality. To investigate this phenomenon, we have built our own experimental mold. The cavity of our experimental mold is schematically shown in figure 3.10. This three-plate mold has different thicknesses: 0.100”, 0.075”, and 0.050”. Figure 3.11 shows a thermal image of our experimental part after 70th cycle in a continuous injection molding process. Because of the thickness difference, we can see the temperature difference of approximately 38 degrees Celsius between thin and thick areas of the part. It is, therefore, important to have a cooling system in the mold that would keep the temperature as uniform as possible regardless of the location in the part. Figures 3.12 and 3.13 show proposed solution for keeping the thermal history of the three-thickness part as uniform as possible so that
when IMC injection takes place, the coated surface temperature is nearly the same. Figure 3.12 shows cooling channels machined in both mold halves. They are located at the same distance from the part, but the temperature of each channel is different. For instance, the temperature of the channel that is located above and below the thick section is the lowest (T1), the temperature of the channel located above and below the thin section is the highest (T3), and the T2 is a temperature of the channel located above and below the middle section of the part and it is equal to some value in between T1 and T3. Figure 3.13 shows a slightly different cooling channels design. In this case, temperatures of the cooling media are kept the same, but the channels themselves are machined at a different distance from the part.

We use equations 3.31, 3.32, and 3.33 in C++ code (see Appendix A) to calculate temperature as a function of time and position anywhere in the thermoplastic and in the mold in a continuous Injection Molding process. The calculated thermoplastic surface temperature is then used to predict the cure time in the IMC reaction model. Figure 3.14 shows the software prediction of the first two consecutive injection molding cycles for the two thicknesses: 0.050” and 0.100”. The injection temperature is 285 and the mold temperature is 140 degrees Celsius. Figure 3.14 clearly shows that the thicker the thermoplastic, the higher the temperature. Figure 3.15 is a continuation of figure 3.14 and it shows the first thirty consecutive injection molding cycles for the two thicknesses. By taking the temperature output and plugging it into the non-isothermal free radical kinetic
model we can examine how cure time deviate as a function of part thickness. Figure 3.16 shows the cure times for the two thicknesses: 0.050” and 0.100”. As can be seen, there is a large discrepancy between thin and thick parts. For instance, for the 0.100” thick part, the reaction finishes four seconds before that of the 0.050” thick part. The solution to this problem is to optimize the initial and boundary conditions, e.g. cooling channels temperature. If we provide additional heat to the thin section we are able to find an optimum solution when the temperature history would be almost identical to ensure uniform solidification. Figure 3.17 shows our attempt to improve the surface temperature. In this case, we use different initial and boundary conditions for the thin section of the part. This results in the cure times being almost the same so when the mold opening occurs, the coating will be fully and uniformly solidified.
Figure 3.1. Arrangement of grid points.
Figure 3.2. Interface between different media.
Figure 3.3. A typical injection molding machine [17].
Figure 3.4. A typical injection molding cycle [18].
Figure 3.5. A typical cavity pressure profile during the injection molding cycle [18].
Figure 3.6. A typical cavity temperature profile during the injection molding cycle.
Figure 3.7. Schematic of one dimensional mold.
Figure 3.8. Thermal image of Honda Civic’s rear bumper. Right side.
Figure 3.9. Thermal image of Honda Civic’s rear bumper. Left side.
Figure 3.10. Schematic of the 3-thickness mold.
Figure 3.11. Thermal image of 3-thickness experimental part. Cycle time is 22 seconds.
Figure 3.12. Cooling channels design. First design.
Figure 3.13. Cooling channels design. Second design.
Figure 3.14. Temperature profile in the first two injection molding cycles.

Software prediction.
Figure 3.15. Temperature profile in the first thirty injection molding cycles. Software prediction.
Figure 3.16. Cure times for 0.050” and 0.100” thick parts. Not optimized.
Figure 3.17. Cure times for 0.050” and 0.100” thick parts. Optimized.
CHAPTER 4

TWO DIMENSIONAL HEAT TRANSFER ANALYSIS

In Chapter 3 we developed the one dimensional heat transfer model and described the approach to solve cases of non-uniform heat transfer. We concluded that without any cooling channels the temperature difference between thin and thick sections of a part can become very large. Thus, it is essential to have a cooling system in the mold that keeps the surface of the part at the same temperature level to ensure uniform coating solidification.

In this chapter, we will develop the two dimensional heat transfer model and discuss the applications of one dimensional and two dimensional models. We will also present injection molding experiments and analysis of parts using infrared camera. Finally, we will predict the experimental data using our heat transfer computer code and compare the predictions to the experimental results.
4.1. Two Dimensional Heat Transfer Equations.

Running any FDA based model that consists of a large number of nodes can be very time consuming. Thus, the main reason for developing two dimensional heat transfer model is to find out how well we can approximate it with one dimensional heat transfer model, which has faster running times and does not require modern computational power. Figure 4.1 displays a cross section of a typical thermoplastic part that has some variation in two coordinates, but has very little variation in the third coordinate. If the boundary conditions on the mold surfaces in contact with the rest of the equipment affect the temperature of the thermoplastic part, we will not be able to apply our approach without considering that equipment, which would make the problem unrealistic. In this case, our approach to control temperature of cooling channels will not be useful. We took recommendations from Honda of America Manufacturing Inc. and used them in developing and testing our two dimensional model. Those recommendations are: the pitch between cooling channels has to be between 70 and 120 mm depending on the steel, distance between cooling channels and the part has to be between 30 and 60 mm depending on the steel, and, finally, the diameter of the cooling channels has to be equal to 18 mm. We can approximate the mold shown in figure 4.1 with number of “unit cells” and then solve each “unit cell” individually, as shown schematically in figure 4.2. We have proved that as long as we keep the recommended dimensions, the boundary conditions on the periphery of the mold (heat transfer coefficient in our case) do not
affect the temperature of the thermoplastic. This important conclusion allowed us to approximate and solve two dimensional heat transfer with our one dimensional computer code. Below we are going to develop equations for the two dimensional heat transfer model. Equation 4.1 represents the 2D heat transfer model for either the thermoplastic or the steel mold. Note that the difference in the material is accounted in the thermal diffusivity \( \alpha \).

\[
\frac{\partial T}{\partial t} = \alpha \left[ \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2} \right] \tag{4.1}
\]

This equation needs to be solved numerically, so we use Explicit Finite Difference Approximation method that allows us to assign nodes and calculate temperature between the nodes using equation 4.2 for the steel material and equation 4.3 for the thermoplastic.

\[
T_{i,j,k+1} = T_{i,j,k} + \alpha_x \Delta t \left[ \frac{T_{i+1,j,k} - 2T_{i,j,k} + T_{i-1,j,k}}{(\Delta x)^2} + \frac{T_{i,j+1,k} - 2T_{i,j,k} + T_{i,j-1,k}}{(\Delta z)^2} \right] \tag{4.2}
\]

\[
T_{i,j,k+1} = T_{i,j,k} + \alpha_{TP} \Delta t \left[ \frac{T_{i+1,j,k} - 2T_{i,j,k} + T_{i-1,j,k}}{(\Delta x_{TP})^2} + \frac{T_{i,j+1,k} - 2T_{i,j,k} + T_{i,j-1,k}}{(\Delta z_{TP})^2} \right] \tag{4.3}
\]

where \( i, j, k \) are x-coordinate, z-coordinate, and time; \( \Delta x \) is distance between nodes in x direction; \( \Delta z \) is distance between nodes in z direction; \( \Delta t \) is a time increment; \( \alpha \) is a thermal diffusivity; \( k \) is thermal conductivity; and S and TP are subscripts for steel and thermoplastic respectively. The temperature at the interface between steel and
thermoplastic can be calculated using equations 4.4 or 4.5. These equations are derived from the principle of equal heat flux at the interface.

\[
T_{i,j,k} = \frac{k_{ip} \Delta x_i T_{i+1,j,k} + k_s \Delta x_{ip} T_{i-1,j,k}}{k_i \Delta x_{ip} + k_{ip} \Delta x_i} \quad (4.4)
\]

\[
T_{i,j,k} = \frac{k_{ip} \Delta x_i T_{i,j+1,k} + k_s \Delta x_{ip} T_{i,j-1,k}}{k_i \Delta x_{ip} + k_{ip} \Delta x_i} \quad (4.5)
\]

Figure 4.3 shows 3-dimensional array of grid points that was used to calculate time dependent temperature in \(x\) and \(z\) directions.

Note, that in certain cases, we cannot assume constant physical properties. For instance, semicrystalline polymers exhibit heat of fusion, which is defined as a heat absorbed by a unit of mass in order to convert from solid to liquid states \([19]\). Examples of semicrystalline polymers include PET and TPO thermoplastics. Heat of fusion can be detected by exposing a small sample of semicrystalline polymer to a controlled temperature program in Differential Scanning Calorimeter. Figure 4.4 shows a DSC run of the TPO semicrystalline polymer. As can be seen from this figure, there is a valley representing heat of fusion as the material is heating up. This energy needs to be absorbed before the sample can transition from solid to liquid states. The same amount of energy is given away as the sample cools down, as represented by the peak in figure 4.4. On the other hand, amorphous thermoplastics do not exhibit any heat of fusion because of their randomly arranged molecular structure. Examples of amorphous polymers include
PCABS and ABS thermoplastics. Figure 4.5 shows a DSC run of the PCABS amorphous polymer. There is no heat of fusion exhibited by the polymer due to its random molecular structure.

In the case of semicrystalline thermoplastics, because they exhibit heat of fusion, we can no longer assume constant physical properties and take them out of the derivatives like we did in equation 4.1. Oppositely, we need to evaluate these physical properties, such as heat capacity, thermal conductivity, and density, as the polymer is heating up or cooling down. It is especially important to know how these properties change as the polymer goes through the state transition. We did the heat transfer modeling using both constant physical properties and properties that change as the polymer goes through the transition state. Since the difference in the results was negligible, it was decided to use constant heat capacity, thermal conductivity, and density in our computer code.

4.2. Injection Molding Experiments.

We did two sets of injection molding experiments with three different cycle times: 22 seconds (8 seconds cooling), 30 seconds (16 seconds cooling), and 38 seconds (24 seconds cooling). The objective of these experiments was to measure the temperature rise in the mold and then use our heat transfer software to see how well it predicts the experimental data. During these experiments, two different part geometries were used: one that has three thicknesses (as shown in figure 3.10) and one that has a uniform
thickness of 0.075 inches. Figure 4.6 illustrates experiments for the three-thickness part. We molded 50 consecutive parts with the cycle time of 30 seconds, 50 parts with the cycle time of 38 seconds, and 70 parts with the cycle time of 22 seconds. Each experimental point in figure 4.6 represents the peak temperature in each injection molding cycle. As can be seen from this figure, the shorter the cycle time the higher the mold temperature. After experiments with the three-thickness mold, we modified the mold geometry from three-thickness to one-thickness and repeated all of the above experiments. Figure 4.7 shows that even though the part geometry has changed, there is very little difference between two different experiments. This indicates that the heat transfer between thermoplastic and mold is one dimensional. Therefore, we decided to use 1D heat transfer computer code instead of 2D heat transfer to see how well it predicts our experimental data. Figure 4.8 shows the comparison between experiments and software predictions for our IMC experimental mold. Figure 4.9 shows our attempt to predict temperatures for the Honda Civic’s thermoplastic bumper using recommended initial and boundary conditions provided by Honda.

4.3. Parts Analysis Using Infrared Camera.

Inframetrics SC-1000 infrared camera was used to obtain thermal images of the parts after ejection from the mold. Pictures of the parts were taken an instant after demolding. We used IR camera in our experiments with the three-thickness part geometry with
different cycle times: 22, 30, and 38 seconds. Figure 4.10, 4.11, 4.12, and 4.13 show thermal images of the 1st, 10th, 20th, 30th, 40th, 50th, 60th, and 70th parts in the continuous injection molding process with the cycle time of 22 seconds. Each thermal image was processed with software that allows identifying temperatures anywhere in the part. We decided to know the temperatures of each section in the part as close to the sensor’s location as possible. We then, used those temperatures which are functions of positions and part numbers to create figures 4.14, 4.15, and 4.16. These figures compare temperatures taken from the IR camera and the sensor for different cycle times: 22, 30, and 38 seconds.
Figure 4.1. Schematic of a two dimensional mold.
Figure 4.2. Schematic of a “unit cell”.

\[
\frac{\partial T}{\partial t} = \alpha_{\text{Steel}} \left[ \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2} \right]
\]

\[
\frac{\partial T}{\partial t} = \alpha_{\text{Thermoplastic}} \left[ \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2} \right]
\]

\[
\frac{\partial T}{\partial t} = \alpha_{\text{Steel}} \left[ \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2} \right]
\]
X-coordinate
Z-coordinate
Y-time

2D + time array

Figure 4.3. Three dimensional array of grid points.
Figure 4.4. DSC temperature ramp of TPO semicrystalline thermoplastic.
PCABS thermoplastic
Temperature ramp from 50°C to 350°C at 5°C/minute

Figure 4.5. DSC temperature ramp of PCABS amorphous thermoplastic.
Figure 4.6. Temperature profiles for different cycle times in continuous injection molding process. Uniform thickness part.
Figure 4.7. Temperature profiles for different cycle times in continuous injection molding process. Three-thickness part.
Figure 4.8. Temperature profiles for different cycle times in continuous injection molding process. Comparison between experimental data and software predictions.
Figure 4.9. Predicted temperature profile for different thickness (2 and 5 mm) for Honda Civic’s thermoplastic bumper.
Figure 4.10. Thermal images of the 1st and the 10th parts in the continuous injection process. Cycle time is 22 seconds.
Figure 4.11. Thermal images of the 20\textsuperscript{th} and the 30\textsuperscript{th} parts in the continuous injection process. Cycle time is 22 seconds.
Figure 4.12. Thermal images of the 40th and the 50th parts in the continuous injection process. Cycle time is 22 seconds.
Figure 4.13. Thermal images of the 60th and the 70th parts in the continuous injection process. Cycle time is 22 seconds.
Figure 4.14. IR camera resource. Cycle time is 22 seconds.
Figure 4.15. IR camera resource. Cycle time is 30 seconds.
Figure 4.16. IR camera resource. Cycle time is 38 seconds.
IMC experiments have been conducted for two main purposes. One is to make parts with different processing conditions for adhesion testing. The other one is to collect temperature and pressure data to validate flow models as part of the future work. In this chapter, we are going to describe our IMC Pilot Facility, show In-Mold Coated ABS, PCABS, and PET parts, and summarize important research findings.

