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Parametric Study of Film Formation and Curing Process for Film Insert Molding

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By

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ABSTRACT

The purpose of this work is to address a manufacturing problem related to the technology of Film Insert Molding (FIM) for the production of vehicle interior parts. The problem occurs in the first stages of the process during the production of the film, prior to injection molding. The film was distorted in some cases. When the distortion of the film was high, the film was not sticking to the mold properly, showing a tendency to pop out. This led to pinching of the film in the mold which caused two main failures: flashing of the resin and ripping of the film. A particular emphasis was put toward the process stages of forming and UV curing, that were identified through a root causes analysis, to induce major distortion of the shape of the film. With the use of a laser scanner and analysis software: Geomagic control X, it was possible to compare the shape of manufactured parts to the original CAD model containing the nominal shape of the film. The analysis was based on two full-factorial plans, one for forming of the film and one for UV curing it. Using analysis of the variance (ANOVA) of the deviations, it was possible to detect the influence of the factors on particular points of the surface of the film. It was found that parameters related to forming: dwell time and temperature, had a significant influence on the deviation of the film, the first accounting for about 50% of the change in deviation. Once the forming parameters were set to achieve the lowest deviation, parameters related to UV curing: UV oven conveyor speed and ink size, did not have an high influence on the distortion of the film.

DEDICATION

To my parents,

who have always believed in me

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LIST OF ABBREVIATIONS

ABS – Acrylonitrile butadiene styrene

ANOVA – Analysis of Variance

CAGR – Compound annual growth rate

CSD – center stack display

CTQ – Critical to quality

DOE – Design of Experiments

DOF – Degrees of freedom

EV – Electric Vehicle

FCA – Fiat Chrysler Automobiles

FIM – Film Insert Molding

GU – Gloss Unit

HIC – High Impact Characteristic

HMI – Human machine interface

HPF – High Pressure Forming

HVAC – Heating, ventilation and air conditioning

IMD – In-mold Decoration

IML – In-mold Labelling

OEM – Original equipment manufacturer

PC - Polycarbonate

PFMEA – Process Failure Modes Effect Analysis

PMMA – polymethyl methacrylate

RPN – Risk Priority Number

CHAPTER 1

INTRODUCTION

1.1 Vehicle Interiors Decoration – Display Size Trends.

Until the 1970s all displays for cars were just gauges lit by bulbs. Often, displays were minimized in dimensions because they had to leave enough room for other car parts such as HVAC air ducts, cables or mechanical elements [1]. Through the years, packaging has acquired more and more importance. Some parts of the vehicle have been minimized in shape, while there has been a fast improvement in the display technology that has led this component to have a predominant role in the center stack area of the panel. Nowadays, the HMI (Human Machine Interface) has acquired more and more importance as in today's vehicles the interaction of drivers and passengers with electronic appliances has become extremely common. As shown in Figure 1, the size of the center stack display (CSD) is constantly increasing through the years. The graph shows a decreasing trend of the small size displays, and an increasing trend, highlighted with the yellow arrow, of medium size displays. The total number of displays is also expected to increase in the following years with a Compound Annual Growth rate (CAGR) of 6.7%[1] [2] .

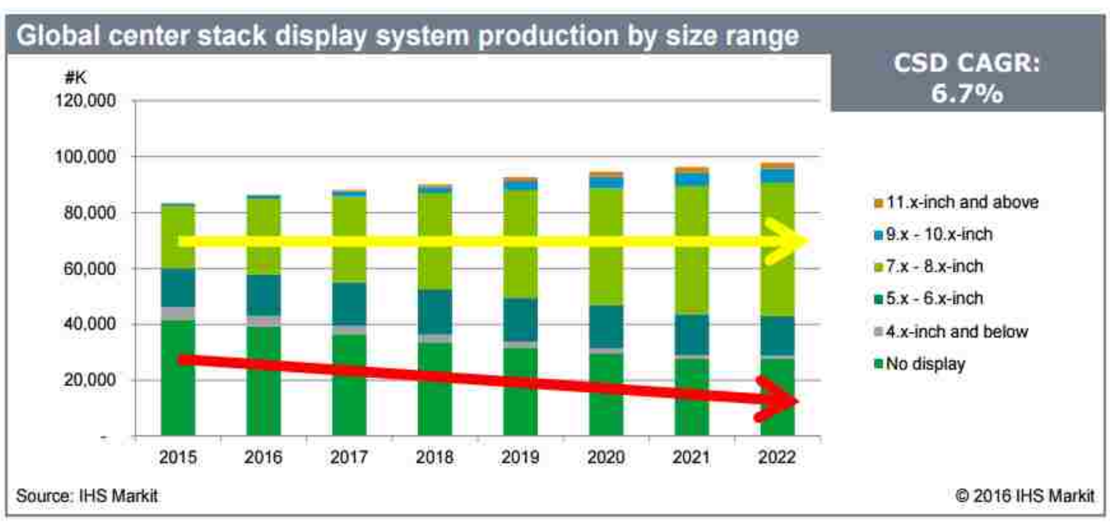


Figure 1: The forecasted increase of display number by size range [2] .

[1] The graph is dated September 2016

The three most important challenges for a display are three:

- Captivating design;
- Functionality for packaging;
- Feasibility for manufacturing.

Displays are usually surrounded with bezels, which aim to provide decoration to the part. Automotive interior trim bezels are a source of differentiation for different car models. Their design has been investigated recently because they have become very popular**.** Different aesthetic looks can be given to the part, using different technologies and manufacturing methods. There is a wide variety of techniques employed for the decoration of plastic parts for automotive interiors. Among them, film insert molding stands out. Film insert molding has become highly popular in recent years. Its purpose is to create a sense of value in customer perception for aesthetic surfaces. An exciting object from the visual point of view would increase the perceived quality and the brand reputation [3]. This technology replaces conventional methods of painting and coating injection molded parts, eliminating the necessity of post-processing operations and lowering the time and the costs of manufacturing. Film Insert Molding is able to provide different surface finishes on the part using a film. Behind the choice of a film there might be requirements from a mechanical, chemical and aesthetic point of view. A thin film is able to provide the plastic part with the required properties such as an increased durability or scratch resistance. Cost savings up to 40% over coated surfaces can be obtained [4]. This technique has shown great results for automobiles, electronic goods, medical devices and domestic appliances.

A plastic film is decorated through the process of screen printing. It can assume different appearances such as monochrome, multicolored, metallic and it can be glossy, textured or matte [4]. The idea of changing the decoration quickly on the same part can be carried out with this technique. There are two different types of FIM. The first one is called In-Mold Decoration (IMD), where the film is applied in the mold without being pre-formed. The second is In-Mold Labelling (IML), in which the film goes through a forming process, before it is physically put in the mold. The latter is a process that involves a more stretching of the film and allows it to reach more convoluted shapes of the part. Figure 2 represents the main features of FIM technology.

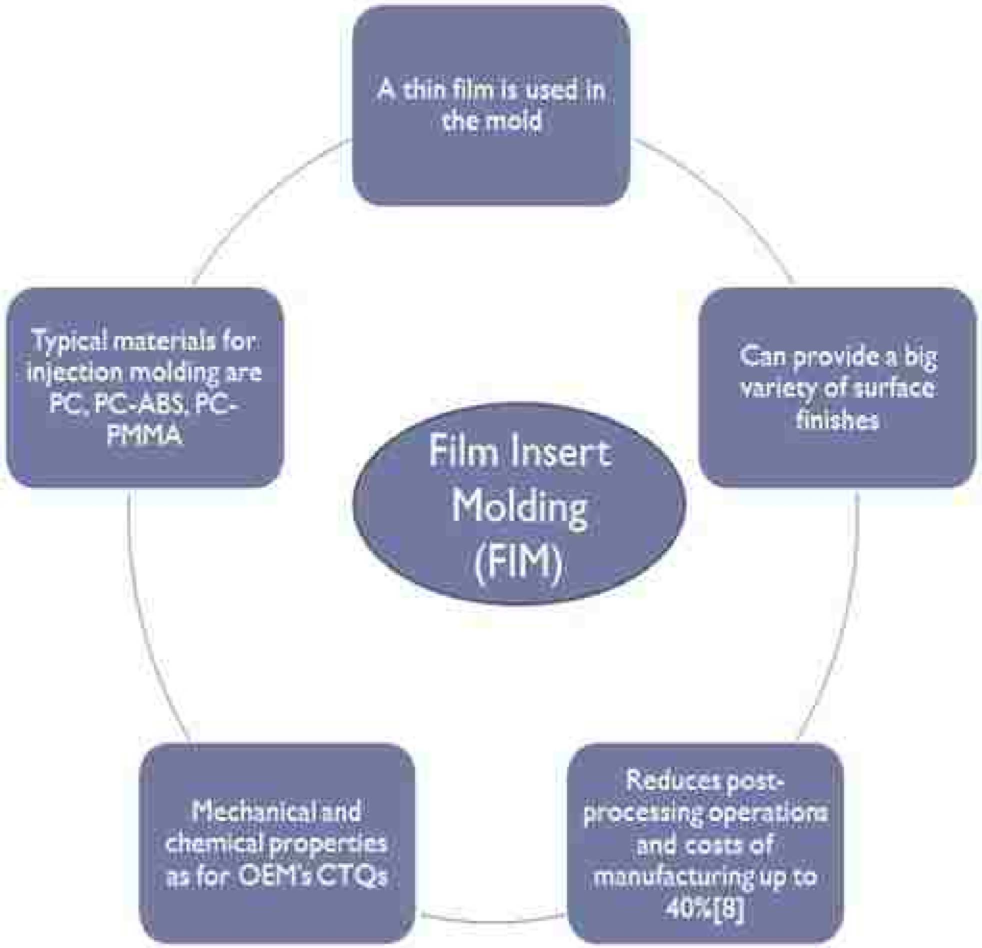


Figure 2: The main characteristics of FIM.