5.1. IMC Pilot Facility.
IMC Pilot Facility consists of the following equipment: 50-ton Sumitomo injection molding machine, high pressure In-Mold Coating unit, mold, heaters, temperature controllers, coating injection nozzle, temperature/pressure sensor, and National Instrument data acquisition system. Figure 5.1 shows our experimental setup. Because of its high complexity, this setup is quite challenging to use and requires both experience and expertise. On the other hand, this equipment is reliable as it allows making parts with great degree of repeatability. All of the obtained experiments are presented in the following format: pressure/temperature graphical data, picture of a part, and the
processing conditions used to make the part. Figure 5.2 shows an example of In-Mold Coated PET with uniform substrate thickness of 0.075 inches. The graph in figure 5.2 has two curves: temperature curve and pressure curve. Following the temperature curve we can see that it is constant for about 5 seconds – mold closing time. Then, we see a sharp temperature increase of approximately 13 degrees Celsius due to the hot plastic injection into the cavity of the mold. During the cooling stage, temperature decreases exponentially. At a time of approximately 25 seconds, coating injection takes place with a sharp temperature drop of about 4 degrees Celsius since the coating is injected at room temperature. Finally, temperature is recovered until it reaches the mold temperature. Following the pressure curve we see a constant pressure when the mold is closing. We then see a pressure peak representing filling of the thermoplastic with a pressure value of approximately 1900 PSI. As the plastic cools down and shrinks the pressure drops to zero value. At a time of approximately 25 seconds, we see another pressure peak representing IMC injection with a pressure value of approximately 2000 PSI. Note, that in some cases the temperature does not decrease when the coating injection takes place. Figure 5.3 shows an example of In-Mold Coated PCABS with uniform substrate thickness of 0.075 inches. This graph shows no temperature decrease due to the higher packing pressure (15% of 2230 \( \frac{kgf}{cm^2} \)) compared to 12% of 2230 \( \frac{kgf}{cm^2} \) in figure 5.2. When such high packing pressure is applied, the clamping pressure is no longer sufficient to keep the
mold closed during the coating injection. Because most of the coating leaks out instead of being injected into the cavity of the mold, we do not see such a drastic temperature decrease.

A total of approximately 180 In-Mold Coated parts were made with ABS, PCABS, and PET thermoplastics. The moldings were done with Stylecoat (coating provided by Omnova Solutions Inc.) catalyzed by 1.5% TBPB. Appendixes D and E contain data for In-Mold Coated ABS and PCABS respectively.

5.2. Analysis of IMC Parts.

In order to find out how different processing conditions affect adhesion and quality of the IMC parts, a full factorial Design of Experiments (DOE) was conducted. We selected several factors that from our experience proved to have an effect on parts appearance: thermoplastic packing pressure, delay time between plastic and coating injection, and coating volume. These three factors were at two levels, plus one replica resulting in 16 In-Mold Coated parts made with each thermoplastic (see Appendixes D and E). The responses of the DOE were: sensor peak pressure reading, coating appearance (IMC fill or unfill), and thermoplastic substrate defects. Tables 5.1 and 5.2 show DOE factors and responses for ABS and PCABS thermoplastics respectively.

We performed DOE analysis as well as Analysis of Variance (ANOVA) in MINITAB for In-Mold Coated ABS parts. Figures 5.4, 5.5, and 5.6 show main effects plots for three
different responses: peak pressure reading, coating appearance, and thermoplastic defects caused by molding at high mold temperature. Table 5.3 summarizes F and p-values from the Analysis of Variance. Both DOE and ANOVA revealed one significant factor – packing pressure. First, the higher the thermoplastic packing pressure the higher the pressure sensor reading which makes perfect sense. Second, if the packing pressure is too high, then the injected coating’s pressure is going to exceed clamping pressure that keeps the mold closed. In this case, the mold opens and the coating leaks resulting in an unfilled part or short shot. Finally, high packing pressure eliminates thermoplastic defects that are caused by moldings at high mold temperature. The recommended mold temperature for ABS is 58 degrees Celsius. The experiments were run at approximately 90 degrees Celsius to ensure complete coating solidification. Thus, in order to make good IMC parts, higher tonnage needs to be used to prevent coating leakage and substrate defects.

We also performed DOE analysis as well as Analysis of Variance in MINITAB for In-Mold Coated PCABS parts. Figures 5.7 and 5.8 show main effects plots for two different responses: peak pressure reading and coating appearance. Since the recommended mold temperature for PCABS is 88 degrees Celsius, thermoplastic substrate showed no defects that we observed in ABS thermoplastic. Table 5.4 summarizes F and p-values from the Analysis of Variance. Again, we see that the higher the thermoplastic packing pressure, the higher the pressure sensor reading. Another factor that can be called significant (p-value is 0.006) is IMC Volume. In the case of In-Mold Coated PCABS, the volume of
injected coating has an affect on IMC part appearance. The more coating is injected, the
greater chance for the part to be fully coated. All of the DOE parts with ABS and PCABS
thermoplastics were tested for adhesion. All of the panels have passed the ASTM D3359
scratch test. This indicates that adhesion of the IMC to ABS or PCABS thermoplastic is
independent of the processing conditions. For more information on adhesion testing,
please, refer to Chapter 6.
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Table 5.1. DOE factors and responses for In-Mold Coated ABS. Maximum pressure is $2230 \frac{kgf}{cm^2}$ (column Pressure). Maximum IMC volume is 60 units, or 3 $in^3$ (column IMC Volume). Rating 1 means that the part is 0% In-Mold Coated, rating 5 means that the part is 100% In-Mold Coated (column Unfill/Fill). Rating 1 means that there are no defects in the substrate, rating 0 means that the defects are present (column Good Part/Bad Part).
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<td>1</td>
</tr>
</tbody>
</table>

Table 5.2. DOE factors and responses for In-Mold Coated PCABS. Maximum pressure is $2230 \frac{kgf}{cm^2}$ (column Pressure). Maximum IMC volume is 60 units, or 3 in$^3$ (column IMC Volume). Rating 1 means that the part is 0% In-Mold Coated, rating 5 means that the part is 100% In-Mold Coated (column Unfill/Fill). Rating 1 means that there are no defects in the substrate, rating 0 means that the defects are present (column Good Part/Bad Part).
<table>
<thead>
<tr>
<th>Factors/Responses</th>
<th>Packing Pressure</th>
<th>Delay Time</th>
<th>IMC Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Peak Pressure</strong>&lt;br&gt; F value</td>
<td>1093.93</td>
<td>0.03</td>
<td>0.01</td>
</tr>
<tr>
<td>p value</td>
<td>less than 0.001</td>
<td>0.873</td>
<td>0.934</td>
</tr>
<tr>
<td><strong>IMC Fill</strong>&lt;br&gt; F value</td>
<td>67.33</td>
<td>0.2</td>
<td>0.57</td>
</tr>
<tr>
<td>p value</td>
<td>less than 0.001</td>
<td>0.662</td>
<td>0.463</td>
</tr>
<tr>
<td><strong>Part Defects</strong>&lt;br&gt; F value</td>
<td>6241.00</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>p value</td>
<td>less than 0.001</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 5.3. F and p-values. Thermoplastic is ABS.
Factors/Responses | Packing Pressure | Delay Time | IMC Volume |
---|---|---|---|
Peak Pressure | | | |
F value | 134.9 | 0.13 | 0.03 |
p value | less than 0.001 | 0.721 | 0.873 |
IMC Fill | | | |
F value | 2.11 | 0.07 | 10.31 |
p value | 0.169 | 0.79 | 0.006 |

Table 5.4. F and p-values. Thermoplastic is PCABS.
Figure 5.1. IMC Pilot Facility.
Figure 5.2. In-Mold Coated PET. Part # 35.
Figure 5.3. In-Mold Coated PCABS. Part # 5.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mold Temperature</td>
<td>92 Degree C</td>
</tr>
<tr>
<td>Barrel Temperature Profile</td>
<td>500   490     465 Degrees F</td>
</tr>
<tr>
<td>Plastic Shot Size</td>
<td>4.25 inches</td>
</tr>
<tr>
<td>Cooling Time</td>
<td>90 seconds</td>
</tr>
<tr>
<td>Screw RPM</td>
<td>30 %</td>
</tr>
<tr>
<td>Velocity</td>
<td>0.65 inches 40%   0.90 inches</td>
</tr>
<tr>
<td>Packing Pressure</td>
<td>7 seconds 15 %   1.60 seconds</td>
</tr>
<tr>
<td>Fill Peak Pressure</td>
<td>37 % of 2230 kgf/cm²²</td>
</tr>
<tr>
<td>Fill Time</td>
<td>1.55 seconds</td>
</tr>
<tr>
<td>Plastication Time</td>
<td>14.50 seconds</td>
</tr>
<tr>
<td>Cushion</td>
<td>0.23 inches</td>
</tr>
<tr>
<td>Delay Time</td>
<td>30 seconds</td>
</tr>
<tr>
<td>Coating Shot Size</td>
<td>10 units</td>
</tr>
</tbody>
</table>
Figure 5.4. Main effects plot for peak pressure. Thermoplastic is ABS.
Figure 5.5. Main effects plot for IMC Fill. Thermoplastic is ABS.
Figure 5.6. Main effects plot for part defect. Thermoplastic is ABS.
Figure 5.7. Main effects plot for peak pressure. Thermoplastic is PCABS.
Figure 5.8. Main effects plot for IMC Fill. Thermoplastic is PCABS.
6.1. Adhesion Theories and Background.

The meaning of the term adhesion is associated with the molecular forces acting across an interface between two solid substrates [20]. In most cases we think of an adhesive as a layer of material between the surfaces, with the purpose to fill at least some of the irregularities and pores and thus achieve a higher degree of molecular contact between them. Initially, the adhesive must have a sufficiently low viscosity to permit it to fill the irregularities and pores of the surfaces, and then solidify. Figure 6.1.a shows two solids brought in contact with each other, and figure 6.1.b shows two solids joined by an adhesive. In the case of In-Mold Coating of thermoplastic substrates, the coating is applied onto a solid substrate. This is demonstrated in figure 6.2.

The different theories of adhesion that have been proposed are the following: mechanical theory, adsorption theory, diffusion theory, and electrostatic theory [20]. According to the mechanical theory (or diffusion on the macro scale), when a porous surface is brought in contact with a liquid adhesive, the latter interlocks around the irregularities and pores of the substrates and acts as a mechanical fastener. According to the adsorption theory, the
adhesive is held on a substrate surface by various forces of attraction. For instance, the primary covalent bonds between atoms in organic polymers are generally \((1-2) \times 10^{-10} m\) in length and 250-840 kJ/mole in strength, and these are the bonds that keep the molecule intact up to the point of chemical breakdown and degradation. The secondary forces acting between adjacent molecules are generally more remote \((2-5) \times 10^{-10} m\) and weaker \((2.1-85\) kJ/mole). The energies of these secondary forces seem low when compared to the energies of the primary covalent forces but it is the fact that the secondary forces are associated with extremely large molecules that is of paramount importance. It is these forces that change gases into liquids and solids as well as introduce viscosity, surface tension, and friction. Diffusion on the micro scale suggests that the molecules of the adhesive diffuse into the substrate, thereby partially eliminating the interface. And finally, the electrostatic theory assumes that electrons are transferred from one material to another so that the surfaces are oppositely charged. The electrostatic mechanism is unlikely to be generally important, especially where polymer substrates are involved. IMC is considered to be bound to the substrate by the combination of mechanical interlocking, diffusion on the microscale, and various forces of attraction unless proven otherwise.
The factors affecting the strength of the forces between adhesive and substrate are sometimes interrelated, and some of them, especially viscosity and the presence of weak boundary layers are relevant to coating problems. We consider the following factors: viscosity, surface energy, weak boundary layers, and stress concentrations.

The viscosity must be low enough to fill the irregularities of the substrate surface, and thus achieve good molecular contact. Lower viscosities will lead to higher bond strengths, and also reduced stress concentrations due to voids. Another parameter that must be considered is the time for which the adhesive is in its low viscosity state. Increasing this time period will lead to higher degree of contact, and thus higher bond strength, but a compromise must be achieved with the acceptable production rate.

The contact angle between the adhesive and substrate will be affected by their surface energies. One way of characterizing a surface is to measure the contact angle $\theta_c$, made by a drop of liquid (adhesive) on the surface at the point where the two phases meet (see figure 6.3). Perfect wetting on the surface occurs when $\cos \theta_c = 1$, that is, when $\theta_c = 0$.

If a region of relatively low strength exists in an adhesive joint, the breaking strength of the joint will be low, even if there is good contact between the substrate and adhesive. If this region exists at the interface, it is often referred to as a weak boundary layer. Possible sources of weak boundary layers involving polymeric substrates include impurities and additives.
The stress-strain characteristics of both the adhesive and the substrate affect the resultant strength of the adhesive joint. If the substrate is very rigid compared with the adhesive, the mechanical properties of the latter will largely determine the strength of the joint. However, if both the adhesive and substrate are flexible structures, the mechanical properties of both play an important part. These properties may differ considerably from those of the bulk materials, due to stress concentrations especially at, or near the interface.

The research and understanding of adhesion mechanisms and factors affecting the strength of the forces between adhesive and substrate is a very challenging and controversial task. It is just as challenging to identify which mechanism plays a dominant role in the case of IMC process of thermoplastics. While studying adhesion mechanisms is beyond the scope of this chapter, our primer objective is to develop an adhesion test that is simple to perform, reliable, and adaptable to the coating and painting industries. In the following sections we will talk about two different adhesion tests: button pull test and scratch test.


The purpose of this test is to measure the mechanical tensile strength of coatings. The sample is subjected to increasing tensile stress until the weakest path through the material fractures [21]. The weakest path could be along an interface between coating and substrate, a cohesive fracture of the substrate, or a combination of these two. To carry out adhesion experiments using button pull test, we designed our own set of stainless steel buttons. Figure 6.4 shows the buttons design. As can be noted, one of the buttons has a diameter of two inches while the other one has a diameter of one inch. The reason for doing that is to make sure that the small button that is glued to the coated side of the part is going to fail first due to the smaller area of contact. The following outlines the testing procedure:

1. Sand blast the button surfaces with 80 grit aluminum oxide and clean them thoroughly with acetone.
2. Glue the 2-inch diameter button to the back side of the coated part using super glue (cyanoacrylate made by Super Glue Corporation).
3. Glue the 1-inch diameter button to the coated side of the part. Make sure the two buttons are perfectly aligned.
4. Once the buttons are glued, put a 28-pound weight on top of the assembly and leave it overnight.

5. Clamp the assembly in tensile testing equipment’s jaws as indicated in figure 6.5.

6. Perform tensile test, collect data, and take pictures of the buttons’ surfaces.

6.2.2. ASTM D3359. Scratch Test.

Unlike the button pull test, the scratch test is a more qualitative method to determine coating adhesion. Figure 6.6 shows the picture of the Elcometer 107 cross hatch cutter that we used to perform ASTM D3359 test. The following outlines the testing procedure:

1. Having selected the appropriate cutter spacing depending on a coating thickness, make a cut of approximately 1-1.5 inches long ensuring that enough force is used to cut all the way down to the substrate.

2. Make a similar length cut at a 90 degree angle with the first cut – again, ensure that the cut is all the way down to the substrate.

3. Brush the coating lightly with a soft brush or tissue to remove any detached flakes or ribbons of coating.

4. Apply a special Japanese adhesive tape [22] on the pattern ensuring that there are no bubbles or detached particles left under the tape.

5. Pull the tape away from the tested surface and count the number of squares that are separated from the part if any.
6.3. Adhesion Testing Results.

Figure 6.7 shows adhesion testing results for In-Mold Coated PCABS. The thickness of the substrate is 0.075 inches. Figure 6.8 shows adhesion testing results for In-Mold Coated PET. The thickness of the substrate is 0.050 inches. Figure 6.9 shows adhesion testing results for In-Mold Coated PET. The thickness of the substrate is 0.075 inches. Figure 6.10 shows adhesion testing results for In-Mold Coated PET. The thickness of the substrate is 0.100 inches. Figure 6.11 shows adhesion testing results for In-Mold Coated SMC. These particular experiments were performed as a reference. The thickness of the substrate is 0.150 inches. The results of ASTM D4541 tests are summarized in table 6.1.

In the case of In-Mold Coated PCABS (see figure 6.7) all of the tested samples resulted in cohesive substrate failure. The average strength at which samples failed and the standard deviation are respectively 2639.97 PSI and 544.46 PSI. Adhesion experiments with In-Mold Coated PET (substrate thickness of 0.050 inches) showed complete coating separation from the substrate (see figure 6.8). The average strength is equal to 851.05 PSI with standard deviation value of 1055.88 PSI. The reason for standard deviation to be so high is because some of the experiments resulted in strength as low as 68.79 PSI (coating failure), some were as high as 2290.44 PSI (cohesive substrate failure), and some were in between those two values. Adhesion experiments with In-Mold Coated PET (substrate thickness of 0.075 inches) resulted in coating failure with some indication of substrate failure (see figure 6.9). Two different sets of panels were tested, but the results were quite
similar (see table 6.1). Adhesion experiments with In-Mold Coated PET (substrate thickness of 0.100 inches) showed cohesive substrate failure (see figure 6.10) with values of average strength and standard deviation of 2301.91 PSI and 616.78 PSI respectively. For comparison purposes only, we have done testing of In-Mold Coated SMC compression molded body panels. The testing resulted in coating failure (see figure 6.11) with values of average strength and standard deviation of 1903.5 PSI and 397.66 PSI respectively.

We have performed a scratch test on all of the DOE parts shown in Appendixes D and E. All of them have passed the scratch test. It is therefore safe to conclude that adhesion of IMC coating to thermoplastic substrate is robust with respect to processing conditions. It is also indicated that adhesion is dependent upon the heat transfer. For instance, we see coating failure and low values of adhesion in the thin section of the 3-thickness part due to the loss of heat during the cooling stage of the injection molding cycle. This premature heat loss, in turn, results in insufficient coating cure, which, in turn, results in poor adhesion. On the other hand of spectrum, the adhesion values in the thick section are high and we see only the cohesive failure of the substrate. Figure 6.12 proves the same point by showing the result of the ASTM D3359 scratch test performed on the 3-thickness In-Mold Coated PET. From this test we can similarly indicate that the adhesion is dependent upon the heat transfer between thermoplastic and mold during the IM/IMC cycle.

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<table>
<thead>
<tr>
<th>Sample</th>
<th>Number of Samples</th>
<th>Average, PSI</th>
<th>Deviation, PSI</th>
<th>Substrate Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMC/PCABS 0.075&quot;</td>
<td>8, uniform thickness part</td>
<td>2639.97</td>
<td>544.46</td>
<td>Yes</td>
</tr>
<tr>
<td>IMC/PET 0.050&quot;</td>
<td>7, three thickness part</td>
<td>851.05</td>
<td>1055.88</td>
<td>No</td>
</tr>
<tr>
<td>IMC/PET 0.075&quot;</td>
<td>4, three thickness part</td>
<td>1770.38</td>
<td>476.97</td>
<td>Partial</td>
</tr>
<tr>
<td>IMC/PET 0.075&quot;</td>
<td>14, uniform thickness part</td>
<td>1386.62</td>
<td>436.8</td>
<td>Partial</td>
</tr>
<tr>
<td>IMC/PET 0.100&quot;</td>
<td>4, three thickness part</td>
<td>2301.91</td>
<td>616.78</td>
<td>Yes</td>
</tr>
<tr>
<td>IMC/SMC 0.150&quot;</td>
<td>4, Omnova's Samples</td>
<td>1903.5</td>
<td>397.66</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 6.1. Adhesion testing results.
Figure 6.1. a) Two solid surfaces brought in contact, b) two solid surfaces joined by an adhesive.
Figure 6.2. In-Mold Coating applied onto a thermoplastic substrate.
Figure 6.3. Characterization of the contact angle $\theta_c$. 
Figure 6.4. Stainless steel buttons designed for the button pull test.
Figure 6.5. Button pull test assembly.
Figure 6.6. Elcometer 107 cross hatch cutter.
Figure 6.7. In-Mold Coated PCABS. Substrate thickness is 0.075 inches.
Figure 6.8. In-Mold Coated PET. Substrate thickness is 0.050 inches.
Figure 6.9. In-Mold Coated PET. Substrate thickness is 0.075 inches.
Figure 6.10. In-Mold Coated PET. Substrate thickness is 0.100 inches.
Figure 6.11. In-Mold Coated SMC. Substrate thickness is 0.150 inches.
Figure 6.12. ASTM D3359 scratch test. Substrate is PET.
7.1. Research Contributions.

The contributions of the research described in this document can be classified as general and specific contributions.

In general: the development of an approach to solve cases of non-uniform heat transfer with emphasis on cycle time, uniformity of cure, and adhesion in the Injection Molding/In-Mold Coating process including both the start up and the steady state stages.

In specific: three significant contributions have resulted as part of this research. The first significant contribution is 1D and 2D heat transfer software development based on Explicit Finite Difference Approximation method. There are many heat transfer software packages commercially available, such as ANSYS or ABAQUS to name a few. To the best of our knowledge, there is no analog of our software in the market at this point. The uniqueness of our computer code is heat transfer analysis between thermoplastic and mold for consecutive injection molding cycles. Our software also uses the calculated temperature profile to further compute coating’s conversion during the chemical reaction. Another advantage of using our computer code is short computational times. The second
significant contribution is IMC Pilot Facility development and setup that allows us to run In-Mold Coating experiments, evaluate different thermoplastics and coatings, make parts for future analysis and testing, and collect data to verify developed mathematical models. The final significant contribution is the development of our own method for adhesion evaluation. This test can easily be adapted anywhere in the industry where coating or painting processes are utilized.

7.2. Future Work.

7.2.1. IMC Fill Pattern and Pressure Predictions.

One of the objectives to make In-Mold Coated parts was to test previously developed mathematical model [23] that predicts fill pattern and pressure during the IMC filling process. This mathematical model is based on the generalized Hele-Shaw approximation. Figure 7.1 shows fill pattern prediction for our IMC experimental part of uniform thickness. Figure 7.2 shows a comparison of experimental pressure versus the pressure predicted by the model. As can be seen from the figures, the model can predict fill pattern well but it cannot well predict pressure. In order to improve pressure prediction, it is necessary to improve rheological model of the coating, experimentally measure slip coefficient between coating and mold wall, and incorporate these advancements into the computer code.
7.2.2. IMC Experimental Work and Adhesion Study.

One of the important conclusions we made in this dissertation is that adhesion is independent of processing conditions. On the other hand, there is indication that adhesion of the coating does depend on heat transfer and, subsequently, on coating’s solidification process. Thus, it is important to prove that by providing a part with appropriate heat transfer it is possible to achieve good adhesion of the coating regardless of part’s thickness. Figure 7.3 shows the design of the cooling plate to provide different sections of our IMC experimental part with different controlled temperatures. The purpose of these experiments is to make In-Mold Coated parts with and without the cooling plate and subsequently test the coating’s adhesion.

7.2.3. Optimization Work.

Acceptance of IMC as a competitor to the traditional painting process will depend upon the improvement of its ability to deliver In-Mold Coated parts in short cycle times at the highest possible quality level. Most optimization studies in reactive polymer processing involve compromising between different performance measures since, frequently, the controllable variables have conflicting effects on these measures. In-Mold Coating process is not an exception to the rule. The performance measures need to be balanced against each other in order to obtain the best compromises. For instance, if the mold temperature is too low, it results in long cure and cycle times. On the other hand, if the
mold temperature is higher than recommended for a particular thermoplastic, it results in plastic defects and possible coating leakage. It is also clear that if the delay time is too short, the injected coating will destroy the surface of a substrate because of insufficient cooling time. Oppositely, if the delay time is too long, the coating will not have enough time to cure before the part is ejected, thus resulting in unacceptable surface finish and poor adhesion.

Optimization strategy to approach cases of Multiple Criteria Optimization in reactive polymer processing has previously been developed [24]. It is suggested to apply this strategy to In-Mod Coating process of thermoplastic substrates. The variables in this optimization problem would include temperature of the melt and the mold, thermoplastic packing pressure, thermoplastic thickness, delay time, and initial concentration of initiator. The performance measures in this optimization problem would include cycle time of the IM/IMC process, part quality, and adhesion of the coating to the substrate.
Figure 7.1. Fill pattern prediction for the IMC experimental part of uniform thickness.
Figure 7.2. Comparison between experimental and predicted pressure.
Figure 7.3. Cooling plate design for the IMC experimental mold.
Figure A.1. Flow chart of “IMC cure under isothermal conditions” code.
#include <math.h>
#include <fstream.h>
double main()
{
    ofstream outf ("C:\Simul\stylecoat.txt");
    double cinitiator;
    //define initiator/catalyst concentration
    cinitiator=0.010;
    //cinitiator=0.015;
    //cinitiator=0.025;
    double B;
    //define B which is a part of the ratio
    B = 2*cinitiator*(exp(-50.219*cinitiator - 3.5615));
    double Ep;
    //define Ep - one of the exponential constant
    //catalyst level = 1.0%
    Ep = 130155.67;
    //catalyst level = 1.5%
    //Ep = 127611.58;
    //catalyst level = 2.5%
    //Ep = 152345.736;
    double kd0;
    //define kd0 (kdzero)
    //catalyst level = 1.0
    kd0 = 1.642;
    //catalyst level = 1.5%
    //kd0 = 2.9809;
    //catalyst level = 2.5%
    //kd0 = 3.206;
    double Ed;
    //define Ed
    //catalyst level = 1.0%
    Ed = 29795.71;
    //catalyst level = 1.5%
    //Ed = 31446.87;
//catalyst level = 2.5%
//Ed = 30997.92;
double kp0;
//define kp0
//catalyst level = 1.0%
kp0 = 9.1697*(pow(10,19));
//catalyst level = 1.5%
//kp0 = 5.29*(pow(10,19));
//catalyst level = 2.5%
//kp0 = 1.43*(pow(10,23));
double R;
//define R - gas constant
R = 8.314;
double T;
//define T - isothermal temperature in Kelvins (degree C + 273.15)
T=413.15;
double tz;
//define tz - inhibition time
tz = ((log(1-(B/(2*cinitiator))))*(-1/kd0)*exp(Ed/(R*T)));
double kd;
//define kd
kd = (kd0*exp(-Ed/(R*T)));
double a;
//define a
a = (2*kp0*cinitiator)*exp(-kd*tz);
double dt;
//define time increment for the equation
dt = 0.001;
double ddt;
//define time increment for the t
ddt = 0.001;
double t;
//define time as a function of the time increment
//t = tz;
double cstar;
//define cstar
cstar = 0;
//initial cstar is equal to zero
double dcstar;
//define dcstar
dcstar = 0;
long int i=0;
cout<<"STARTING\n";
while (dcstar<0.999999)
{
    dcstar = (cstar + (a*(exp(-Ep/(R*T)))*(1-cstar)*(1-(exp(-kd*(t-tz)))))*dt));
cout << "incremental time = " << t << "", incremental conversion = " << dcstar << "\n";
if ((i % 100) == 0)
{
    outf << "time, " << t <<", conversion, " << dcstar <<"\n";
}
i++;
cstar = dcstar;
t = tz + ddt;
ddt = ddt + 0.001;
}cout << "cinitiator = " << cinitiator << "\nB = " << B;
cout << "Ep = " << Ep << "kd0 = " << kd0;
cout << "Ed = " << Ed << "R = " << R << "T = " << T;
cout << "ntz = " << tz << "kd = " << kd << "kp0 = " << kp0;
cout << "na = " << a;
cout << "FINISHED\n";
return 0;
}ITERALFUNCTIONS
THE END