The technology of FIM has multiple advantages, among the others, it consists of a process that takes place in only one location. The process starts with a flat polymeric film and yields a decorated injection molded part, ready to be assembled in the vehicle. This work will be focused on the process of IML, paying particular attention to the process stages of forming and UV curing. Pre-injection molding steps have to be set up properly, in order for the film to reach the proper shape and to fit in the mold adequately. Forming is the process stage that transform a flat polymeric sheet in a 3D shaped sheet. In the case of IML the forming process generally employed is high pressure forming, that involves a pre-heating of the film (for a certain dwell time) and then the forming itself that takes place in a sealed forming tool, where high pressure is achieved. Also, the film has to be cured, because it has to achieve some mechanical and chemical properties as specified by different OEMs. OEMs requirements play a fundamental role, because the ultimate goal of the part is to pass these requirements to be sold to car manufacturers. If the film does not have a proper shape at the moment in which it has to be put in the mold, it means that some of the stages prior to injection molding were not well accomplished. This may result in the problem of pinching. The film may be pinched between the two mold cavities in the moment in which the mold closes for injection molding. If the film is pinched, injection molding cannot take place properly, causing defects such as flashing of the molten resin from the mold, and ripping of the film itself. This defect requires attention, as it may cause customer dissatisfaction, especially if the decoration of the part is not done properly.

1.2 Objectives

The main objective of this thesis is to minimize the occurrence of an high-rated problem of the IML process: pinching. The work aims at reducing the Risk Priority Number (RPN) of the failure mode in the Process Failure Mode Effect Analysis (PFMEA) through improvement of the process parameters for the manufacturing of the film to reduce occurrence.

1.3 Scope

This thesis was developed assisting a plastic manufacturer in the pre-production process of a display's bezel. The part was designed to fit in the vehicle center stack, and it serves as a modular bezel for a display. The pre-production process is a phase in which the manufacturing cell has to be set and made ready for production. In the pre-production phase, especially if simulation software is not available for a specific type of process, a set of trials and errors is generally performed. In order to reduce waste, and also reduce the lead time for production, it is fundamental that the parameters in the pre-production process are properly set in the shortest time possible. The process parameters have to be set properly in this phase in order to be ready to produce high quality parts in the actual production process. This is also a critical phase for the occurrence and detection of defects, that have to be properly identified and addressed in the shortest time possible. In this thesis, the main variables of the process will be identified, focusing on the ones that mainly influence the shape and the distortion of the part, as to prevent the occurrence of the pinching defects. The main focus will be toward the processes of forming and UV curing. A parametric study was performed, varying the parameters among certain values:

There will be two major outcomes of the thesis:

1. the parameters that mainly influence the process and the deviation of the part, and their percentages of contribution.
2. the set of parameter values that minimize the deviation, so as to assist the plastic manufacturer in the determination of parameters values for the actual production process.

The benefits of the work will be increased part quality (absence of visible defects), and a reduction of the lead time for original equipment manufacturers (OEMs), obtained through general guidelines for setting production process parameters.

CHAPTER 2

BACKGROUND

2.1 Description of different types of bezels

As a first important step, it is fundamental to distinguish between two different types of bezels:

- Modular
- Integrated

The first one works as a frame for the display. Its shape surrounds the display in order to provide a decorative function. In this case the lens of the display is not part of the bezel but it constitutes a different part. It is possible to notice a little step between the surface of the lens and the surface of the bezel as a tactile sensation as shown in Figure 3 On the other hand, an integrated display is a display that has been integrated with the rest of the dashboard. The plastic bezel constitutes the frame that surrounds the display and it also includes a lens, underneath which the display is applied. With this solution, there is a seamless feeling to the surface, as there is no distinction between the vehicle's interior trim and the display. An example of integrated bezel is shown in Figure 4.

Figure 3: Modular bezel surrounding the display [5]. (Chrysler Pacifica)

Figure 4: Integrated bezel covering the entire surface of the display [6]. (Alfa Romeo Giulia)

At this point it is also fundamental to distinguish between the functions of these different types of display. The bezel has to be:

- Decorative
- Functional

Decoration provides to the part a certain aesthetic value, which increases perceived value and brand reputation [7]. Decoration is usually achieved by both types of displays. It is fundamental as far as vehicle interiors are concerned. Tolerances in the production process have to be as tight as possible, because graphics have to be positioned in the right position as they were designed. With an integrated display, since the lens of the display becomes part of the bezel, it has to provide another characteristic: functionality. This means that the bezel has to meet some requirements as specified by OEMs in order to meet customers' requirements.

What follows is an overview of these requirements. It is important to consider that these are specified by OEMs according to their priorities and the market.

2.2 Optical requirements

Visibility is one of the first requirements: The lens has to have optical characteristics best suited to conditions inside the vehicle. The lens has to provide a certain transmittance so that the radiant energy coming out from the display reaches the users' eyes. Transmittance basically defines the passage of electromagnetic radiation though a medium. It is the ratio of transmitted radiant power to incident radiant power. It has to be as high as possible and commonly reaches 90%.

On the other hand, reflectance should be lowered as much as possible. It is an unwanted effect that sunlight, or light coming from other sources, is reflected directly in the drivers' eyes. Reflectance is usually very low. Its value should be kept below 10%. In some cases, it can be lowered below 5% with an Anti-Glare lens.

A lens can present a matte or a glossy surface. Gloss is a measure of specular reflection. It is measured by quantifying the amount of light reflected by a surface. It is measured in gloss units (GU). Table 1 aims at quantifying the specular gloss for an angle of 60˚. A matte surface helps in reducing the reflection. In order to have an Anti-Glare lens, the Gloss Unit has to be kept low.

Table 1: Classification of gloss based on specular gloss units [8]

Gloss range with 60˚ Gloss meter	Value
Low Gloss	<10 GU
Semi Gloss	10 to 70 GU
High Gloss	>70 GU

Another parameter that has to be factored in is haze. In Figure 5 haze is represented with the purple arrows. Haze is a measure of the diffusion of the transmitting light passing through a medium. When a light beam goes through a medium, which in this case could be a lens, the total transmittance is the entire amount of radiation through the transmission medium. A part of this light will be diffused, another part transmitted without change in direction, defined as parallel transmittance.

A low value of haze is usually required in order to have good visibility of the display. The parallel transmittance is a measure of the display clarity. Contrary to haze, its value has to be as high as possible.

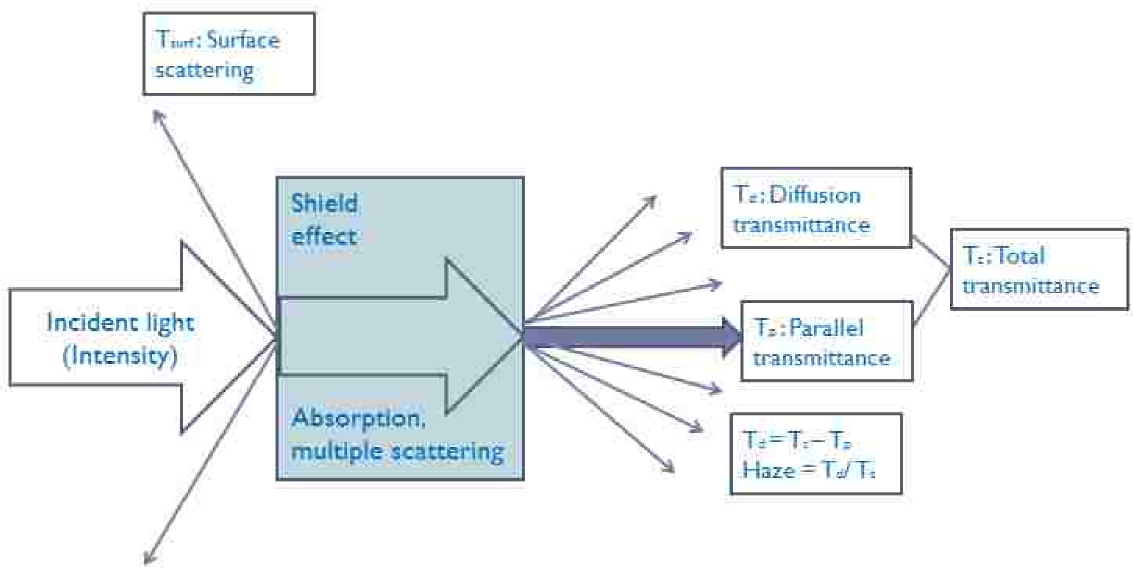


Figure 5: Representation of total transmittance through a medium as the sum of diffused transmittance (haze) and parallel transmittance [9].

It is curious to notice that from the light transmission point of view, the lens has to provide as much clarity as possible, reducing the amount of diffused transmittance (haze) as much as possible. On the other hand, from the reflection point of view, the lens has to diffuse the incident light, in order to avoid light reflection in the driver's eyes. Antiglare coatings are often used for this purpose (Figure 6).

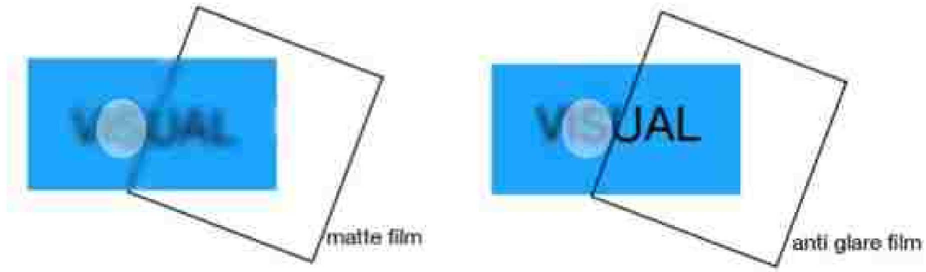


Figure 6: Difference between a matte film and an anti-glare film [10].

2.3 Physical requirements

The lens has to provide sufficient characteristics from the mechanical point of view as well as from the chemical point of view. The durability of the part has to be guaranteed. Some of the most important tests that the lens has to withstand are shown in Table 2:

Table 2: Most common mechanical test standards.

Test name	Purpose
Adhesion **Fiat 50457** [11]	It is a test method to assess the resistance of coatings to separation from substrates. It measures the property of adhesion of the coating to the substrate.
Resistance to wear **Fiat 50488/02** [12]	It is used to determine the fretting resistance of decorative coatings.
Five Finger Test **LP-463DD-18-01** [13]	It is used to determine the scratch and the mar resistance of coatings using a linearly-oriented, one pass, multi-fingered scratching device.