//*****************************************************/
//The End
//*****************************************************************/
APPENDIX B
ONE DIMENSIONAL HEAT TRANSFER
C++ CODE
Figure B.1. Flow chart of “one dimensional heat transfer” code.
This program calculates the 1D solidification of PCABS MC 1300 (made by GEPlastics) and the output (temperature vs. time) gets imported into the non-isothermal cure model.

```c
#include <fstream.h>
#include <math.h>

int main()
{
  ofstream outf ("E:\Simul\1dheat.txt");
  //ofstream outf1 ("E:\Simul\stylecoat.txt");
  ofstream outf2 ("E:\Simul\1doutput.txt");
  int i,j;
  //int I,J;
  //i is coordinate (z-direction)
  //j is time
  //Properties of Thermoplastic
  double ktp;
  ktp = 0.23;
  //thermal conductivity in W/(m*degC)
  double cptp;
  cptp = 2090;
  //heat capacity in J/(kg*degC)
  double rotp;
  rotp = 1116.1;
  //density in kg/(m^3)
  //Properties of the Steel
  double cpsteel;
  cpsteel = 486;
  //heat capacity in J/(kg*degC)
  double rosteel;
  rosteel = 7870;
  //density in kg/(m^3)
  double ksteel;
  ksteel = 51.9;
  //thermal conductivity in W/(m*degK)
  //Delta z inside the mold
```

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double dzsteel;
dzsteel = 0.00018;
//meter
//Delta z inside the mold
double dzsteels;
dzsteels = 0.0001;
//meter
//Delta z inside the thermoplastic
double dztps;
dztps = 0.0001;
//meter
//Delta t (time)
double dt;
dt = 0.000000005;
//seconds
long int n;
//define k
n = 0;
//heat transfer coefficient for air (free convection)
double hair;
hair = 2500;
//W/m*K
//normally the heat transfer coefficient is 300
//heat transfer coefficient for water
//double hwater;
//hwater = 2500;
//W/m*K
//air temperature far away from boundary
double Tair;
Tair = 140;
//degree C
//for water temperatures far away from boundary please refer to cooling channels
double t;
//define time
cout << "The time delay between thermoplastic and coating injection is assigned to 15 seconds";
t = 0;
double alfatp;
//define alfatp
alfatp = ktp/(rotp*cptp);
//cout << "alfa thermoplastic = " << alfatp;
dauble alfasteel;
alfasteel = ksteel/(rosteel*cpsteel);
//cout << "alfa steel = " << alfasteel;
//initial conditions @ time zero
//boundary conditions at any time, on the right
double Tinitialwall;
Tinitialwall= 140;
//thermoplastic at time zero
dauble TThermoplastic;
TThermoplastic= 285;
//cooling channels at any time
//double Tcooling1;
//Tcooling1 = 120;
//cooling channels at any time
//double Tcooling2;
//Tcooling2 = 120;
dauble T[694][10];
//total i is equal to 694 nodes
//I = 694;
//J = 10;
//**********************************************************************
//For time "j" zero
//**********************************************************************
for (i=1, j=0; i<334; i++)
{
    T[i][j] = Tinitialwall;
}
i=0;
j=0;
T[i][j] = ((ksteel*T[i+1][j])+(dzsteel*hair*Tair))/(ksteel+dzsteel*hair);
i=335;
j=0;
T[i][j] = TThermoplastic;
i=334;
j=0;
T[i][j] = ((ktp*dzsteels*T[i+1][j])+(ksteel*dztps*T[i-1][j]))/((ksteel*dztps)+(ktp*dzsteels));
for (i=336,j=0; i<359; i++)
{ 
T[i][j] = Tthermoplastic;
}
i=360;
j=0;
T[i][j] = Tinitialwall;
i=359;
j=0;
T[i][j] = ((ktp*dzsteels*T[i-1][j])+(ksteel*dztps*T[i+1][j]))/((ksteel*dztps)+(ktp*dzsteels));
for (i=361,j=0; i<693; i++)
{ 
T[i][j] = Tinitialwall;
}
i=693;
j=0;
T[i][j] = ((ksteel*T[i-1][j])+(dzsteel*hair*Tair))/(ksteel+dzsteel*hair);
for (i=0, j=0; i<694; i++)
{ 
outf << T[i][j] <<"."
outf <<"n"
} 
//**********************************************************************
//loop for the time greater than zero
//**********************************************************************
int z;
z = 9*66667;
int iter1;
for (iter1 = 0; iter1 < 50; iter1++)
{ 
double cinitiator;
//define initiator concentration
 cinitiator = 0.025;
double B;
//define B which is a part of the ratio
B = 2*cinitiator*(exp(-50.219*cinitiator - 3.5615));
double Ep;
//define Ep - one of the exponential constant
Ep = 152345.736;
double kd0;
}
//define kd0 (kdzero)
k0 = 3.206;
double Ed;
//define Ed
Ed = 30997.92;
double R;
//define R - gas constant
R = 8.314;
double kp0;
//define kp0
kp0 = 1.43*(pow(10,23));
double citizstar;
citzstar = B/(2*cinitiator);
double cistar;
//define cistar
cistar = 0;
//initial cistar is equal to zero
double cistarr;
//define cistarr
cistarr = 0;
double cstar;
//define cstar
cstar = 0;
double cmstar;
//define cmstar
cmstar = 0;
int iter=0;
while (iter<66667)
{
  if (iter!=0)
  {
    for (i=0; i<694; i++)
    {
      T[i][0]=T[i][9];
    }
  }
  for (j=1; j<10; j++)
  {
    for (i=1; i<334; i++)
    {

\[ \begin{align*}
T[i][j] &= T[i][j-1] + \text{alfasteel} \times (dt / (\text{pow}(dzsteel, 2))) \times (T[i+1][j-1] - 2 \times T[i][j-1] + T[i-1][j-1]) \;
\}
\end{align*} \]
i = 0;

\[ \begin{align*}
T[i][j] &= ((\text{ksteel} \times T[i+1][j-1]) + (dzsteel \times \text{hair} \times Tair)) / (\text{ksteel} + dzsteel \times hair) 
\end{align*} \]
i = 335;

\[ \begin{align*}
T[i][j] &= T[i][j-1] + \text{alfatp} \times (dt / (\text{pow}(dztps, 2))) \times (T[i+1][j-1] - 2 \times T[i][j-1] + T[i-1][j-1]) 
\end{align*} \]
i = 334;

\[ \begin{align*}
T[i][j] &= T[i][j-1] + ((\text{kt} \times \text{dzsteels} \times T[i+1][j-1] - T[i][j-1] \times (\text{kt} \times \text{dzsteels} + \text{ksteel} \times \text{dztps}) + \text{ksteel} \times \text{dztps} \times T[i-1][j-1]) / ((2 \times dt) / (dztps \times dzsteels) \times (\text{alfatp} \times \text{alfasteel}) / (\text{alfasteel} \times \text{kt} \times \text{dztps} + \text{alfatp} \times \text{ksteel} \times \text{dzsteels})) 
\end{align*} \]

//here comes the cure program

double kd;
//define kd
kd = kd0 \times (\exp(-\text{Ed} / (\text{R} \times (T[i][j] + 273.15))));
double kp;
//define kp
kp = kp0 \times (\exp(-\text{Ep} / (\text{R} \times (T[i][j] + 273.15))));
//cout << "ninitiator = " << cinitiator << "nB = " << B;
//cout << "nEp = " << Ep << "nk0 = " << kd0;
//cout << "nT = " << T;
//cout << "nEd = " << Ed << "nR = " << R << "ncitzstar = " << citzstar;
//cout << "nk = " << kd << "np0 = " << kp0;
//cout <<"nSTARTING\n";
if (t > 0 && cmstar < 0.99999)
{
    //cout << "cistar = " << cistar << " t= " << t << "n"
    //cout << "ncistarr = " << cistarr;
    cistarr = cistar + kd \times (1-cistar) \times dt;
    cistar = cistarr;
    //cout << "ntime = " << t;
    //cout << "ncistar = " << cistar;
    //cout << "ncistarr = " << cistarr;
    //cout << "ncstar = " << cstar;
    //cout << "ncmstar = " << cmstar;
    //cout << "ncitzstar = " << citzstar;
    cmstar = cstar + 2 \times kp \times cinitiator \times (1-cstar) \times (cistarr-citzstar) \times dt;
    if (cistarr <= citzstar)
    {
        cmstar = 0;
    }
cstar = cmstar;
//cout << "ncstar = " << cstar;
//cout << "ncmstar = " << cmstar;
//cout << "\ntime = " << t << ", incremental conversion = " << cmstar << "\n";
//if ((n % 400) == 0 )
//{
//outf1 << "time, " << t <<"," << "conversion, " << cmstar <<"\n";
//}
//here ends the cure program
for (i=336; i<359; i++)
{
    T[i][j] = T[i][j-1] + alfatp*(dt/(pow(dztps,2)))*(T[i+1][j-1] - 2*T[i][j-1] + T[i-1][j-1]);
}
i=360;
T[i][j] = T[i][j-1] + alfatp*(dt/(pow(dzsteel,2)))*(T[i+1][j-1] - 2*T[i][j-1] + T[i-1][j-1]);
i=359;
T[i][j] = T[i][j-1] + ((ktp*dzsteels*T[i-1][j-1] - T[i][j-1]*(ktp*dzsteels + ksteel*dztps) + ksteel*dztps*T[i+1][j-1])*((2*dt)/(dztps*dzsteels)))+((alfatp*ksteel)*ktp*dztps + alfatp*ksteel*dzsteels));
for (i=361; i<693; i++)
{
    T[i][j] = T[i][j-1] + alfatp*(dt/(pow(dzsteel,2)))*(T[i+1][j-1] - 2*T[i][j-1] + T[i-1][j-1]);
}
i=693;
T[i][j] = ((ksteel*T[i-1][j-1])+(dzsteel*hair*Tair))/(ksteel+dzsteel*hair);
t = t + dt;
if ((n % 800) == 0 )
{
    outf <<"\n";
}
n++;
if ((n % z) == 0 )
{
for (i=0; i<694; i++)
{
{ 
    outf2 << T[i][9] << ",";
    outf2 <<"n";
    }
    outf2 <<"\n";
    }
    if ((n % z) == 0 )
    {
        for (i=0; i<335; i++)
        {
            T[i][0] = T[i][9];
        }
    }
    if ((n % z) == 0 )
    {
        for (i=335; i<359; i++)
        {
            T[i][0] = Tthermoplastic;
        }
    }
    if ((n % z) == 0 )
    {
        for (i=359; i<694; i++)
        {
            T[i][0] = T[i][9];
        }
    }
    if ((n % z) == 0 )
    {
        for (i=0; i<694; i++)
        {
            outf2 << T[i][0] << ",";
            outf2 <<"n";
        }
        outf2 <<"\n";
    }
    iter++;
    }
outf.close();
//outf1.close();
outf2.close();
return 0;
}
APPENDIX C

TWO DIMENSIONAL HEAT TRANSFER

C++ CODE
Figure C.1. Flow chart of “two dimensional heat transfer” code.
//2-D Heat Transfer Program "Unit Cell"
//Solidification of the thermoplastic PCABS MC1300 (made by GE Plastics)
//in the mold. Rectangular cooling channels included.
//*****************************************************************

#include <fstream.h>
#include <math.h>

int main()
{
    //main
    cout.flush();
    ofstream outf("C:\Simul\2dheat.txt");
    //ofstream outf1("C:\Simul\stylecoat.txt");
    ofstream outf2("C:\Simul\2doutput.txt");
    int i,j,k;
    //int I,J,K;
    //i is coordinate (x-direction)
    //j is coordinate (z-direction)
    //k is time
    //Properties of Thermoplastic
    double ktp; // thermal conductivity in W/(m*degC)
    ktp = 0.23;
    //heat capacity in J/(kg*degC)
    double cptp; // heat capacity in J/(kg*degC)
    cptp = 2090;
    //density in kg/(m^3)
    double rotp; // density in kg/(m^3)
    rotp = 1116.1;
    //Properties of the Steel
    double cpsteel; // heat capacity in J/(kg*degC)
    cpsteel = 486;
    //density in kg/(m^3)
    double rosteel; // density in kg/(m^3)
    rosteel = 7870;
    //thermal conductivity in W/(m*degK)
    double ksteel; // thermal conductivity in W/(m*degK)
    ksteel = 51.9;
    //Delta x and Delta z inside the mold

    // Delta x and Delta z inside the mold

double dxsteel;
dxsteel = 0.003;
//meter
double dzsteel;
dzsteel = 0.003;
//meter
//Delta z inside the thermoplastic region
double dzsteels;
dzsteels = 0.0002;
//meter
//Delta x and Delta z inside the thermoplastic
double dxtp;
dxtp = 0.003;
//meter
double dztp;
dztp = 0.003;
//meter
//Delta z inside the thermoplastic region
double dztps;
dztps = 0.0002;
//meter
//Delta t (time)
double dt;
dt = 0.000000002;
//seconds
//heat transfer coefficient for air (free convection)
double hair;
hair = 15;
//W/m*K
//heat transfer coefficient for water
double hwater;
hwater = 2500;
//W/m*K
//air temperature far away from boundary
double Tair;
Tair = 25;
//degree C
//for water temperatures far away from boundary please refer to cooling channels
temperatures
double t;
//define time
//cout <<"The time delay between thermoplastic and coating injection is assigned to 15
seconds":
t = 0;
//thermal diffusivity of thermoplastic
double alfatp;
alfatp = ktp/(rotp*cptp);
//cout <<"alfa thermoplastic = " <<alfatp;
//thermal diffusivity of steel
double alfasteel;
alfasteel = ksteel/(rosteel*cpsteel);
//cout << "alfa steel = " <<alfasteel;
//steel at time zero
double Tinitialwall;
Tinitialwall = 25;
//thermoplastic at time zero
double Tthermoplastic;
Tthermoplastic = 210;
//cooling channels at any time
double Tcooling1;
Tcooling1 = 25;
//cooling channels at any time
double Tcooling2;
Tcooling2 = 25;
//3-dimensional array: i is coordinate x, j is coordinate z, k is time
double T[40][97][10];
//x=40, z=97, k=10
//I = 40;
//J = 97;
//K = 10;
long int n;
n=0;
//initial values for the free radical non-isothermal model are bellow
//double cinitiator;
//define initiator concentration
cinitiator = 0.025;
//cout <<"nPlease, enter catalyst concentration of coating \n(in decimals)";
//cin >> cinitiator;
//double B;
//define B which is a part of the ratio
// $B = 2*\text{cinitiator}*(\exp(-50.219*\text{cinitiator} - 3.5615))$;
// define Ep;
// define Ep - one of the exponential constant
// Ep = 152345.736;
// define kd0;
// define kd0 (kdzero)
// kd0 = 3.206;
// define Ed;
// define Ed
// Ed = 30997.92;
// define R;
// define R - gas constant
// R = 8.314;
// define kp0;
// define kp0
// kp0 = 1.43*(\text{pow}(10,23));
// define citzstar;
// citzstar = B/(2*\text{cinitiator});
// define cistar
// cistar = 0;
// initial cistar is equal to zero
// define cistarr;
// define cistarr
// cistarr = 0;
// define cistar;
// define cistar
// cistar = 0;
// define cmstar;
// define cmstar
// cmstar = 0;
// the cure model needs to be implemented inside the code once it is clear what nodes will
// be used as temperature output
// code for time $k=0$

k=0;
// boundary condition starting from [ ] to the right to [ ]
// top section of the upper mold half between top mold wall and cooling channel
for (j=1; j<20; j++)
{
  for (i=1; i<39; i++)
  {
    ...
  
  }
}
{ 
T[i][j][k] = Tinitialwall; 
} 
for (i=0, j=1; j<20; j++)
{
T[i][j][k] = T[i+2][j][k];
}
for (i=39, j=1; j<20; j++)
{
T[i][j][k] = T[i-2][j][k];
}
//boundary condition starting from [ ][ ][ ] to the right to [ ][ ][ ]
//section of the upper mold half between left mold wall and cooling channel
for (j=20; j<26; j++)
{
for (i=1; i<17; i++)
{
T[i][j][k] = Tinitialwall;
}
for (i=0, j=20; j<26; j++)
{
T[i][j][k] = T[i+2][j][k];
}
//boundary condition starting from [ ][ ][ ] to the right to [ ][ ][ ]
//section of the upper mold half between the cooling channel and right mold wall
for (j=20; j<26; j++)
{
for (i=23; i<39; i++)
{
T[i][j][k] = Tinitialwall;
}
for (i=39, j=20; j<26; j++)
{
T[i][j][k] = T[i-2][j][k];
}
//boundary condition starting from [ ][ ][ ] to the right to [ ][ ][ ]
//section of the upper mold half between the cooling channel and the mold cavity

}
for (j=26; j<36; j++)
{
  for (i=1; i<39; i++)
  {
    T[i][j][k] = Tinitialwall;
  }
}
for (i=0, j=26; j<36; j++)
{
  T[i][j][k] = T[i+2][j][k];
}
for (i=39, j=26; j<36; j++)
{
  T[i][j][k] = T[i-2][j][k];
}
//boundary condition starting from [][] to the right to [][][]
//boundary conditions for the first cooling channel in the upper mold half
for (j=21; j<25; j++)
{
  for (i=18; i<22; i++)
  {
    T[i][j][k] = Tcooling1;
  }
}
//corner nodes for the first cooling channel (4 nodes per cooling channel)
for (j=20, i=18; i<22; i++)
{
  T[i][j][k] = ((ksteel*T[i][j-1][k])+(dzsteel*hwater*Tcooling1))/(ksteel+dzsteel*hwater);
}
for (i=22, j=21; j<25; j++)
{
  T[i][j][k] = ((ksteel*T[i+1][j][k])+(dxsteel*hwater*Tcooling1))/(ksteel+dxsteel*hwater);
}
\( T[22][25][k] = \frac{(ksteel*T[i+1][j+1][k])+(pow((pow(dxsteel,2)+pow(dzsteel,2)),0.5)*hwater*Tcooling1))}{(ksteel+pow((pow(dxsteel,2)+pow(dzsteel,2)),0.5)*hwater)}; \)

for \( (j=25, i=18; i<22; i++) \)

\[
T[i][j][k] = \frac{(ksteel*T[i][j+1][k])+(dzsteel*hwater*Tcooling1))}{(ksteel+dzsteel*hwater)}; 
\]

\( T[17][25][k] = \frac{(ksteel*T[i-1][j+1][k])+(pow((pow(dxsteel,2)+pow(dzsteel,2)),0.5)*hwater*Tcooling1))}{(ksteel+pow((pow(dxsteel,2)+pow(dzsteel,2)),0.5)*hwater)}; \)

for \( (i=17, j=21; j<25; j++) \)

\[
T[i][j][k] = \frac{(ksteel*T[i-1][j][k])+(dxsteel*hwater*Tcooling1))}{(ksteel+dxsteel*hwater)}; 
\]

//boundary condition starting from [][][] to the [][][]
//section in the lower mold half between mold cavity and cooling channel
for \( (j=61; j<71; j++) \)

\[
for (i=1; i<39; i++) 
\]

\[
T[i][j][k] = Tinitialwall; 
\]

//boundary condition starting from [][][] to the [][][]
//section of the lower mold half between left wall and the first cooling channel
for \( (j=71; j<77; j++) \)

\[
for (i=1; i<17; i++) 
\]

\[
T[i][j][k] = Tinitialwall; 
\]
for (i=0, j=71; j<77; j++)
{
T[i][j][k] = T[i+2][j][k];
}
//boundary condition starting from [][][] to the [][][]
//section of the lower mold half between first and second cooling channels
for (j=71; j<77; j++)
{
for (i=23; i<39; i++)
{
T[i][j][k] = Tinitialwall;
}
}
for (i=39, j=71; j<77; j++)
{
T[i][j][k] = T[i-2][j][k];
}
//boundary condition starting from [][][] to the [][][]
//section of the lower mold half between the cooling channels and bottom mold wall
for (j=77; j<96; j++)
{
for (i=1; i<39; i++)
{
T[i][j][k] = Tinitialwall;
}
}
for (i=0, j=77; j<96; j++)
{
T[i][j][k] = T[i+2][j][k];
}
for (i=39, j=77; j<96; j++)
{
T[i][j][k] = T[i-2][j][k];
}
//boundary condition starting from [][][] to the right to [][][]
//boundary conditions for the second cooling channel in the lower mold half
for (j=72; j<76; j++)
{
for (i=18; i<22; i++)
{
\[ T[i][j][k] = T_{\text{cooling}2}; \]
\[
//\text{corner nodes for the second, forth, and sixth cooling channels (4 nodes per cooling channel), total of 12}
\]
\[
\text{for (j=}71, i=18; i<22; i++)}
\[
\{
T[i][j][k] = (k_{\text{steel}}*T[i][j-1][k])+(dz_{\text{steel}}*h_{\text{water}}*T_{\text{cooling}2})/(k_{\text{steel}}+dz_{\text{steel}}*h_{\text{water}}); \\
T[17][71][k] = (k_{\text{steel}}*T[i-1][j-1][k])+\left((\text{pow}(\text{pow}(dx_{\text{steel}},2)+\text{pow}(dz_{\text{steel}},2)),0.5)*h_{\text{water}}*T_{\text{cooling}2}\right)/(k_{\text{steel}}+\text{pow}(\text{pow}(dx_{\text{steel}},2)+\text{pow}(dz_{\text{steel}},2)),0.5)*h_{\text{water}}); \\
T[22][71][k] = (k_{\text{steel}}*T[i+1][j-1][k])+\left((\text{pow}(\text{pow}(dx_{\text{steel}},2)+\text{pow}(dz_{\text{steel}},2)),0.5)*h_{\text{water}}*T_{\text{cooling}2}\right)/(k_{\text{steel}}+\text{pow}(\text{pow}(dx_{\text{steel}},2)+\text{pow}(dz_{\text{steel}},2)),0.5)*h_{\text{water}}); \\
\text{for (i=}22, j=72; j<76; j++)
\[
\{
T[i][j][k] = (k_{\text{steel}}*T[i+1][j][k])+(dx_{\text{steel}}*h_{\text{water}}*T_{\text{cooling}2})/(k_{\text{steel}}+dx_{\text{steel}}*h_{\text{water}}); \\
T[22][76][k] = (k_{\text{steel}}*T[i+1][j+1][k])+\left((\text{pow}(\text{pow}(dx_{\text{steel}},2)+\text{pow}(dz_{\text{steel}},2)),0.5)*h_{\text{water}}*T_{\text{cooling}2}\right)/(k_{\text{steel}}+\text{pow}(\text{pow}(dx_{\text{steel}},2)+\text{pow}(dz_{\text{steel}},2)),0.5)*h_{\text{water}}); \\
\text{for (j=}76, i=18; i<22; i++)
\[
\{
T[i][j][k] = (k_{\text{steel}}*T[i][j+1][k])+(dz_{\text{steel}}*h_{\text{water}}*T_{\text{cooling}2})/(k_{\text{steel}}+dz_{\text{steel}}*h_{\text{water}}); \\
T[17][76][k] = (k_{\text{steel}}*T[i-1][j+1][k])+\left((\text{pow}(\text{pow}(dx_{\text{steel}},2)+\text{pow}(dz_{\text{steel}},2)),0.5)*h_{\text{water}}*T_{\text{cooling}2}\right)/(k_{\text{steel}}+\text{pow}(\text{pow}(dx_{\text{steel}},2)+\text{pow}(dz_{\text{steel}},2)),0.5)*h_{\text{water}}); \\
\text{for (i=}17, j=72; j<76; j++)
\[
\{
T[i][j][k] = (k_{\text{steel}}*T[i-1][j][k])+(dx_{\text{steel}}*h_{\text{water}}*T_{\text{cooling}2})/(k_{\text{steel}}+dx_{\text{steel}}*h_{\text{water}}); \\
//\text{boundary condition starting from }[][][\text{] to the }[]][\text{]}
//\text{boundary condition for the upper part of the thickest section of the mold cavity}
\text{for (j=}37; j<60; j++)
\[
\{
\text{for (i=}1; i<39; i++)
\[
\{
T[i][j][k] = T_{\text{thermoplastic}};
for (i=0, j=37; j<60; j++)
{
    T[i][j][k] = T[i+2][j][k];
}
for (i=39, j=37; j<60; j++)
{
    T[i][j][k] = T[i-2][j][k];
}
//corner nodes with formulas for the thermoplastic region go here
for (j=36, i=1; i<39; i++)
{
    T[i][j][k] = (ktp*dzsteels*T[i][j+1][k]+ksteel*dztps*T[i][j-1][k])/(ksteel*dztps+ktp*dzsteels);
}
T[0][36][k] = T[2][36][k];
T[39][36][k] = T[37][36][k];
for (j=60, i=1; i<39; i++)
{
    T[i][j][k] = (ktp*dzsteels*T[i][j-1][k]+ksteel*dztps*T[i][j+1][k])/(ksteel*dztps+ktp*dzsteels);
}
T[0][60][k] = T[2][60][k];
T[39][60][k] = T[37][60][k];
//boundary condition starting from [][][] to the right to [][][]
for (j=96, i=1; i<39; i++)
{
    T[i][j][k] = ((ksteel*T[i][j-1][k])+(dzsteel*hair*Tair))/(ksteel+dzsteel*hair);
}
T[0][96][k] = T[2][96][k];
T[39][96][k] = T[37][96][k];
//boundary conditions for the top, bottom, left, and right walls start here. They include
heat transfer coefficient equations
for (j=0, i=1; i<39; i++)
{
    T[i][j][k] = ((ksteel*T[i][j+1][k])+(dzsteel*hair*Tair))/(ksteel+dzsteel*hair);
}
T[0][0][k] = T[2][0][k];
T[39][0][k] = T[37][0][k];
/boundary conditions end here
for (j=0; j<97; j++)
{
for (i=0; i<40; i++)
{
outf << T[i][j][0] << "\n";
}
outf << "\n";
outf << "\n";
int z;
z = 9*44445;
//code for time k>0
int iter1;
for (iter1 = 0; iter1 < 50; iter1++)
{
int iter=0;
while (iter<44445)
{
if (iter!=0)
{
for (j=0;j<97;j++)
{
for (i=0;i<40;i++)
{
T[i][j][0]=T[i][j][9];
}
}
for (k=1; k<10; k++)
{
for (j=1; j<20; j++)
{
for (i=1; i<39; i++)
{
T[i][j][k] = T[i][j][k-1] + alfasteel*dt*(((T[i+1][j][k-1] - 2*T[i][j][k-1] + T[i-1][j][k-1])/(pow(dxsteel,2))) + ((T[i][j+1][k-1] - 2*T[i][j][k-1] + T[i][j-1][k-1])/(pow(dzsteel,2))));
}
}
for (i=0; j<20; j++)
{
    T[i][j][k] = T[i+2][j][k];
}
for (i=39; j<20; j++)
{
    T[i][j][k] = T[i-2][j][k];
}
//boundary condition starting from [][] to the right to [][]
for (j=20; j<26; j++)
{
    for (i=1; i<17; i++)
    {
        T[i][j][k] = T[i][j][k-1] + alfasteel*dt*((T[i+1][j][k-1] - 2*T[i][j][k-1] + T[i-1][j][k-1])/(pow(dxsteel,2))) + ((T[i][j+1][k-1] - 2*T[i][j][k-1] + T[i][j-1][k-1])/(pow(dzsteel,2)));
    }
}
for (i=0; j=20; j<26; j++)
{
    T[i][j][k] = T[i+2][j][k];
}
//boundary condition starting from [][] to the right to []
for (j=26; j<36; j++)
{
for (i=1; i<39; i++)
{
    T[i][j][k] = T[i][j][k-1] + alfasteel*dt*((T[i+1][j][k-1] - 2*T[i][j][k-1] + T[i-1][j][k-1])/(pow(dxsteel,2))) + ((T[i][j+1][k-1] - 2*T[i][j][k-1] + T[i][j-1][k-1])/(pow(dzsteel,2))));
}
}

for (i=0, j=26; j<36; j++)
{
    T[i][j][k] = T[i+2][j][k];
}

for (i=39, j=26; j<36; j++)
{
    T[i][j][k] = T[i-2][j][k];
}

//boundary condition starting from [][][] to the right to [][][]
for (j=21; j<25; j++)
{
    for (i=18; i<22; i++)
    {
        T[i][j][k] = Tcooling1;
    }
}

for (j=20, i=18; i<22; i++)
{
    T[i][j][k] = ((ksteel*T[i][j][k]) + (dzsteel*hwater*Tcooling1))/(ksteel+dzsteel*hwater);
}