As part of the interior trim of vehicles, the bezels have to overcome a set of chemical resistance tests in order to be approved; the part has to show no cracking, blistering, etching or wrinkling on its topcoat after exposure to various chemicals. Common ones are shown in Table 3:

Table 3: Common chemical test standards for coating resistance to fluids.

Test name	Global commercial fluids
Armor All **LP-463PB-31-01 B** [14]	"Armor All" products [spot test]
Windex glass cleaner **LP-463PB-31-01 B** [14]	"Windex glass cleaner" products [spot test]
Suntan Lotion SPF 50 **LP-463PB-31-01 D** [14]	"Suntan Lotion SPF 50" products [Suntan Lotion test]
Royal Pine solid air freshner **LP-463PB-31-01 K** [14]	"Royal Pine solid air" products [Air freshener resistance test]
Acid .1 N H2S04 **LP-463PB-31-01 H** [14]	"H2S04" products [Acid or Alkali spot test]
Alkali .1 NaOH **LP-463PB-31-01 H** [14]	"NaOH" products [Acid or Alkali spot test]
Resistance to Ethyl alcohol **FIAT 9.55842/01** [15]	"Ethyl alcohol" products

As the display's bezel is not supposed to be replaced for the duration of the vehicle's life, and its durability has to be equal or greater than the one of the vehicle itself, it is fundamental that the part meets the requirements specified for aging. Some of these are shown in Table 4:

Table 4: Most common aging test standards.

Test	Purpose
Natural weathering ASTM G24 – ASTM D3359 B [16]	Evaluate the resistance of nonmetallic materials to solar radiation filtered through glass in passively ventilated and non-vented enclosures.
Accelerated aging SAE J2412 [17]	Specify the operating procedures for a controlled irradiance, xenon arc apparatus for the accelerated exposure of various automotive trim components
Humidity FIAT 50184/B [18]	Simulate effects of the same nature as those encountered during service on vehicle under various environmental conditions. In particular: Humidity
Thermocycle FIAT 50184 [18]	Simulate effects of the same nature as those encountered during service on vehicle under various environmental conditions. In particular: Temperature
Heat Age LP-463LB-13-01 [19]	Provide an accelerated method of testing the resistance of materials to heat aging

2.4 Design properties

As shown in Figure 1, the market is moving towards always bigger displays. Since the size of displays is continuously increasing, as a consequence, also their shape must be changing. In the past, it was possible to keep the shape of the display flat, because the dimensions were not a major concern. However, larger displays are more difficult to integrate into the center stack if they are not curved. As specified in a market analysis [2], the CAGR for curved display is at 53.4%. showing a very strong trend towards 3D shaped displays. Figure 7 shows the dashboard of a Chrysler Portal. On the one hand, the figure shows a captivating design, generating customer desirability. On the other hand, it creates a big challenge for manufacturing, which has to make sure that the shapes are achievable. The picture shows two large size displays fully integrated in the dashboard located at its top and bottom. The displays have a strong convoluted shape.

Figure 7: Chrysler Portal, EV of FCA @ CES 2017 Las Vegas [20].

Some limitations for manufacturing of FIM parts have to be respected. There are some limitations on the shape of the part, because current tooling does not allow the part to be bigger than certain dimensions. Also the depth of forming is one of the major concerns. In the design phase the radii of the part should not be smaller than a value that depends on the characteristics of the film, in particular, its thickness.

2.5 Manufacturing of bezels

Bezels are usually made of plastic, and their decoration is commonly accomplished by the process of injection molding followed by painting [21]. Various surface finishes can be achieved with the processes of painting and coating. Painting allows the required decoration; coatings are applied on the part to increase its mechanical and chemical properties, providing strength and cohesion.

Drawbacks of this way to manufacture plastic parts have arisen. As an example, in order to manufacture a bezel with two different surface finishes a two-piece approach would be used, injection molding the two parts separately. Diverse post treatments, including different coatings would provide different appearances to the surfaces. Joining the two parts together can be challenging and cost demanding. Furthermore, painting defects such as orange peel, sag and paint spits could give a poor surface appearance. A solution could be to injection mold only one piece and treat parts of it differently for the different surface finishes required. Disadvantages of the second approach include the requirement of a long supply chain and labor-intensive steps [22]. Sun [23] has pointed out the possibility of manufacturing the part through a multi-shot operation, co-molding two different materials in the same part. This can help to ease post-treatments, requiring less labor-intesive steps, because the different materials would react differently with the coatings that will be applied. The application of the process depends on the material availability and feasibility with different coatings. The idea of injection molding two different materials to make the same plastic part has also been supported by Scarabelli et al. [24] who found a very versatile method to reduce post treatment processes and associated costs in order to have various colors on a plastic surface.

Another study conducted by Ongena [25] aims at reducing the defects that arise from the compression molding process, such as pits and porosity shrink cracks with a technique called 'in-mold coating'. In-mold coating implies the application of a coating in the mold with the purpose to solve these defects. The main problem is that the opening and closing of the mold for coating application involves a depressurization and a repressurization of the mold cavity, resulting in an increased cycle time and defects. The problem of opening-closing of the mold was overcome in this study with the application of a coating injected in the mold at a high pressure. The substrate is first injected, and then cured until it has a surface able to receive the coating. Then the coating is applied. The technique allows a saving of 5 to 20% of the total molding and coating time and is more flexible so can be applied to other molding processes. Improvements in this technology are also brought by Hyuga et al. [26]. They worked on the reduction of coating material leakage from the mold. The problem derives from the fact that the resin, once injected in the cavity, cools down, leaving a small gap between the molded part and the cavity. The gap is the cause of coating material leakage.

Kitamura et al. [27] developed a way to decorate plastic parts with a particular injection molding process followed by a decoration molding to achieve the desired surface finish. The method is called In-Mold Coat Molding, where a decorative film is injected on top of a plastic part. Common problems described in the patent, such as the necessity to have the mold at two different temperatures during the first injection molding and the successive decorative molding, have been solved by employing individual cavity molds for the parts of the process. Using two mold cavities in this way the issue of heating up the mold cavity to a higher temperature is overcome.

2.5.1 In-Mold Labelling

The process of In-Mold Labelling (IML) consists of different phases. The process is slightly longer than IMD, because the film has to go through several steps before it is actually put in place in the mold. One of these operations is film forming which allows the achievement of more convoluted shapes and geometries compared to IMD. The film used for IML is usually thicker than the one used for IMD. The required number of operations for IML, before the actual injection molding, can vary from 3 to 4, depending on the requirements of the film. The process in total has five different operations [28]:

- Screen printing
- Forming
- UV curing
- Trimming
- Injection Molding

These phases are shown in the following diagram of Figure 8

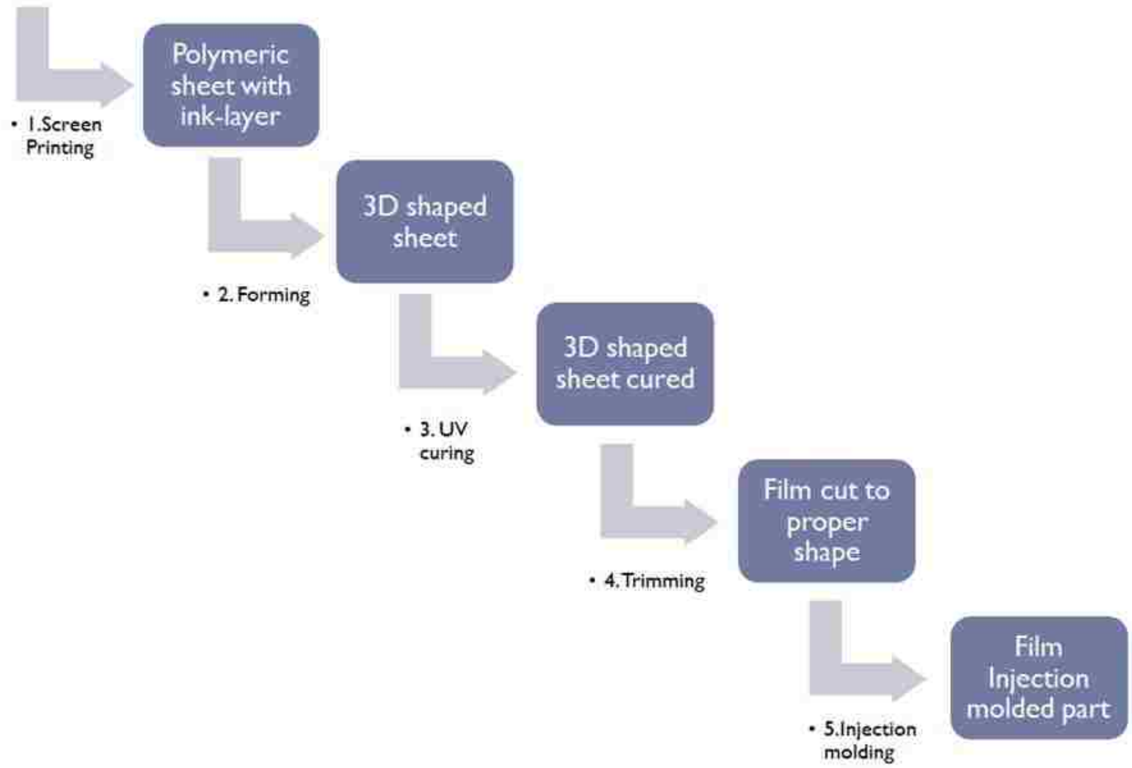


Figure 8: Process stages for FIM.

Each of these operations provides the film with an added value and allows the possibility of customizing the part, depending on the priorities of the customer. Usually film suppliers are different from mold suppliers, so cooperation between all members of the supply chain is needed to obtain the best performance.

The process of Film Insert Molding starts when hard-coated clear polymeric sheets are screen printed.

2.5.1.1 Screen Printing

Screen printing is the printing technique usually employed for IML [29]. It is an extremely important phase for decoration, because it is when the ink is applied. The final color of the part and the registration (which includes decorations and letters) depend on this phase of the process. A light sensitive layer is poured onto the screen fabric, exposed with the print image. On the screen some ink-permeable and ink-impermeable areas are created so that the ink only sticks to the section where it is needed. The printing ink needs to have some important characteristics such as flexibility and adherence to the film surface. The ink on the film has also to be resistant in the sense that it has to stick to the part since it will go through all the following stages of the process, when it will undergo thermal stress and high shear forces.

2.5.1.2 Forming

Forming is a very delicate part of the process through which the polymeric sheet acquires a 3D shape. Forming has to guarantee that the film has the desired shape within tight tolerances. An excellent formed film would result in an optimal shape that matches with the tools used for subsequent operations. Poor forming instead would cause a non-optimal shape of the film that will not match with the mold, resulting in scrap. The number of scraps in the film insert molding process is then related to the forming process. The forming process changes depending on the requirements of the film. The temperature is a key factor and can be set to the process used. There are two main techniques utilized to form the film. The most common one is thermoforming that involves heating the film to a very high temperature, above the polymer's glass transition temperature. The film comes either in a roll or in sheet form, depending on the type of forming machine. It is heated above its glass transition temperature through the use of radiant heaters [29]. Thermoforming is suitable when higher stretching of the film is required [30]. It means that forming precision is higher for thermoforming than for high pressure forming, especially when the part has a very convoluted 3D shape. Thermoforming is not recommended when the decorations on the part have to be in a specific area with a tight tolerance, which is often the case for cars' interior trim. Thermoforming is often not appropriate for matte and textured films because it makes matte films glossy and damages textures.

As mentioned, the other technique used for forming is high pressure forming (HPF). The film is initially preheated for a certain time. It comes as a sheet on a pallet and it is slid in a chamber where ceramic heaters provide heat. Heat is transferred through convection.

Ceramic heaters are both above and below the polymeric sheet, but they are kept at a certain distance. The temperature of each one of these heaters can be set according to the needs: if a part or one side of the film needs to be stretched more because a more convoluted shape is required, then that specific part of the sheet can be heated more and has to reach a higher temperature. Preheating assumes a fundamental role in the process of forming because it not only has to heat up the sheet, but it also has to provide the right amount of heat to specific parts of the film. Once the sheet is warmed up to a temperature higher than the glass transition temperature of the polymer, it softens. In order to have an idea of the temperature involved in the process, a polycarbonate (PC) sheet is usually heated to about 190˚C (the glass transition temperature of polycarbonate is about 147˚C [31]) in order to be formed properly. If the temperature is too low, cracking can occur, if the temperature is too high, the film may be damaged [32].

In a research carried out by Kurt Niebling [32] the temperature of a PC film of thickness 375 µm was analyzed after pre-heating. Differences in forming of the film were noticed according to the temperature of the film. Table 5 is aimed at providing an idea of the importance of the temperature that the film assumes after pre-heating in order to have proper forming.

Table 5: Forming results obtained pre-heating a film at different temperatures.

Surface temperature of the film	**Forming results** [32]
150˚C	Film distorted, base surface not flat, inaccurate removal from mold, cracking detectable in the material (stretch marks). Film material not sufficiently flexibilized
176 ˚C	Reduction in stresses, swelling of the base surface, improved removal from mold, significant reduction in cracking. Tendency towards improvement
192 ˚C	Virtually stress free dial, very good flatness, accurate removal from the mold, structure undamaged. Good value found.
210 ˚C	Virtually stress free dial, very good flatness after separation, slight blistering, matt-black film content looks “flinty” (glossing). Forming process too hot

After pre-heating, the heated sheet is transferred to another cell where the actual forming process takes place. The time lapse between pre-heating and forming has to be kept as low as possible so that the cycle time is lower, and the film does not cool down excessively before it is formed. The time elapsing between these two sub-stages of forming is usually 1 second. In the forming cell the flat sheet is put in a mold tool that has the desired final shape. The mold is set at a relatively low temperature, below the glass transition temperature of the polymer. The purpose of the heated mold is to keep the film warm enough during forming, avoiding early cooling of the film. When the mold closes, air at a very high pressure is blown on top of the film. The pressure easily reaches values of 300 bar [30]. High pressure air is pushed onto the film for a time close to 10 seconds, depending on the requirements of the part to be manufactured. The tool then releases the pressure over a time defined as the ‘outlet time’, and for safety reasons it opens when the pressure is lower than 2 bar. The big advantage of high pressure forming is that it allows for a better registration and tighter tolerances. In other words, decorations, letters, windows are kept in the designed positions with a better accuracy. This happens if the temperature of the film after pre-heating is kept low. In cars' interiors tolerances are a fundamental parameter. The machine most commonly used to perform this type of forming is made by Niebling GmbH (Penzberg, Germany), which allows the fabrication of large components for vehicle interiors with high accuracy.

The forming process cannot cause excessive stretching of the film, so that decorations are kept in the programmed positions. Tolerances in the order of 0.3 mm are ensured and cycle times vary between 10-15 s [30].

The main advantages of using HPF are listed below:

- Low stretching
- Tight tolerances
- Retention of surface finish (glossy, textured or matte)
- Suitable for large and thick parts (up to 12 mm thick)
- Good capability to form chemically and mechanically resistant films.

2.5.1.3 UV curing

Once the sheet has been formed and reaches the desired shape, it has to be UV cured in order to harden the top of the polymeric layer. It is fundamental that the part is UV cured as soon as possible in the process, in order to avoid the part being damaged, as its hardness is very low until the moment in which the film is cured. The UV curing stage is based on an important trade-off: at the exit of the curing oven, on one hand the part has to be cured enough so that it meets the OEMs requirements for mechanical and chemical resistance, and passes the specifications; on the other hand a prolonged curing could cause the film to reach a too high temperature in the oven, causing it to warp. A dosage of UV rays is provided to the part through lamps and reflectors. The dose is measured in Joules and the intensity of the lamps in W/cm^2. The dose depends on the intensity and on the velocity of the conveyor. The formed sheet is put on a conveyor, the speed of which determines the duration of UV rays the sheet receives. An higher speed gives a lower dose, a lower speed, intuitively cures the part more. Film specifications very often require that the film is not heated above a certain temperature in the oven in order to avoid warpage of the part. Of course, the longer the film is physically in the oven, the higher the temperature it reaches. The UV oven is a very sensitive part of the process because it may induce warpage and a distortion of the part, resulting in scraps.

2.5.1.4 Trimming

The formed sheet of polymeric material is then at a stage in which the unnecessary parts have to be trimmed out. So the sheet is put in a trimming die and cut. Unnecessary parts of the sheet are thrown away and the decorated, formed and cured fil is extracted from the die. The dimensions of the formed sheet have to match the dimensions of the die in order to perform cutting properly. Moreover, it is fundamental to ensure that the tool works properly and it is sharp enough. Replacement of the trimming tool after a certain number of pieces is necessary in order to keep the trimming tool working properly. The cutting area has to be kept free of debris in order to avoid inducing any possible distortion in the foil.

2.5.1.5 Injection Molding

The film is usually placed in the injection molding machine by an automatic end-of-arm tool. Again, the film has to be kept free of distortion until the moment in which it is put in the mold. At this stage it is fundamental that no dirt and no dust are present on the film and on the surface of the mold so as to avoid contamination. The A surface of the film (the front part) will be squeezed against one side of the mold, so any debris would result in a defect.

The back injection of the resin is actually the same process as for common injection molding machines. The injection molding cycle is repeated according to volume of production. For this reason it becomes fundamental to accurately set the process parameters and make sure the process proceeds smoothly. The cycle is usually made up of the following stages [4]:

1. The film is inserted in the machine by an end of arm tool;
2. The mold is closed;
3. Molten polymeric material is injected in the cavity by the injection unit;
4. Holding pressure is applied if needed;
5. Cooling time is provided to the part;
6. The injection unit moves back, it gets filled again with new material and gets ready for the following cycle;
7. The mold opens;
8. The component is ejected and the cycle starts over.

The time varies a lot depending on the part to be produced. Factors influencing the cycle time are the part geometry (thickness), the material and the tool [4].

Cooling the polymer inside the mold is a fundamental step of the process. A quick cooling of the part allows for a lower cycle time, saving time and money. The problem of cooling is also strictly related to the ensured quality after molding. Part shrinkage and residual stresses depend on the uniformity of part cooling. The time lapse between the injection of the material and the ejection of the part is defined as cooling time because in this phase the material’s temperature only decreases. It accounts for 60% of the total cycle time, so it is intuitive that its reduction would lead to time and cost savings. The heat transfer has to be considered. When a film is applied in the mold, the cooling assumes an even more complicated function. If the injected polymer contacts the film, the heat transfer between the polymeric film and the resin would be different than the one between the resin and the steel tool [4]. The retardation-induced temperature is the difference in temperature of the mold cavity between the case in which a film is present and the case in which there is no film. For a given injection speed, coolant temperature and melt temperature, considering a film made of polycarbonate, the retardation-induced temperature is observed to increase as the thickness of the film increases [33]. This phenomenon is of high interest for the problem of warping. Warping may occur if a non-uniform heat distribution takes place between the mold and the plastic part. Warping of film-insert molded parts increases as the thickness of the film increases and decreases with the increase of the substrate thickness [34].

Another important aspect related to the injection molding stage is that it is fundamental that the film is held in the mold in a stable position. Sometimes the geometry of the part is sufficient so that the film is able to hold itself in a stable position throughout the molding process without tilting. In some other cases some techniques to keep the film in the right position can be utilized. The most common and known techniques used are air pins, vacuum and electrostatic charges. Air pins are pins coming out from one side of the mold cavity, aimed at holding the film in place. They are basically applied on the B side of the film, pushing the A side towards the mold cavity. Air pins should be located properly in the mold so that a good result is achievable. Vacuum is another commonly used technique. It mainly consists of holes in the mold cavity from which a negative pressure is generated. Vacuum holes suck the A surface of the film toward the mold cavity. The vacuum has to be applied carefully, especially if the film is thin or soft. An excessive vacuum pressure could cause the film to be sucked in the holes, resulting in deformation of the A surface. A trade off between holding the film properly and avoiding the generation of surface defects has to be found. Electrostatic charges are also used as a common method to hold the film in place. A static charge is applied on the film and so it will be attracted by the metal surface of the mold. It is important in this case to consider the material of the film. It has to be able to accept and maintain a static charge for the entire time in which the film is kept in the injection molding tool [35].