T[17][20][k] = ((ksteel*T[i][j][k]) + (pow((pow(dxsteel,2)+pow(dzsteel,2)),0.5)*hwater*Tcooling1))/(ksteel+pow((pow(dxsteel,2)+pow(dzsteel,2)),0.5)*hwater);
T[22][20][k] = ((ksteel*T[i+1][j][k]) + (pow((pow(dxsteel,2)+pow(dzsteel,2)),0.5)*hwater*Tcooling1))/(ksteel+pow((pow(dxsteel,2)+pow(dzsteel,2)),0.5)*hwater);
for (i=22, j=21; j<25; j++)
{
    T[i][j][k] = ((ksteel*T[i+1][j][k]) + (dxsteel*hwater*Tcooling1))/(ksteel+dxsteel*hwater);
}

T[22][25][k] = ((ksteel*T[i+1][j+1][k]) + (pow((pow(dxsteel,2)+pow(dzsteel,2)),0.5)*hwater*Tcooling1))/(ksteel+pow((pow(dxsteel,2)+pow(dzsteel,2)),0.5)*hwater);
for (j=25, i=18; i<22; i++)
{
    T[i][j][k] = ((ksteel*T[i][j+1][k])+(dzsteel*hwater*Tcooling1))/(ksteel+dzsteel*hwater);
}
T[17][25][k] = ((ksteel*T[i-1][j+1][k])+(pow((pow(dxsteel,2)+pow(dzsteel,2)),0.5)*hwater*Tcooling1))/(ksteel+pow((pow(dxsteel,2)+pow(dzsteel,2)),0.5)*hwater);
for (i=17, j=21; j<25; j++)
{
    T[i][j][k] = ((ksteel*T[i-1][j][k])+(dxsteel*hwater*Tcooling1))/(ksteel+dxsteel*hwater);
}
//boundary condition starting from []][] to the []][]
for (j=61; j<71; j++)
{
    for (i=1; i<39; i++)
    {
        T[i][j][k] = T[i][j][k-1] + alfasteel*dt*(((T[i+1][j][k-1] - 2*T[i][j][k-1] + T[i-1][j][k-1])/(pow(dxsteel,2))) + ((T[i][j+1][k-1] - 2*T[i][j][k-1] + T[i][j-1][k-1])/(pow(dzsteel,2))));
    }
    for (i=0, j=61; j<71; j++)
    {
        T[i][j][k] = T[i+2][j][k];
    }
    for (i=39, j=61; j<71; j++)
    {
        T[i][j][k] = T[i-2][j][k];
    }
//boundary condition starting from []][] to the []][]
for (j=71; j<77; j++)
{
    for (i=1; i<17; i++)
    {
        T[i][j][k] = T[i][j][k-1] + alfasteel*dt*(((T[i+1][j][k-1] - 2*T[i][j][k-1] + T[i-1][j][k-1])/(pow(dxsteel,2))) + ((T[i][j+1][k-1] - 2*T[i][j][k-1] + T[i][j-1][k-1])/(pow(dzsteel,2))));
    }
    for (i=0, j=71; j<77; j++)
    {
        T[i][j][k] = T[i+2][j][k];
    }
    for (i=39, j=71; j<77; j++)
    {
        T[i][j][k] = T[i-2][j][k];
    }
}
\begin{verbatim}
\{ 
  T[i][j][k] = T[i+2][j][k];
  
  //boundary condition starting from [][][] to the [][][]
  for (j=71; j<77; j++)
  {
    for (i=23; i<39; i++)
    
      T[i][j][k] = T[i][j][k-1] + alfasteel*dt*(((T[i+1][j][k-1] - 2*T[i][j][k-1] + T[i-1][j][k-1])/(pow(dxsteel,2))) + ((T[i][j+1][k-1] - 2*T[i][j][k-1] + T[i][j-1][k-1])/(pow(dzsteel,2))));
    
  }
  
  for (i=39, j=71; j<77; j++)
  {
    T[i][j][k] = T[i-2][j][k];
  }
  
  //boundary condition starting from [][][] to the [][][]
  for (j=77; j<96; j++)
  {
    for (i=1; i<39; i++)
    
      T[i][j][k] = T[i][j][k-1] + alfasteel*dt*(((T[i+1][j][k-1] - 2*T[i][j][k-1] + T[i-1][j][k-1])/(pow(dxsteel,2))) + ((T[i][j+1][k-1] - 2*T[i][j][k-1] + T[i][j-1][k-1])/(pow(dzsteel,2))));
    
  }
  
  for (i=0, j=77; j<96; j++)
  {
    T[i][j][k] = T[i+2][j][k];
  }
  
  for (i=39, j=77; j<96; j++)
  {
    T[i][j][k] = T[i-2][j][k];
  }
  
  //boundary condition starting from [][][] to the right to [][][]
  for (j=72; j<76; j++)
  {
    for (i=18; i<22; i++)
    
  }
\}
\end{verbatim}
T[i][j][k] = Tcooling2;
}
for (j=71, i=18; i<22; i++)
{
T[i][j][k] = ((ksteel*T[i][j-1][k]+(dzsteel*hwater*Tcooling2))/(ksteel+dzsteel*hwater);
}
T[17][71][k] = ((ksteel*T[i-1][j-1][k]+(pow((pow(dxsteel,2)+pow(dzsteel,2)),0.5)*hwater*Tcooling2))/(ksteel+pow((pow(dxsteel,2)+pow(dzsteel,2)),0.5)*hwater);
T[22][71][k] = ((ksteel*T[i+1][j-1][k]+(pow((pow(dxsteel,2)+pow(dzsteel,2)),0.5)*hwater*Tcooling2))/(ksteel+pow((pow(dxsteel,2)+pow(dzsteel,2)),0.5)*hwater);
for (i=22, j=72; j<76; j++)
{
T[i][j][k] = ((ksteel*T[i+1][j][k]+(dxsteel*hwater*Tcooling2))/(ksteel+dxsteel*hwater);
}
T[22][76][k] = ((ksteel*T[i+1][j+1][k]+(pow((pow(dxsteel,2)+pow(dzsteel,2)),0.5)*hwater*Tcooling2))/(ksteel+pow((pow(dxsteel,2)+pow(dzsteel,2)),0.5)*hwater);
for (j=76, i=18; i<22; i++)
{
T[i][j][k] = ((ksteel*T[i][j+1][k]+(dzsteel*hwater*Tcooling2))/(ksteel+dzsteel*hwater);
}
T[17][76][k] = ((ksteel*T[i-1][j+1][k]+(pow((pow(dxsteel,2)+pow(dzsteel,2)),0.5)*hwater*Tcooling2))/(ksteel+pow((pow(dxsteel,2)+pow(dzsteel,2)),0.5)*hwater);
for (i=17, j=72; j<76; j++)
{
T[i][j][k] = ((ksteel*T[i-1][j][k]+(dxsteel*hwater*Tcooling2))/(ksteel+dxsteel*hwater);
}
//boundary condition starting from [[ ]] to the [[ ]] for (j=37; j<60; j++)
{
for (i=1; i<39; i++)
{
T[i][j][k] = T[i][j][k-1] + alfatp*dt*((T[i+1][j][k-1] - 2*T[i][j][k-1] + T[i-1][j][k-1])/(pow(dxtp,2)) + ((T[i][j+1][k-1] - 2*T[i][j][k-1] + T[i][j-1][k-1])/(pow(dztps,2)));
}
}
for (i=0, j=37; j<60; j++)
{
    T[i][j][k] = T[i+2][j][k];
}
for (i=39, j=37; j<60; j++)
{
    T[i][j][k] = T[i-2][j][k];
}
for (j=36, i=1; i<39; i++)
{
    T[i][j][k] = (ktp*dzsteels*T[i][j+1][k]+ksteel*dztps*T[i][j-1][k])/(ksteel*dztps+ktp*dzsteels);
}
T[0][36][k] = T[2][36][k];
T[39][36][k] = T[37][36][k];
for (j=60, i=1; i<39; i++)
{
    T[i][j][k] = (ktp*dzsteels*T[i][j-1][k]+ksteel*dztps*T[i][j+1][k])/(ksteel*dztps+ktp*dzsteels);
}
T[0][60][k] = T[2][60][k];
T[39][60][k] = T[37][60][k];
//boundary condition starting from [][] to the right to [][]
for (j=96, i=1; i<39; i++)
{
    T[i][j][k] = ((ksteel*T[i][j-1][k])+(dzsteel*hair*Tair))/(ksteel+dzsteel*hair);
}
T[0][96][k] = T[2][96][k];
T[39][96][k] = T[37][96][k];
//boundary conditions for the top, bottom, left, and right walls start here. They include
//heat transfer coefficient equations
for (j=0, i=1; i<39; i++)
{
    T[i][j][k] = ((ksteel*T[i][j+1][k])+(dzsteel*hair*Tair))/(ksteel+dzsteel*hair);
}
T[0][0][k] = T[2][0][k];
T[39][0][k] = T[37][0][k];
//boundary conditions end here
    t = t + dt;
    if ((n % 60) == 0)
{ 
outf << n << "," << t << "," << T[1][36][k] << "," << T[1][60][k] << "," << T[19][36][k] << "," << T[19][60][k] << "," << T[38][36][k] << "," << T[38][60][k] << "," << T[17][25][k] << "," << T[17][71][k] << "," << T[22][25][k] << "," << T[22][71][k] << "," << T[1][0][k] << "," << T[1][96][k] << "," << T[38][0][k] << "," << T[38][96][k] << "," << T[19][48][k];
outf << "n";
} 
n++; 
if ((n % z) == 0 ) 
{
for (j=0; j<97; j++)
{
for (i=0; i<40; i++)
{
outf2 << T[i][j][9] << ",";
}
outf2 << ",n";
}
outf2 << "n";
} 
if ((n % z) == 0 ) 
{
for (j=0; j<37; j++)
{
for (i=0; i<40; i++)
{
T[i][j][0] = T[i][j][9];
}
}
}
if ((n % z) == 0 ) 
{
for (j=37; j<60; j++)
{
for (i=0; i<40; i++)
{
T[i][j][0] = Thermoplastic;
}
}
}
if ((n % z) == 0 )
{
  for (j=60; j<97; j++)
  {
    for (i=0; i<40; i++)
    {
      T[i][j][0] = T[i][j][9];
    }
  }
}
if ((n % z) == 0 )
{
  for (j=0; j<97; j++)
  {
    for (i=0; i<40; i++)
    {
      outf2 << T[i][j][0] << ",";
    }
    outf2 << "\n";
  }
  outf2 << "\n";
}
iter++;
outf.close();
//outf1.close();
outf2.close();
return 0;
APPENDIX D

IN-MOLD COATED ABS PARTS
Figure D.1. In-Mold Coated ABS. Part # 43.
Figure D.2. In-Mold Coated ABS. Part # 44.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mold Temperature</td>
<td>94 Degree C</td>
</tr>
<tr>
<td>Barrel Temperature Profile</td>
<td>470  450  420  380 Degrees F</td>
</tr>
<tr>
<td>Plastic Shot Size</td>
<td>4.25 inches</td>
</tr>
<tr>
<td>Cooling Time</td>
<td>90 seconds</td>
</tr>
<tr>
<td>Screw RPM</td>
<td>30 %</td>
</tr>
<tr>
<td>Velocity</td>
<td>0.65 inches 40% 0.90 inches</td>
</tr>
<tr>
<td>Packing Pressure</td>
<td>7 seconds 20% 1.60 seconds</td>
</tr>
<tr>
<td>Fill Peak Pressure</td>
<td>43 % of 2230 kg/cm²²</td>
</tr>
<tr>
<td>Fill Time</td>
<td>1.60 seconds</td>
</tr>
<tr>
<td>Plastication Time</td>
<td>14.10 seconds</td>
</tr>
<tr>
<td>Cushion</td>
<td>0.29 inches</td>
</tr>
<tr>
<td>Delay Time</td>
<td>20 seconds</td>
</tr>
<tr>
<td>Coating Shot Size</td>
<td>8 units</td>
</tr>
</tbody>
</table>
Figure D.3. In-Mold Coated ABS. Part # 45.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Mold Temperature</td>
<td>94 Degree C</td>
</tr>
<tr>
<td>Barrel Temperature Profile</td>
<td>470 450 420 380 Degrees F</td>
</tr>
<tr>
<td>Plastic Shot Size</td>
<td>4.25 inches</td>
</tr>
<tr>
<td>Cooling Time</td>
<td>90 seconds</td>
</tr>
<tr>
<td>Screw RPM</td>
<td>30 %</td>
</tr>
<tr>
<td>Velocity</td>
<td>0.65 inches 40% 0.90 inches</td>
</tr>
<tr>
<td>Packing Pressure</td>
<td>7 seconds 20% 1.60 seconds</td>
</tr>
<tr>
<td>Fill Peak Pressure</td>
<td>43 % of 2230 kgf/cm²²</td>
</tr>
<tr>
<td>Fill Time</td>
<td>1.60 seconds</td>
</tr>
<tr>
<td>Plastication Time</td>
<td>14.10 seconds</td>
</tr>
<tr>
<td>Cushion</td>
<td>0.29 inches</td>
</tr>
<tr>
<td>Delay Time</td>
<td>20 seconds</td>
</tr>
<tr>
<td>Coating Shot Size</td>
<td>8 units</td>
</tr>
</tbody>
</table>
Figure D.4. In-Mold Coated ABS. Part # 46.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mold Temperature</td>
<td>93.5 Degree C</td>
</tr>
<tr>
<td>Barrel Temperature Profile</td>
<td>470 450 420 380 Degrees F</td>
</tr>
<tr>
<td>Plastic Shot Size</td>
<td>4.25 inches</td>
</tr>
<tr>
<td>Cooling Time</td>
<td>90 seconds</td>
</tr>
<tr>
<td>Screw RPM</td>
<td>30 %</td>
</tr>
<tr>
<td>Velocity</td>
<td>0.65 inches 40% 0.90 inches</td>
</tr>
<tr>
<td>Packing Pressure</td>
<td>7 seconds 20% 1.60 seconds</td>
</tr>
<tr>
<td>Fill Peak Pressure</td>
<td>43 % of 2230 kgf/cm^2</td>
</tr>
<tr>
<td>Fill Time</td>
<td>1.60 seconds</td>
</tr>
<tr>
<td>Plastication Time</td>
<td>14.10 seconds</td>
</tr>
<tr>
<td>Cushion</td>
<td>0.29 inches</td>
</tr>
<tr>
<td>Delay Time</td>
<td>40 seconds</td>
</tr>
<tr>
<td>Coating Shot Size</td>
<td>8 units</td>
</tr>
<tr>
<td>Parameter</td>
<td>Value</td>
</tr>
<tr>
<td>----------------------------</td>
<td>--------------------------------------------</td>
</tr>
<tr>
<td>Mold Temperature</td>
<td>93.5 Degree C</td>
</tr>
<tr>
<td>Barrel Temperature Profile</td>
<td>470 450 420 380 Degrees F</td>
</tr>
<tr>
<td>Plastic Shot Size</td>
<td>4.25 inches</td>
</tr>
<tr>
<td>Cooling Time</td>
<td>90 seconds</td>
</tr>
<tr>
<td>Screw RPM</td>
<td>30 %</td>
</tr>
<tr>
<td>Velocity</td>
<td>0.65 inches 40% 0.90 inches</td>
</tr>
<tr>
<td>Packing Pressure</td>
<td>7 seconds 20% 1.60 seconds</td>
</tr>
<tr>
<td>Fill Peak Pressure</td>
<td>43 % of 2230 kgf/cm²2</td>
</tr>
<tr>
<td>Fill Time</td>
<td>1.60 seconds</td>
</tr>
<tr>
<td>Plastication Time</td>
<td>14.10 seconds</td>
</tr>
<tr>
<td>Cushion</td>
<td>0.29 inches</td>
</tr>
<tr>
<td>Delay Time</td>
<td>40 seconds</td>
</tr>
<tr>
<td>Coating Shot Size</td>
<td>15 units</td>
</tr>
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Figure D.5. In-Mold Coated ABS. Part # 47.
Figure D.6. In-Mold Coated ABS. Part # 48.