Scraps due to tilting or popping out of the film during the injection process are common. If the film comes slightly out from the mold cavity, when the mold closes it will remain stuck between the two cavities and would cause pinching, with bad consequences for the resulting part and causing uneven wear of the mold.

2.6 Film Description

Goto et al. [36] worked to provide a good film for FIM. The purpose was to avoid cracks generated in a deep drawn part or at a small curvature radius part, while maintaining a good moldability and hardness. The film was made of three or four layers. The first was a hard coat. The hard coat layer thickness is between 2 and 20 μm in order to let the part have a good level of hardness. If the thickness of the layer increases the hardness of the film increases as well, especially when the film is UV cured. A too thick hard coat layer would instead be the cause of a bad moldability of the film, because it cannot be stretched enough. The second part is the film itself. This is usually made of the materials above-mentioned. The thickness of the film changes according to the part that has to be manufactured. It usually ranges between 10 and 300 µm but it can also be thicker. A thinner film is usually used when a large stretching of the film is not required (and often the film is not even pre-formed before injection molding). If the film had a thickness lower than 10 µm, it would not be able to resist injection molding and would break easily. The third part is a binder layer. It is not always required as its function is to make the ink layer stick to the film layer. If the ink itself allows for a better adhesion with the film, the binder layer is not needed. The fourth part is Ink layer. Its thickness is usually lower than 20 µm. The ink layer is generally applied on the first stage of the production process through the process of Screen Printing. Ink gives aesthetical properties and it is the first customizable operation that differentiates the products.

Generally, the film used for Film Insert Molding is made of PC, polymethyl methacrylate (PMMA), or a combination of the two. Some films also are made of a combination of PC and ABS (acrylonitrile-butadiene-styrene). Some research has been done in order to provide a good film for film insert molding. Goto [36] claimed the film has to be fabricated in such a way to avoid issues of cracks generated in a deep drawn part or at a small curvature radius part. The film has to be a trade-off between good moldability and hardness. The films used in the process of IML are usually made of three or four parts as shown in Figure 9.

Hard coat	2-20µm (preferably 4-10µm)	FILM
Film	10-300µm (preferably 25-250µm)	
Ink layer	<20 µm	
Resin	3-4 mm	SUBSTRATE

Figure 9: Representation of film composition.

The film has to be tested and to pass specific requirements for its function. OEMs usually provide a list of specifications that the film has to pass, as shown in Table 2. Once approved, the film can start to be used in production. The necessity of approval for the film has lead the film manufactures to make their products as versatile as possible, so that it does not have to be tested numerous times.

2.7 Problem statement

It is often a common problem in the pre-production phase that the shape of the film is improper, after the curing stage of the process. An improper shape of the film, showing distortion or improper dimensions, causes problems for the subsequent stages of the process. The cured film is supposed to be put in the trim die mold and then eventually in the injection molding tool. Some sections of the part may fit in the mold, where the surface is flat, whereas some others, especially where a certain curvature has to be guaranteed, have a tendency to pop out. If the shape of the film is not the expected one, problems related to pinching may occur. Pinching takes place when the film is put in the mold. Here it pops out from its original, designated position and moves towards the edges of the mold cavity. When the two mold cavities close, prior to injection molding, the film may remain trapped between the edges of the mold cavities. Pinching of the film in the mold has basically two potential failure modes: flashing and ripping.

The first type of failure is flashing of resin. It takes place because if the film is trapped between the two mold cavities, the mold is not properly sealed. When the resin is injected, it is at a very high temperature and so it has low viscosity. The molten resin is free to move in the mold cavity, but would be free to move also outside the mold tool if it finds an opening. The pinched foil at the edge of the cavity provides such an opening. When the resin temperature cools down, it solidifies, remaining stuck to the side of the part (Figure 10). Having a piece of plastic coming out from the part is not desired mainly for three main reasons:

- There is a waste of resin
- If some resin escaped from the boundaries of the part, it means that there is less resin within the boundaries. The final part might present some further defects related to this, such as holes or deformation.
- The resin flashed has to be removed, adding a further step to the process. The removal of the plastic part has to be carried out carefully in order to avoid any further damages to the part like scratches or cracking.

Figure 10: Representation of flash of the resin. Some injected resin flowed out from the edges when it was still hot.

The second effect of failure is the one depicted in Figure 11. It shows a detail of the film on the final part. The film edge is represented with the black line. Intuitively it is supposed to be straight and to follow a straight line. As is evident from Figure 11, it shows an improper profile, having being ripped during the molding process, when the part was ejected. Since the film is also an aesthetical element for decoration, it is not acceptable to have a ripped profile of the film in a final part for a vehicle.

Figure 11: Representation of a ripped edge of the film, showing an improper contour.

The film used for this analysis is Xtraform High Gloss provided by MacDermid Autotype (Ferndale, Michigan). It is a Polycarbonate film with thickness 380µm. The film is regarded as thick compared to other films used for IML process. The reason is that it can stretch more which allows it to reach more convoluted shapes. The film is made of an XtraForm Coating of 6 µm thickness constituting the first layer, the hard coat; the second layer is a PC layer 380 µm thick. The third layer is applied onto the part through the process of Screen Printing. Black ink is applied.

2.7.1 How to rank issues in the PFMEA and proper countermeasures

The problem was reported in the Process FMEA (Failure Mode Effect Analysis) as shown in Table 6. The Process FMEA is a worldwide used tool in the identification of production issues. Its main purpose is to keep track of all the main issues happening during the pre-production and the production phase. The idea is that once an issue has been identified, it is properly rated in a scale from 1 to 10 through three main categories which are Severity, Occurrence and Detection. The product of these three indicators is defined as RPN, Risk Priority Number. The RPN is the main indicator to which one has to refer to when dealing with top rated issues. An RPN of 200 is generally considered a high value and it means that the priority to solve the issue is high. Other cases of high priority concern the case of a low RPN but single category values of 9 or 10. The issue analyzed in this thesis falls in the first category, where an RPN of 200 or higher is found. The RPN is often seen as an arbitrary value that comes out as a result of arbitrary numbers assigned to each category. Appendix A shows the chart that was used to attribute the grades to the categories of Severity, Detection and Occurrence [37].

Severity is generally ranked when a potential failure mode results in a final customer or manufacturing assembly defect. If both occur at the same time, the higher between the two values has to be used. A high value of 10 means that the failure mode affects the safe vehicle operation and the failure could occur without warning. In this work, a moderate value of 5 was chosen, as the item is operable but at a reduced level of performance and would see the customer dissatisfied. It means that 100% of the product may have to be reworked to fix the issue [37].

Occurrence is strictly related to the probability of failure. The failure mode has to be related to the frequency with which it occurs. The main categories for Occurrence are persistent failures, frequent failures, moderate, low and remote failures. For the issue in this thesis a value of 5 has been chosen, falling in occasional failures. A value of 5 implies that the there is more than 1 and less than 5 failures per thousand items [37].

Detection concerns the likelihood of detection of a certain failure mode. Detection’s scale works in an opposite way. In other words, if it is easy to detect a failure, and the control system is certain to detect it the value will be very low, like 1 or 2. If it is almost impossible to detect a failure and there is absolute certainty of non-detection the failure mode will be ranked with a 10. For the problem of pinching, a value of 8 has been assigned [37]. 8 is a high value and it means that the controls have poor chance of detection. The choice turns out to be 8 because at the facility, control is only achieved with visual inspection. Visual inspection is not a technical or a statistical way to detect the issue.

Table 6: Line of the PFMEA developed for the problem of pinching

Current situation									
Process Function	Potential Failure Mode	Potential Effect(s) of Failure	S e v	C l a s s	Potential Cause(s)/ Mechanism(s) of Failure	O c c u r	Current Process Controls	D e t e c	R P N
Forming – UV curing	Improper Shape and Distortion. Pinching of the film in the mold	Flash of the resin. Ripped film	5	HIC (High Impact Characteristic)	Improper parameters of forming and curing	5	Visual Inspection	8	200

Countermeasures		Actions taken				
Recommended Action(s)	Responsibility and Target Completion Date	Action Results				
		Actions Taken	S e v	O c c	D e t	R P N
Optimization of forming and UV curing parameters, Use of laser scanner	End of pre-production phase					

The first part of the table shows a picture of the current situation. The problem occurs during the stages of trimming and injection molding. The failure mode is considered to be the pinching of the film in the mold. The flash of the resin and ripped film, are the above-mentioned effects of failure. The issue is classified as a High Impact Characteristic (HIC) because it can easily be noticed by customers and would negatively influence their perception of the quality. It is important to notice that the potential causes – root causes- of the problem were defined as "improper parameters of forming and curing'. The risk priority number (RPN), being the product of Severity, Occurrence and Detection, turns out to be 200. In addition to meeting the threshold to categorize it as a high priority, this is also the highest ranked issue in the pre-production phase. The aim of this thesis is to lower the RPN of the Process FMEA acting especially on the values – Occurrence and Detection – that make the total product very high. Lowering the RPN would mean lowering the values of Occurrence and Detection of the problem, reducing a top priority problem.

2.8 Solution to the problem

Countermeasures are proposed in order to lower the new RPN. The countermeasures proposed are:

- Use of laser scanning to improve “Detection”.
- Improvement of forming and UV curing process parameters to improve “Occurrence”.

The last part of Table 6 has been left blank because it will be filled in only once the results from the analysis re implemented and then it will be possible to quantify the effects. At that point, new values for Severity, Detection and Occurrence will be put in the table and the RPN will be re-evaluated.

2.8.1 Root causes identification

The root causes were found by looking back to the process and trying to understand which ones are the stages that can influence more deeply the shape of the film causing a deviation from the nominal shape. The following Ishikawa diagram depicted in Figure 12 has been useful to detect the root causes.

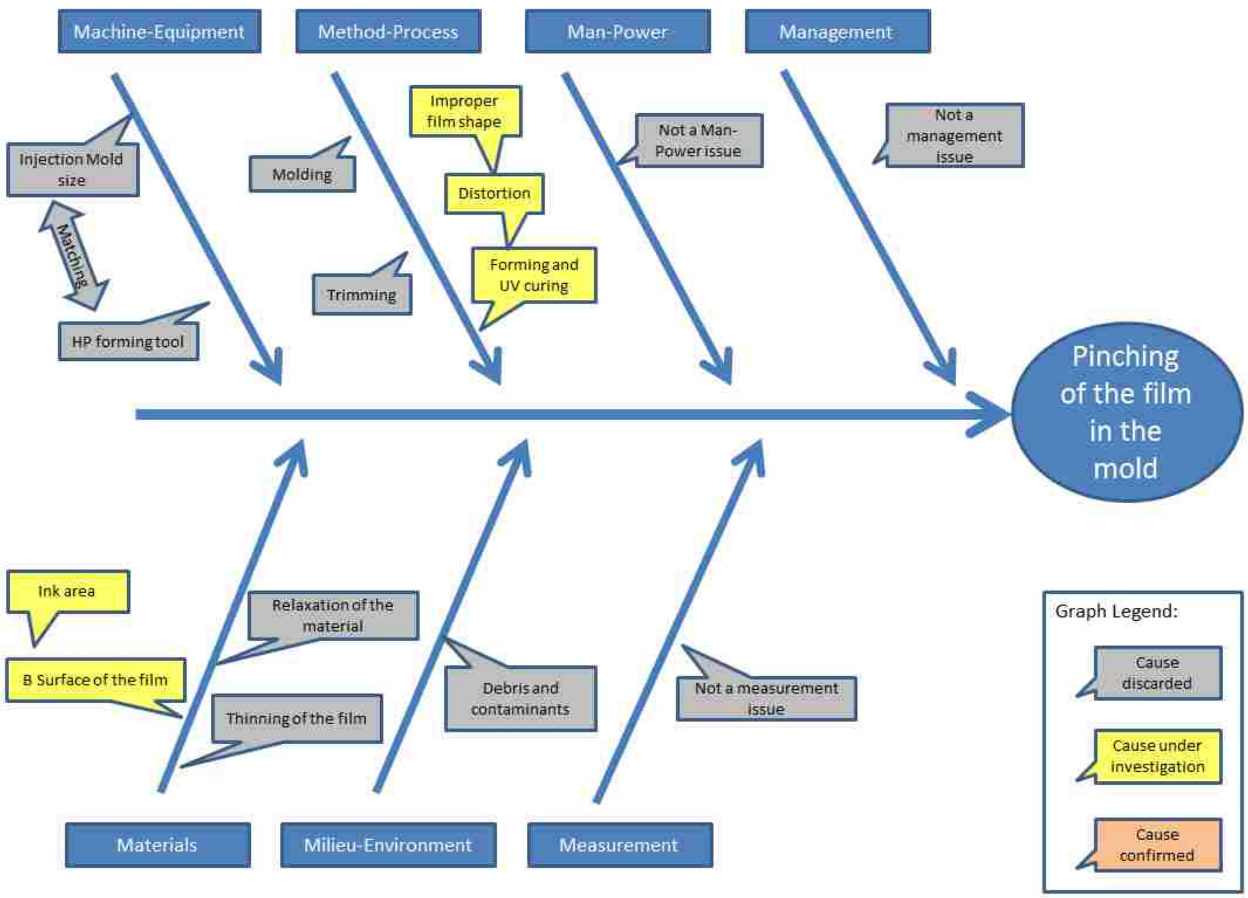


Figure 12: Ishikawa diagram representing root causes identification for the pinching issue.

Some causes have been already discarded because previous studies, specific for this part have been carried out and have shown that pinching is not related to them. Specifically the relaxation of the material after high pressure forming has been taken into consideration by the tool supplier when the tools where designed. Differences in the size of forming, trimming and injection molding tool have been accounted for by the tool supplier for the specific film used, so this has been discarded as the possible cause of pinching.

Another very important aspect to be considered is the thinning of the film. Thinning of the film during the forming process has also been shown not to play a role in the occurrence of the defect. Analysis has been carried out using a microtome to cut a cross section of the part, and a microscope to measure it. The draw ratio is calculated as follows [38]:

$$\frac{Thickness\ of\ formed\ film}{Original\ film\ thickness}\ x\ 100 = \%\ of\ original\ thickness \qquad (1)$$

Film specifications claim that the film may be drawn until it reaches up to 50% of its original thickness (50% draw ratio).

Different cross sections, in different areas of the part have been considered. Where the film has a more flat shape, the draw ratio was found to be around 90%, whereas in the curved area, the draw ratio turned out to be above 65%, showing that thinning of the film is likely not an issue in the process, because it remains above the minimum draw ratio.

Debris are considered not to be an issue for the shape of the part, because the type of defect is not related to contamination.

2.9 Approach to the study

This work aims at finding the gaps in knowledge in the current pre-production process, related to the effect of process parameters. This gap is also due to the fact that a simulation software for the technology does not exist and there is often no starting point in the determination of the process parameter values. This work, through different tests of parts manufactured with different process parameter values will show which are the significant parameters in the process for the determination of the distortion of the part. Also this work will serve to define the set of parameters for which this distortion is minimized, in order to prevent the occurrence of film shape related defects, such as pinching.

CHAPTER 3

METHODOLOGY

3.1 Description of the approach used

In order to lower the RPN of the Process FMEA, the following methodology was followed. The main idea was to increase the detectability of the deviation of the film first, with the use of a laser scanner and analysis software. Once the detectability of the shape was improved, it would be easier to understand which process parameters were more influential. Two DOEs were performed, one for forming and one for UV curing to understand how the shape of the film is influenced by the parameters evaluated. The first DOE performed was the one related to forming for the determination of the best set of parameters for that stage of the process, and once the forming parameters were set to achieve the lowest deviation, a DOE for UV curing was also performed. The nominal value for the shape of the film is considered to be the CAD model of the finished part. All the manufactured parts, produced under different process conditions were compared to the CAD model and a measure of the deviation at specific points was recorded. An Analysis of Variance (ANOVA) was performed to compare the deviation at certain points of the produced part from the CAD drawing, to determine if the variation in dimension actually depended on the variation of the process parameters or on some unknown factor and on the fact that the tolerances of the production process are too high. It was fundamental to undertake some corrective actions to fix the parameters to a value suitable for production. The map in Figure 13 gives an idea of the methodology followed for this thesis.

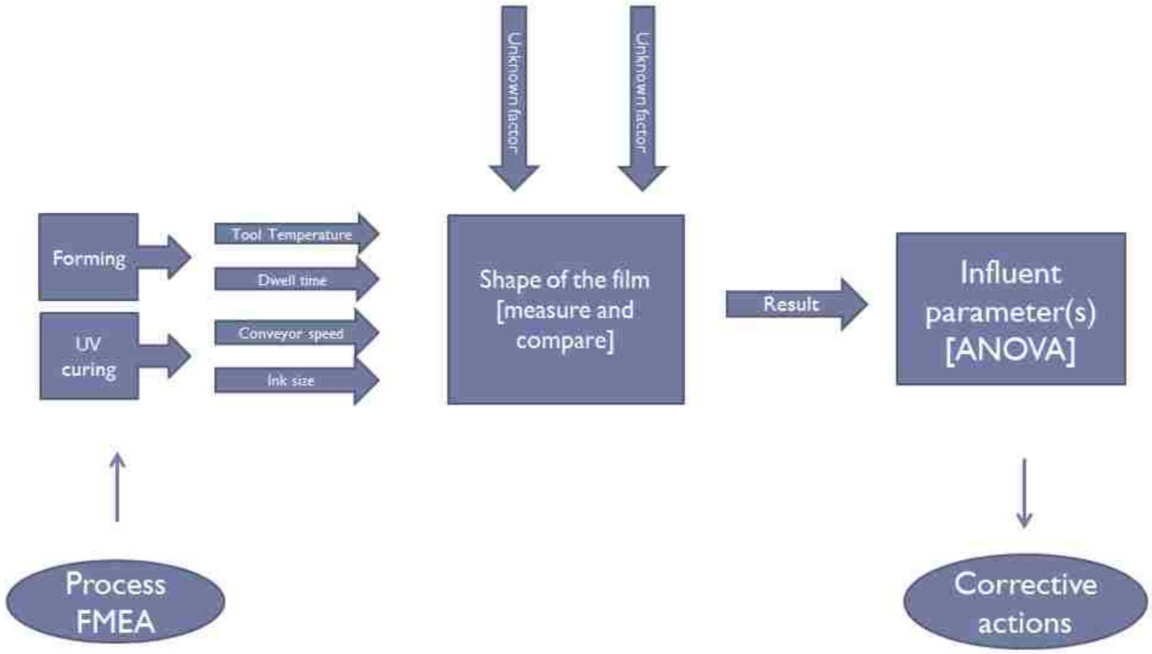


Figure 13: Map representing the steps taken in the thesis

3.2 Measurement and analysis equipment

3.2.1 Laser scanning

Laser scanning gives the possibility to acquire a digital version of the shape of a manufactured part. The technology for 3D scanning has advanced much in recent years, so that a scan with relatively good accuracy can be obtained for a reasonable price. The scanner used for the analysis was a ‘Next Engine desktop 3D scanner’ (NextEngine, Inc., Santa Monica, California) which is available at the University of Windsor. The scanner is able to create highly detailed full digital models. It is shown in Figure 14

Figure 14: Next Engine Desktop 3D scanner [39]

The two most important features of the scanner to be considered for the analysis are the accuracy and the field of view. The specified accuracy of the scanner is 100 μm [40]. The field of view defines the area that the scanner is able to capture. Intuitively, the area increases as the part to be scanned is set further from the scanner. The larger field of view that the scanner can reach is 40.6 x 55.9 cm if the scanner is set at a distance of 76.2 cm from the part. In order to have a scan with proper definition and ideal conditions, product specifications suggest setting the part at a distance of 43.2 cm from the scanner, in which case the field of view is reduced to 25.4 x 33.0 cm.

Figure 15: HMI of the laser scanner, showing list of possible settings for scanning

The HMI of the scanner is very intuitive and not complex. From Figure 15 it is possible to see how to set the parameters that influence the scanning.