<table>
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<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Mold Temperature</td>
<td>93 Degree C</td>
</tr>
<tr>
<td>Barrel Temperature Profile</td>
<td>470 450 420 380 Degrees F</td>
</tr>
<tr>
<td>Plastic Shot Size</td>
<td>4.25 inches</td>
</tr>
<tr>
<td>Cooling Time</td>
<td>90 seconds</td>
</tr>
<tr>
<td>Screw RPM</td>
<td>30 %</td>
</tr>
<tr>
<td>Velocity</td>
<td>0.65 inches 40% 0.90 inches</td>
</tr>
<tr>
<td>Packing Pressure</td>
<td>7 seconds 10 % 1.60 seconds</td>
</tr>
<tr>
<td>Fill Peak Pressure</td>
<td>43 % of 2230 kgf/cm²²</td>
</tr>
<tr>
<td>Fill Time</td>
<td>1.60 seconds</td>
</tr>
<tr>
<td>Plastication Time</td>
<td>14.10 seconds</td>
</tr>
<tr>
<td>Cushion</td>
<td>0.61 inches</td>
</tr>
<tr>
<td>Delay Time</td>
<td>20 seconds</td>
</tr>
<tr>
<td>Coating Shot Size</td>
<td>8 units</td>
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</table>
Figure D.7. In-Mold Coated ABS. Part # 49.
Figure D.8. In-Mold Coated ABS. Part # 50.

<table>
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</tr>
<tr>
<td>Barrel Temperature Profile</td>
<td>470  450  420  380 Degrees F</td>
</tr>
<tr>
<td>Plastic Shot Size</td>
<td>4.25 inches</td>
</tr>
<tr>
<td>Cooling Time</td>
<td>90 seconds</td>
</tr>
<tr>
<td>Screw RPM</td>
<td>30 %</td>
</tr>
<tr>
<td>Velocity</td>
<td>0.65 inches 40%  0.90 inches</td>
</tr>
<tr>
<td>Packing Pressure</td>
<td>7 seconds 20%  1.60 seconds</td>
</tr>
<tr>
<td>Fill Peak Pressure</td>
<td>43 % of 2230 kgf/cm²²</td>
</tr>
<tr>
<td>Fill Time</td>
<td>1.60 seconds</td>
</tr>
<tr>
<td>Plastication Time</td>
<td>14.10 seconds</td>
</tr>
<tr>
<td>Cushion</td>
<td>0.29 inches</td>
</tr>
<tr>
<td>Delay Time</td>
<td>20 seconds</td>
</tr>
<tr>
<td>Coating Shot Size</td>
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</table>
Figure D.9. In-Mold Coated ABS. Part # 51.

<table>
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<tr>
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<tbody>
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<td>Mold Temperature</td>
<td>93 Degree C</td>
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<tr>
<td>Barrel Temperature Profile</td>
<td>470 450 420 380 Degrees F</td>
</tr>
<tr>
<td>Plastic Shot Size</td>
<td>4.25 inches</td>
</tr>
<tr>
<td>Cooling Time</td>
<td>90 seconds</td>
</tr>
<tr>
<td>Screw RPM</td>
<td>30 %</td>
</tr>
<tr>
<td>Velocity</td>
<td>0.65 inches 40% 0.90 inches</td>
</tr>
<tr>
<td>Packing Pressure</td>
<td>7 seconds 20 % 1.60 seconds</td>
</tr>
<tr>
<td>Fill Peak Pressure</td>
<td>43 % of 2230 kgt/cm²</td>
</tr>
<tr>
<td>Fill Time</td>
<td>1.60 seconds</td>
</tr>
<tr>
<td>Plastication Time</td>
<td>14.10 seconds</td>
</tr>
<tr>
<td>Cushion</td>
<td>0.29 inches</td>
</tr>
<tr>
<td>Delay Time</td>
<td>40 seconds</td>
</tr>
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<td>Coating Shot Size</td>
<td>15 units</td>
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<tr>
<td>Parameter</td>
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<tr>
<td>Mold Temperature</td>
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<tr>
<td>Barrel Temperature Profile</td>
<td>470 450 420 380 Degrees F</td>
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<tr>
<td>Plastic Shot Size</td>
<td>4.25 inches</td>
</tr>
<tr>
<td>Cooling Time</td>
<td>90 seconds</td>
</tr>
<tr>
<td>Screw RPM</td>
<td>30 %</td>
</tr>
<tr>
<td>Velocity</td>
<td>0.65 inches 40% 0.90 inches</td>
</tr>
<tr>
<td>Packing Pressure</td>
<td>7 seconds 10 % 1.60 seconds 5</td>
</tr>
<tr>
<td>Fill Peak Pressure</td>
<td>43 % of 2230 kgf/cm^2</td>
</tr>
<tr>
<td>Fill Time</td>
<td>1.60 seconds</td>
</tr>
<tr>
<td>Plastication Time</td>
<td>14.10 seconds</td>
</tr>
<tr>
<td>Cushion</td>
<td>0.63 inches</td>
</tr>
<tr>
<td>Delay Time</td>
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Figure D.10. In-Mold Coated ABS. Part # 52
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<tr>
<td>Barrel Temperature Profile</td>
<td>470  450  420  380 Degrees F</td>
</tr>
<tr>
<td>Plastic Shot Size</td>
<td>4.25 inches</td>
</tr>
<tr>
<td>Cooling Time</td>
<td>90 seconds</td>
</tr>
<tr>
<td>Screw RPM</td>
<td>30 %</td>
</tr>
<tr>
<td>Velocity</td>
<td>0.65 inches 40%  0.90 inches</td>
</tr>
<tr>
<td>Packing Pressure</td>
<td>7 seconds 20%  1.60 seconds</td>
</tr>
<tr>
<td>Fill Peak Pressure</td>
<td>43 % of 2230 kgf/cm²</td>
</tr>
<tr>
<td>Fill Time</td>
<td>1.60 seconds</td>
</tr>
<tr>
<td>Plastication Time</td>
<td>14.10 seconds</td>
</tr>
<tr>
<td>Cushion</td>
<td>0.29 inches</td>
</tr>
<tr>
<td>Delay Time</td>
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Figure D.11. In-Mold Coated ABS. Part # 53.
Figure D.12. In-Mold Coated ABS. Part # 54.
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<tr>
<td>Barrel Temperature Profile</td>
<td>470  450  420  380 Degrees F</td>
</tr>
<tr>
<td>Plastic Shot Size</td>
<td>4.25 inches</td>
</tr>
<tr>
<td>Cooling Time</td>
<td>90 seconds</td>
</tr>
<tr>
<td>Screw RPM</td>
<td>30 %</td>
</tr>
<tr>
<td>Velocity</td>
<td>0.65 inches 40%  0.90 inches</td>
</tr>
<tr>
<td>Packing Pressure</td>
<td>7 seconds 10%  1.60 seconds 5%</td>
</tr>
<tr>
<td>Fill Peak Pressure</td>
<td>43% of 2230 kgf/cm²</td>
</tr>
<tr>
<td>Fill Time</td>
<td>1.60 seconds</td>
</tr>
<tr>
<td>Plastication Time</td>
<td>14.10 seconds</td>
</tr>
<tr>
<td>Cushion</td>
<td>0.63 inches</td>
</tr>
<tr>
<td>Delay Time</td>
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<td>Coating Shot Size</td>
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Figure D.13. In-Mold Coated ABS. Part # 55.
Figure D.14. In-Mold Coated ABS. Part # 56.

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<tr>
<td>Barrel Temperature Profile</td>
<td>470  450  420  380 Degrees F</td>
</tr>
<tr>
<td>Plastic Shot Size</td>
<td>4.25 inches</td>
</tr>
<tr>
<td>Cooling Time</td>
<td>90 seconds</td>
</tr>
<tr>
<td>Screw RPM</td>
<td>30 %</td>
</tr>
<tr>
<td>Velocity</td>
<td>0.65 inches 40%  0.90 inches</td>
</tr>
<tr>
<td>Packing Pressure</td>
<td>7 seconds 10 %  1.60 seconds 5</td>
</tr>
<tr>
<td>Fill Peak Pressure</td>
<td>43 % of 2230 kgf/cm²2</td>
</tr>
<tr>
<td>Fill Time</td>
<td>1.60 seconds</td>
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<tr>
<td>Plastication Time</td>
<td>14.10 seconds</td>
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<tr>
<td>Cushion</td>
<td>0.63 inches</td>
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<tr>
<td>Delay Time</td>
<td>20 seconds</td>
</tr>
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<td>Coating Shot Size</td>
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Figure D.15. In-Mold Coated ABS. Part # 57.

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<td>Barrel Temperature Profile</td>
<td>470 450 420 380 Degrees F</td>
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<tr>
<td>Plastic Shot Size</td>
<td>4.25 inches</td>
</tr>
<tr>
<td>Cooling Time</td>
<td>90 seconds</td>
</tr>
<tr>
<td>Screw RPM</td>
<td>30 %</td>
</tr>
<tr>
<td>Velocity</td>
<td>0.65 inches 40% 0.90 inches</td>
</tr>
<tr>
<td>Packing Pressure</td>
<td>7 seconds 10% 1.60 seconds 5</td>
</tr>
<tr>
<td>Fill Peak Pressure</td>
<td>43 % of 2230 kgf/cm²?</td>
</tr>
<tr>
<td>Fill Time</td>
<td>1.60 seconds</td>
</tr>
<tr>
<td>Plastification Time</td>
<td>14.10 seconds</td>
</tr>
<tr>
<td>Cushion</td>
<td>0.63 inches</td>
</tr>
<tr>
<td>Delay Time</td>
<td>40 seconds</td>
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<td>Coating Shot Size</td>
<td>15 units</td>
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Figure D.16. In-Mold Coated ABS. Part # 58.
APPENDIX E

IN-MOLD COATED PCABS PARTS
Figure E.1. In-Mold Coated PCABS. Part # 36.

<table>
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<tr>
<td>Barrel Temperature Profile</td>
<td>500 490 490 465 Degrees F</td>
</tr>
<tr>
<td>Plastic Shot Size</td>
<td>4.25 inches</td>
</tr>
<tr>
<td>Cooling Time</td>
<td>90 seconds</td>
</tr>
<tr>
<td>Screw RPM</td>
<td>30 %</td>
</tr>
<tr>
<td>Velocity</td>
<td>0.65 inches 40% 0.90 inches</td>
</tr>
<tr>
<td>Packing Pressure</td>
<td>7 seconds 10 % 1.60 seconds 5</td>
</tr>
<tr>
<td>Fill Peak Pressure</td>
<td>37 % of 2230 kgf/cm²²</td>
</tr>
<tr>
<td>Fill Time</td>
<td>1.55 seconds</td>
</tr>
<tr>
<td>Plastication Time</td>
<td>14.50 seconds</td>
</tr>
<tr>
<td>Cushion</td>
<td>0.56 inches</td>
</tr>
<tr>
<td>Delay Time</td>
<td>40 seconds</td>
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<tr>
<td>Coating Shot Size</td>
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Figure E.2. In-Mold Coated PCABS. Part # 37.

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<tr>
<td>Barrel Temperature Profile</td>
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<tr>
<td>Cooling Time</td>
<td>90 seconds</td>
</tr>
<tr>
<td>Screw RPM</td>
<td>30 %</td>
</tr>
<tr>
<td>Velocity</td>
<td>0.65 inches 40% 0.90 inches</td>
</tr>
<tr>
<td>Packing Pressure</td>
<td>7 seconds 20% 1.60 seconds</td>
</tr>
<tr>
<td>Fill Peak Pressure</td>
<td>37% of 2230 kgf/cm²</td>
</tr>
<tr>
<td>Fill Time</td>
<td>1.55 seconds</td>
</tr>
<tr>
<td>Plastication Time</td>
<td>14.50 seconds</td>
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<tr>
<td>Cushion</td>
<td>0.02 inches</td>
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<tr>
<td>Coating Shot Size</td>
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210
Figure E.3. In-Mold Coated PCABS. Part # 38.

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<tr>
<td>Barrel Temperature Profile</td>
<td>500 490 490 465 Degrees F</td>
</tr>
<tr>
<td>Plastic Shot Size</td>
<td>4.25 inches</td>
</tr>
<tr>
<td>Cooling Time</td>
<td>90 seconds</td>
</tr>
<tr>
<td>Screw RPM</td>
<td>30 %</td>
</tr>
<tr>
<td>Velocity</td>
<td>0.65 inches 40% 0.90 inches</td>
</tr>
<tr>
<td>Packing Pressure</td>
<td>7 seconds 10% 1.60 seconds 5</td>
</tr>
<tr>
<td>Fill Peak Pressure</td>
<td>37% of 2230 kgf/cm²2</td>
</tr>
<tr>
<td>Fill Time</td>
<td>1.55 seconds</td>
</tr>
<tr>
<td>Plastication Time</td>
<td>14.50 seconds</td>
</tr>
<tr>
<td>Cushion</td>
<td>0.54 inches</td>
</tr>
<tr>
<td>Delay Time</td>
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Figure E.4. In-Mold Coated PCABS. Part # 39.