The scanner uses a laser that hits the surface to be scanned and this reflects back the light to it. In this way, it is possible to measure the position of the object. The principle under which the scanner works is to measure the position of different points on the surface. The acquisition speed is 50,000 processed points/s [39]. The image is acquired digitally as a cloud of points. A point cloud can then be built up as a mesh in a software application by generating triangles between points. Once the mesh has been generated, it is possible to better visualize the object.

3.2.2 Analysis software

The analysis software that was used to build the mesh was "Geomagic control X" (Morrisville, North Carolina). The program enables the user to reconstruct the mesh starting from the points cloud. It is possible to import into the program the points cloud of the scanned part in its .xyz extension and a CAD file with a .stp extension. The program also allows the user to compare the shape of the scanned part with the CAD file, showing a measure of the deviation. The most valuable outputs of the program were:

- A color map showing the average deviation of sections of the scanned part from the original CAD model
- The deviation of every single point detected on the surface from the CAD model
- A histogram with the distribution of points around the nominal value

3.3 Analysis

The work-flow for arriving at deviation values was as shown in Figure 16:

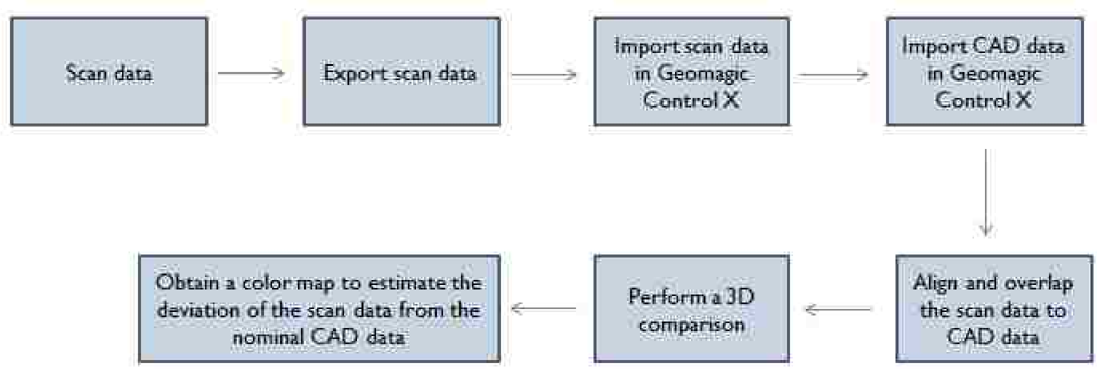


Figure 16: Map representing the procedure to follow to perform the analysis

3.3.1 Scan Data

In order to comply with the specifications of the scanner, so that it is possible to compute an accurate scan, the part was set at a distance of 43.2 cm away from the scanner with the use of an adjustable support. In this case, roughly three quarters of the part fit in the view of the scanner, because the field of view was 25.4 x 33 cm.

The film to be analyzed consists of a flat part and a curved one. The left-hand side of the part is assumed to be of the proper dimensions, since pinching and tearing did not occur in that section of the part, and thinning of the film is not an issue, because it does not stretch. On the contrary, the section of the part that generates more interest is the right-hand side, in which a curvature and some holes - with the purpose of holding the part in place in the mold - are present. This leads to analyzing the right-hand side of the part as it is the section of major interest. Details of the part are given in Section 4.1

The part is a thin film of thickness 380 μm with a black and glossy surface. A 360˚ scanning of the part was not possible to be performed because the part would need to be hanged and rotated while the scanner acquired the shape. The nature of the part –its material and geometry- would cause it to swing and the final representation viewed by the scanner would be distorted. To scan the part, it was fundamental that the film remained steady during the whole scanning process. Any form of distortion of the part had to be avoided. In order to minimize this factor, the part was put with its B surface (back of the film) faced upwards.

The scanner was supported with a rigid aluminum frame and kept in a flat, steady position 43.2 cm above the part. Since only B surface of the part was scanned, its thickness was not determined by this method. However, its curvature could be analyzed. It is not fundamental to have a measure of the thickness of the part because this was assumed not to constitute a problem for the shape of the film. Thinning of the film, as stated by the film manufacturer is not an issue and does not influence the shape of the part if it does not exceed a certain value. Before the scanning takes place Spotcheck SKD-S2 Developer (Magnaflux, Glenview, Illinois) spray was applied on the B surface of the film. In this way, a thin (about 5 μm) layer was added to the thickness of the part. The spray was needed in order to create a white matte surface, which can be captured more easily by the scanner. The spray is assumed not to influence the final result for the following reasons:

- The thickness of the part is not going to be acquired by the scanner. Only one surface is scanned (B surface), so the result will show just the curvature and the other two dimensions.
- The thickness of the sprayed layer is only 5 μm assumed to be evenly distributed on the surface, so no differences will be shown.
- The accuracy of the scanner is 100 μm, much more coarse than the thickness of the sprayed layer.

For these reasons, the use of the spray is not considered to be a problem for the analysis.

3.3.2 Export and import of data

The process of exporting the scanned data from the scanner program was straight forward. The cloud of points was exported as an .xyz file in order to be an input to the analysis software.

The process of importing the files in Geomagic control X was also very simple and straight forward. First, the scanned file was imported, then the CAD file. The scanned file is usually stored as unit-less data. It was important to define the unit of measure: millimeters or inches. For easy import, the CAD file has to have a .stp (Standard for Exchange of Product) extension.

3.3.3 Align and overlap the scanned data to CAD

Aligning the scanned data to CAD is a fundamental process for the comparison of the parts. The quickest way to align data is to use the 'Initial Alignment' command in Geomagic control X. The program itself finds similarities between the two shapes. If the scanned part has some missing parts or for any reason it is cut in a certain location, the program itself is not able to reconstruct the alignment itself and needs the users help to find it. In this case, some constraints have to be applied between the scan data and the CAD data, highlighting common points of the two figures. It is possible to do this through the command 'Transform Alignment'. It was common practice, in this case, to choose three points from the scanned part and highlight the same points on the CAD data.

Once the first alignment was performed, this could be improved with the command ‘Best fit Alignment’. Again, the program itself worked on improving the alignment between the two files in order to obtain more accurate results, keeping as a reference the ‘Transform Alignment’ that the user had manually done. The command ‘Best alignment’ was needed in order to minimize variability in aligning the shapes, to minimize the effect of human errors.

3.3.4 3D comparison and color map

Once the alignment has been performed correctly, it was then possible to compare the two parts though a 3D comparison. The kind of analysis that could be performed was an analysis of the shape of the two parts, based on the B surface.

The sampling ratio was set to 100% so that all the points scanned were actually compared to the CAD model. The value of the sampling ratio could be decreased in case the density of points of the scan was too high and the analysis needed to be speeded up. In the section ‘Method’ the ‘Shape’ option was selected because the surface of the part was the one of main interest.

The program calculated the deviation (offset of the scanned part from the CAD) along the shortest direction to the CAD. The main outcome of the analysis was the creation of a color map where the deviation – expressed in terms of millimeters – of the scanned part from the CAD data was shown. It was also possible to check the deviation of each point scanned from its nominal value. Figure 17 represents an example of a color map achievable with the program Geomagic Control X [41]. The actual part tested is in pre-production phase and its shape is proprietary.

Figure 17: Color map as outcome of the Software Geomagic Control X [41]

It was possible to define a green interval which is the acceptable deviation. As long as the scanned file is within this deviation, its shape is within tolerance. Of course, the purpose of this study was to minimize the blue and the red areas, which respectively correspond to under tolerance and over tolerance. An excessive deviation would result in an incorrect shape of the part and so it would not fit in the mold properly. Figure 17 shows the color map, showing the average deviation of each specific area. It was possible to analyze the deviation of every single point in the figure.

3.4 Influential parameters

In the manufacturing process, the shape of the film was manly determined by the forming and UV curing operations. Screen printing was assumed not to bring any modification to the shape of the part. The assumption arose from the fact that during screen printing, the only operation performed is to add a layer of ink on the surface when the polymeric sheet is still flat. The foil enters as a flat sheet in the forming tool. Here it is formed and becomes a 3D shape. The following operation, the UV curing phase, in theory should not to bring modification to the shape of the film, but can distort it. There are different parameters in the manufacturing process that can be set and influence the shape of the film. Some of these parameters are listed in Table 7.

Table 7: List of process parameters for forming and UV curing.

Parameter	[Unit of measure]	Current value	Estimated optimal value	Status
Upper right heater	˚C	300	300	FIXED
Upper left heater	˚C	370	370	FIXED
Lower right blue	˚C	300	300	FIXED
Lower left yellow	˚C	340	340	FIXED
Air heater	˚C	300	300	FIXED
Form tool temperature	˚C	130	125-133	FIXED
High pressure	bar	75	75	FIXED
High pressure max	bar	80	80	FIXED
Preheating (dwell) time	s	10	8.5-10.2	VARIABLE
High pressure time	s	7	7-10	VARIABLE
Outlet time	s	10	8-10	VARIABLE
Form out support	s	1	N/A	VARIABLE

Table 7 (continued)

Parameter	[Unit of measure]	Current value	Estimated optimal value	Status
Fast closing forming station	s	10	N/A	VARIABLE
Tool closing speed	%	100%	100%	VARIABLE
Tool opening speed	%	10%	10%	VARIABLE
Slow speed opening tool	#	6	6	FIXED
Ink size	N/A	Regular	To be determined	VARIABLE
UV oven conveyor speed	fpm	40	30-45	VARIABLE

The parameters labeled as ‘FIXED’ in the table may be fixed for two reasons: either the tool supplier suggested to set the value at that specific magnitude, or the parameter was considered to be set to a reasonably good value. Parameters labeled as ‘VARIABLE’ are instead those for which an optimization was still possible and some research is going forward. The column showing the “Estimated Optimal Value” shows what, based on observation and based on some constraints, was believed to be the current best value. The influence of the parameters on the production process, which is depicted in Table 7, was based on observation. From Table 7 it is evident that there are many parameters involved in the analysis and so the investigation was narrowed down to the ones regarded as the most influential (see Section 3.5) after the set of trials was performed.

3.5 Procedure

Simulation software for the forming process was not available, so an intense set of trial and error experiments has been performed. After the first trials, the parameters which were more influential were determined. Accurate measurements of the shape of the part were not made, because an instrument able to accurately detect the shape of the film was not available at the factory.