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<tr>
<td>Barrel Temperature Profile</td>
<td>500 490 490 465 Degrees F</td>
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<tr>
<td>Plastic Shot Size</td>
<td>4.25 inches</td>
</tr>
<tr>
<td>Cooling Time</td>
<td>90 seconds</td>
</tr>
<tr>
<td>Screw RPM</td>
<td>30 %</td>
</tr>
<tr>
<td>Velocity</td>
<td>0.65 inches 40% 0.90 inches</td>
</tr>
<tr>
<td>Packing Pressure</td>
<td>7 seconds 20% 1.60 seconds</td>
</tr>
<tr>
<td>Fill Peak Pressure</td>
<td>37% of 2230 kgf/cm²</td>
</tr>
<tr>
<td>Fill Time</td>
<td>1.55 seconds</td>
</tr>
<tr>
<td>Plastication Time</td>
<td>14.50 seconds</td>
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<tr>
<td>Cushion</td>
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<tr>
<td>Delay Time</td>
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<tr>
<td>Coating Shot Size</td>
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212
Figure E.5. In-Mold Coated PCABS. Part # 40.

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<tr>
<td>Barrel Temperature Profile</td>
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<tr>
<td>Plastic Shot Size</td>
<td>4.25 inches</td>
</tr>
<tr>
<td>Cooling Time</td>
<td>90 seconds</td>
</tr>
<tr>
<td>Screw RPM</td>
<td>30 %</td>
</tr>
<tr>
<td>Velocity</td>
<td>0.65 inches 40% 0.90 inches</td>
</tr>
<tr>
<td>Packing Pressure</td>
<td>7 seconds 20% 1.60 seconds</td>
</tr>
<tr>
<td>Fill Peak Pressure</td>
<td>37 % of 2230 kgf/cm²</td>
</tr>
<tr>
<td>Fill Time</td>
<td>1.55 seconds</td>
</tr>
<tr>
<td>Plastication Time</td>
<td>14.50 seconds</td>
</tr>
<tr>
<td>Cushion</td>
<td>0.02 inches</td>
</tr>
<tr>
<td>Delay Time</td>
<td>40 seconds</td>
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<tr>
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Figure E.6. In-Mold Coated PCABS. Part # 41.

<table>
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<td>Plastic Shot Size</td>
<td>4.25 inches</td>
</tr>
<tr>
<td>Cooling Time</td>
<td>90 seconds</td>
</tr>
<tr>
<td>Screw RPM</td>
<td>30 %</td>
</tr>
<tr>
<td>Velocity</td>
<td>0.65 inches 40% 0.90 inches</td>
</tr>
<tr>
<td>Packing Pressure</td>
<td>7 seconds 20% 1.60 seconds</td>
</tr>
<tr>
<td>Fill Peak Pressure</td>
<td>37 % of 2230 kgf/cm²</td>
</tr>
<tr>
<td>Fill Time</td>
<td>1.55 seconds</td>
</tr>
<tr>
<td>Plastication Time</td>
<td>14.50 seconds</td>
</tr>
<tr>
<td>Cushion</td>
<td>0.02 inches</td>
</tr>
<tr>
<td>Delay Time</td>
<td>20 seconds</td>
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<td>Coating Shot Size</td>
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Figure E.7. In-Mold Coated PCABS. Part # 42.

<table>
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<tr>
<td>Barrel Temperature Profile</td>
<td>500 490 490 465 Degrees F</td>
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<tr>
<td>Plastic Shot Size</td>
<td>4.25 inches</td>
</tr>
<tr>
<td>Cooling Time</td>
<td>90 seconds</td>
</tr>
<tr>
<td>Screw RPM</td>
<td>30 %</td>
</tr>
<tr>
<td>Velocity</td>
<td>0.65 inches 40% 0.90 inches</td>
</tr>
<tr>
<td>Packing Pressure</td>
<td>7 seconds 10 % 1.60 seconds 5</td>
</tr>
<tr>
<td>Fill Peak Pressure</td>
<td>37 % of 2230 kgf/cm²</td>
</tr>
<tr>
<td>Fill Time</td>
<td>1.55 seconds</td>
</tr>
<tr>
<td>Plastication Time</td>
<td>14.50 seconds</td>
</tr>
<tr>
<td>Cushion</td>
<td>0.50 inches</td>
</tr>
<tr>
<td>Delay Time</td>
<td>20 seconds</td>
</tr>
<tr>
<td>Coating Shot Size</td>
<td>13 units</td>
</tr>
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</table>
Figure E.8. In-Mold Coated PCABS. Part # 43.
### Parameter | Value
--- | ---
Mold Temperature | 88.5 Degree C
Barrel Temperature Profile | 500 490 490 465 Degrees F
Plastic Shot Size | 4.25 inches
Cooling Time | 90 seconds
Screw RPM | 30 %
Velocity | 0.65 inches 40% 0.90 inches
Packing Pressure | 7 seconds 10% 1.60 seconds 5
Fill Peak Pressure | 37 % of 2230 kgf/cm²
Fill Time | 1.55 seconds
Plastication Time | 14.50 seconds
Cushion | 0.50 inches
Delay Time | 20 seconds
Coating Shot Size | 18 units

Figure E.9. In-Mold Coated PCABS. Part # 44.
<table>
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<td>Plastic Shot Size</td>
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<tr>
<td>Cooling Time</td>
<td>90 seconds</td>
</tr>
<tr>
<td>Screw RPM</td>
<td>30 %</td>
</tr>
<tr>
<td>Velocity</td>
<td>0.65 inches 40% 0.90 inches</td>
</tr>
<tr>
<td>Packing Pressure</td>
<td>7 seconds 20 % 1.60 seconds</td>
</tr>
<tr>
<td>Fill Peak Pressure</td>
<td>37 % of 2230 kgf/cm²2</td>
</tr>
<tr>
<td>Fill Time</td>
<td>1.55 seconds</td>
</tr>
<tr>
<td>Plastification Time</td>
<td>14.50 seconds</td>
</tr>
<tr>
<td>Cushion</td>
<td>0.02 inches</td>
</tr>
<tr>
<td>Delay Time</td>
<td>20 seconds</td>
</tr>
<tr>
<td>Coating Shot Size</td>
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Figure E.10. In-Mold Coated PCABS. Part # 45.
Figure E.11. In-Mold Coated PCABS. Part # 46.

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<tr>
<td>Barrel Temperature Profile</td>
<td>500 490 490 465 Degrees F</td>
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<tr>
<td>Plastic Shot Size</td>
<td>4.25 inches</td>
</tr>
<tr>
<td>Cooling Time</td>
<td>90 seconds</td>
</tr>
<tr>
<td>Screw RPM</td>
<td>30 %</td>
</tr>
<tr>
<td>Velocity</td>
<td>0.65 inches 40% 0.90 inches</td>
</tr>
<tr>
<td>Packing Pressure</td>
<td>7 seconds 20 % 1.60 seconds</td>
</tr>
<tr>
<td>Fill Peak Pressure</td>
<td>37 % of 2230 kg/cm²2</td>
</tr>
<tr>
<td>Fill Time</td>
<td>1.55 seconds</td>
</tr>
<tr>
<td>Plastication Time</td>
<td>14.50 seconds</td>
</tr>
<tr>
<td>Cushion</td>
<td>0.02 inches</td>
</tr>
<tr>
<td>Delay Time</td>
<td>40 seconds</td>
</tr>
<tr>
<td>Coating Shot Size</td>
<td>18 units</td>
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Figure E.12. In-Mold Coated PCABS. Part # 47.

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<td>Plastic Shot Size</td>
<td>4.25 inches</td>
</tr>
<tr>
<td>Cooling Time</td>
<td>90 seconds</td>
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<td>Screw RPM</td>
<td>30 %</td>
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<tr>
<td>Velocity</td>
<td>0.65 inches 40% 0.90 inches</td>
</tr>
<tr>
<td>Packing Pressure</td>
<td>7 seconds 10% 1.60 seconds 5</td>
</tr>
<tr>
<td>Fill Peak Pressure</td>
<td>37% of 2230 kgf/cm²²</td>
</tr>
<tr>
<td>Fill Time</td>
<td>1.55 seconds</td>
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<td>Plastication Time</td>
<td>14.50 seconds</td>
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<tr>
<td>Cushion</td>
<td>0.49 inches</td>
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<tr>
<td>Delay Time</td>
<td>20 seconds</td>
</tr>
<tr>
<td>Coating Shot Size</td>
<td>13 units</td>
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<td>Parameter</td>
<td>Value</td>
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<td>--------------------------------------------</td>
</tr>
<tr>
<td>Mold Temperature</td>
<td>91 Degree C</td>
</tr>
<tr>
<td>Barrel Temperature Profile</td>
<td>500 490 490 465 Degrees F</td>
</tr>
<tr>
<td>Plastic Shot Size</td>
<td>4.25 inches</td>
</tr>
<tr>
<td>Cooling Time</td>
<td>90 seconds</td>
</tr>
<tr>
<td>Screw RPM</td>
<td>30 %</td>
</tr>
<tr>
<td>Velocity</td>
<td>0.65 inches 40% 0.90 inches</td>
</tr>
<tr>
<td>Packing Pressure</td>
<td>7 seconds 10% 1.60 seconds 5</td>
</tr>
<tr>
<td>Fill Peak Pressure</td>
<td>37% of 2230 kgf/cm²2</td>
</tr>
<tr>
<td>Fill Time</td>
<td>1.55 seconds</td>
</tr>
<tr>
<td>Plastication Time</td>
<td>14.50 seconds</td>
</tr>
<tr>
<td>Cushion</td>
<td>0.50 inches</td>
</tr>
<tr>
<td>Delay Time</td>
<td>20 seconds</td>
</tr>
<tr>
<td>Coating Shot Size</td>
<td>18 units</td>
</tr>
</tbody>
</table>

Figure E.13. In-Mold Coated PCABS. Part # 48.
<table>
<thead>
<tr>
<th>Parameter</th>
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<tbody>
<tr>
<td>Mold Temperature</td>
<td>91 Degree C</td>
</tr>
<tr>
<td>Barrel Temperature Profile</td>
<td>500 490 490 465 Degrees</td>
</tr>
<tr>
<td>Plastic Shot Size</td>
<td>4.25 inches</td>
</tr>
<tr>
<td>Cooling Time</td>
<td>90 seconds</td>
</tr>
<tr>
<td>Screw RPM</td>
<td>30 %</td>
</tr>
<tr>
<td>Velocity</td>
<td>0.65 inches 40% 0.90 inches</td>
</tr>
<tr>
<td>Packing Pressure</td>
<td>7 seconds 20% 1.60 seconds</td>
</tr>
<tr>
<td>Fill Peak Pressure</td>
<td>37% of 2230 k gf/cm²²</td>
</tr>
<tr>
<td>Fill Time</td>
<td>1.55 seconds</td>
</tr>
<tr>
<td>Plascitation Time</td>
<td>14.50 seconds</td>
</tr>
<tr>
<td>Cushion</td>
<td>0.02 inches</td>
</tr>
<tr>
<td>Delay Time</td>
<td>40 seconds</td>
</tr>
<tr>
<td>Coating Shot Size</td>
<td>13 units</td>
</tr>
</tbody>
</table>

Figure E.14. In-Mold Coated PCABS. Part # 49.
Figure E.15. In-Mold Coated PCABS. Part # 50.

<table>
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<th>Parameter</th>
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<tbody>
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</tr>
<tr>
<td>Barrel Temperature Profile</td>
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</tr>
<tr>
<td>Plastic Shot Size</td>
<td>4.25 inches</td>
</tr>
<tr>
<td>Cooling Time</td>
<td>90 seconds</td>
</tr>
<tr>
<td>Screw RPM</td>
<td>30 %</td>
</tr>
<tr>
<td>Velocity</td>
<td>0.65 inches 40% 0.90 inches</td>
</tr>
<tr>
<td>Packing Pressure</td>
<td>7 seconds 10 % 1.60 seconds 5</td>
</tr>
<tr>
<td>Fill Peak Pressure</td>
<td>37 % of 2230 kgf/cm²</td>
</tr>
<tr>
<td>Fill Time</td>
<td>1.55 seconds</td>
</tr>
<tr>
<td>Plastication Time</td>
<td>14.50 seconds</td>
</tr>
<tr>
<td>Cushion</td>
<td>0.50 inches</td>
</tr>
<tr>
<td>Delay Time</td>
<td>40 seconds</td>
</tr>
<tr>
<td>Coating Shot Size</td>
<td>13 units</td>
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Figure E.16. In-Mold Coated PCABS. Part # 51.

<table>
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<tbody>
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</tr>
<tr>
<td>Barrel Temperature Profile</td>
<td>500 490 490 465 Degrees F</td>
</tr>
<tr>
<td>Plastic Shot Size</td>
<td>4.25 inches</td>
</tr>
<tr>
<td>Cooling Time</td>
<td>90 seconds</td>
</tr>
<tr>
<td>Screw RPM</td>
<td>30 %</td>
</tr>
<tr>
<td>Velocity</td>
<td>0.65 inches 40% 0.90 inches</td>
</tr>
<tr>
<td>Packing Pressure</td>
<td>7 seconds 20% 1.60 seconds</td>
</tr>
<tr>
<td>Fill Peak Pressure</td>
<td>37 % of 2230 kgf/cm²</td>
</tr>
<tr>
<td>Fill Time</td>
<td>1.55 seconds</td>
</tr>
<tr>
<td>Plastication Time</td>
<td>14.50 seconds</td>
</tr>
<tr>
<td>Cushion</td>
<td>0.02 inches</td>
</tr>
<tr>
<td>Delay Time</td>
<td>20 seconds</td>
</tr>
<tr>
<td>Coating Shot Size</td>
<td>18 units</td>
</tr>
</tbody>
</table>
BIBLIOGRAPHY


6. www.tainstruments.com


17. Toha Candy, M.S. Project, The Ohio State University, 2004

18. http://islnotes.cps.msu.edu


21. www.dfdirnstruments.co.uk

22. Honda of America Manufacturing, Paint Testing Department, www.hondaresearch.com