This thesis has the purposes: a) to verify that the most influent parameters in forming and UV curing, as far as the shape of the applique is concerned, are the ones described in the table, and b) to lower the distortion of the film by varying those parameters. The analysis was performed by developing two full-factorial plans, varying four main parameters, two per plan. The parameters that were varied are the four regarded as the most influential ones based on observation. The first two of the four parameters belong to the forming process, the following ones to the UV curing stage:

- Forming tool temperature
- Preheating (dwell) time
- UV oven conveyor speed
- Ink size

The forming tool has to be kept at a sufficiently high temperature so that the polymeric sheet, once preheated does not cool down too early and remains at a sufficiently high temperature during high pressure forming. This temperature has been observed, over the trial and error session, to have the highest influence on the shape of the film. The optimum value is considered to be between 125˚C and 133˚C. This range has been accurately chosen considering the results achievable. If the tool temperature goes below 125˚C, it was noticed that the film did not always form properly; the radius of curvature was too small and it was not possible to accomplish the following stages of the process because the film did not fit completely in the subsequent tools (trimming and injection molding). The higher limit was set for other reasons. In particular, the forming tool struggles to reach a higher temperature, and also the appearance of some other defects was noticed on the surface of the film, such as blistering.

The preheating time is also considered to have a very high influence in the process. It is the time that the sheet is kept between the ceramic heaters, also called dwell time. The outcome of the preheating time is the temperature of the sheet before forming. The polycarbonate sheet has to reach a high enough temperature in order to be formed (see

Section 2.5.1.2 Forming). The temperature of the sheet will influence the viscosity of the material and so its formability. The dwell time cannot be increased too high, otherwise it would cause the sheet to liquefy.

An infrared camera was used in order to check the surface temperature of the film after the pre-heating time. A section of the part, the one with a more convoluted shape, was heated more by setting its heaters at a higher temperature. The other section, the flat one, was instead heated less. It was noted that an average difference in temperature of about 20˚C was present between the two sections of the same part. Preheating time was changed among a fairly wide range of values, to understand the temperature at which the sheet was after pre-heating. Points were manually selected to compare tempearures as shown in Figure 18. With a dwell time of 8.5 s, it turned out that the temperature on the convoluted side was about 174˚C, whereas on the flat side it was about 162˚C. Increasing the dwell time, the temperature increased as well: a dwell time of 9.5 s brought the curved part to a temperature of 195˚C, with the flat part being at 176˚C. Figure 18 shows the trend of temperature for a specific point on the surface of the part with the variation of dwell time.

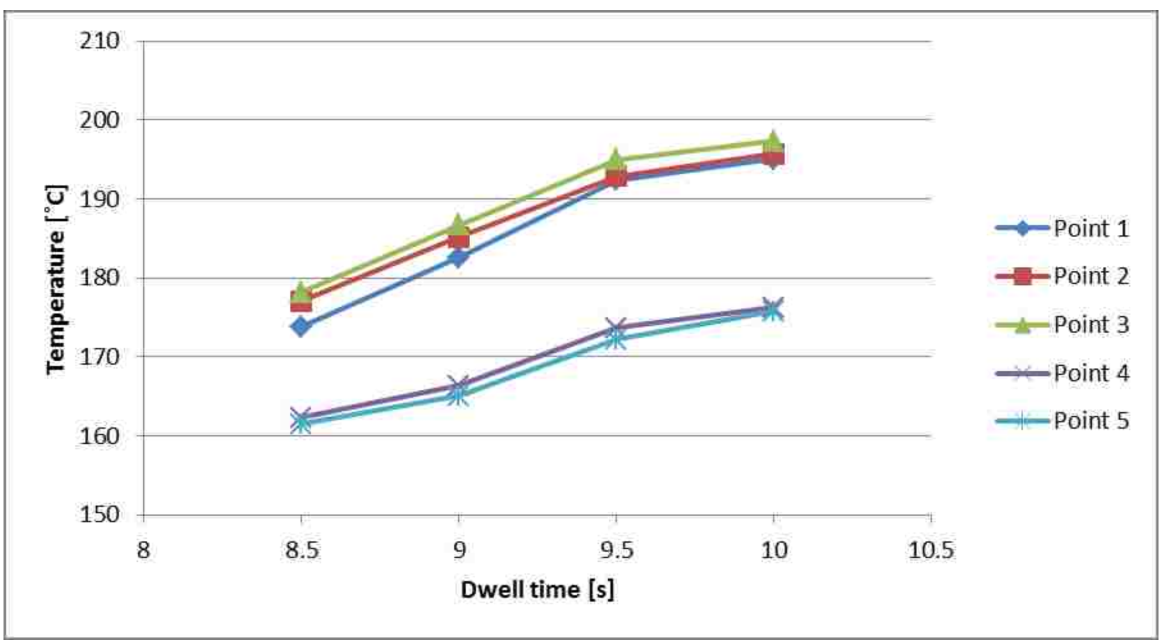


Figure 18: Relation between the Temperature of the film and the pre-heating (dwell) time for a specific location.

The value of the temperatures was kept within the range specified by the pre-heating study of Table 5. For this reason, the values considered for dwell time were chosen to be between 8.5 s and 10.2 s. A lower value would bring the flat part of the film to even lower temperatures, resulting in a non-formable film. A value higher than 10.2 s would instead cause some other types of defects - like blistering on the surface - as the temperature would go above 200 ˚C.

A calculation was implemented in order to show how the temperature of the film varies, with the variation of the dwell time. Considering a convective heat transfer between the ceramic heaters and the polymeric sheet, a one-dimensional analytical model was created. The main purpose of the model is to help one to determine the dwell time a priori in order to reach a certain temperature of the film. The model allows one to set the parameters related to the temperature of the ceramic heaters and then to have a rough estimate of the dwell time needed to bring the temperature of the film up to a desired value, which, according to Table 5, are close to the value of 190 ˚C. The average heat convection coefficient, h, turns out to be 21.6 W/m^2K. The average value of h could be used as a starting point for future models, when a dwell time has to be established. The details of the calculation are shown in Appendix B.

Another parameter considered to be of particular interest was the ink size of the film on the sheet. Ink, for the sake of decoration is applied on the sheet. The regular ink size corresponds to the minimum amount of ink (covering about one – third of the uncut sheet), printed on the sheet in order to have the required decoration. Ink was thought to influence the shape because in the UV oven the sheet is exposed to UV light. The opaque ink absorbs light, so a larger area of ink would absorb more light and heat up the film more. On the other hand, having a ink size larger than the part (about one half of the sheet), would minimize distortion due to uneven heating. The larger ink size would not be a problem from the decoration point of view because the ink areas in excess will be cut off by the trimming process afterwards; the only drawback of this solution would be a higher quantity of ink used.

The fourth parameter that was considered is the speed of the UV oven’s conveyor. The speed of the conveyor influences the amount of curing that the part receives. If the speed is high, the part remains in the oven for a shorter time, receiving less curing. If the speed is low, the part is cured more, but the increase of temperature could cause a distortion of the part. An upper limit to the speed of the conveyor was applied based of OEMs requirements for surface hardness. The part, in order to pass all the tests discussed in Section 2.3 has to be cured enough. Durability, scratch and impact resistance are the properties that the part has to obtain from the curing process. On the other hand, a lower limit was set because of the temperature of the sheet in the UV oven. It is common practice of film supplier to recommend a certain temperature that the film should not exceed in the UV oven in order to avoid distortion and warpage.

Table 8 represents the four parameters considered in the analysis and the values that they were assigned in the DOE. Every parameter has been labelled with a letter and the number of levels defined.

Table 8: Factor and relative levels used for DOE.

	FORMING		UV CURING	
Factor/ Level	**Tool temperature ˚C**	**Dwell time s**	**Conveyor speed m/s (fpm)**	**Ink size**
#	A	B	C	D
1	125	8.5	0.15 (30)	Regular
2	130	9	0.20 (40)	Larger
3	133	9.5	0.23 (45)	-
4	-	10	-	-
5	-	10.2	-	-

A test matrix for forming

Table 9 and another test matrix for UV curing Table 10 were used.

Table 9: Test matrix for forming

	FACTORS	
Test number #	Tool temperature (A)	Dwell time (B)
1	1	1
2	1	2
3	1	3
4	1	4
5	1	5
6	2	1
7	2	2
8	2	3
9	2	4
10	2	5
11	3	1
12	3	2
13	3	3
14	3	4
15	3	5

For the forming factors DOE, the UV oven conveyor speed was set to 35 fpm and the ink size to regular. After which, the forming factors were set to those giving the lowest deviation and the test matrix for UV curing was completed.

Table 10: Test matrix for UV curing

	FACTORS	
Test number #	Conveyor speed (C)	Ink size (D)
1	1	1
2	1	2
3	2	1
4	2	2
5	3	1
6	3	2

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Results for forming

With the experimental procedure 45 tests for forming were expected to be carried out (

Table 9, 3 samples per test). In an initial phase of the development of the project it was thought to conduct the analysis only for the higher values of dwell time. In this phase only two samples for each set of parameters were made for testing. As tests were conducted, it was decided to include also lower dwell time values, for which 3 samples per condition were created. Thus, in the case of forming some tests were carried out only two times rather than three. The analysis of variance (ANOVA) calculations could still be conducted with this variable number of replicates.

For each sample, three points were chosen as measures of the outcome. The deviation has been calculated for these three points as these were the most representative of the fit of the film in the mold. The exact location of the points was identified, looking at different scanned parts and noticing where the main deviations were present. The first one is just beside a round hole. It is fundamental that the hole fits in the cavity of the mold perfectly without creating obstruction or being too loose. The area just beside the hole was then considered to be of interest. The second point was chosen at the middle height of the part, at the rightmost location on the surface. The reason for this choice is that the part is shaped with a certain curvature. Especially, the right side of the part is the one for which the curvature is the most influential. A measure of the deviation at the rightmost point on the surface was identified as a measure of how well the part was formed. The third point has been chosen on the top right side of the part for the two reasons discussed above. The third point is beside a hole in the plastic that is needed in order to assemble the part into the vehicle. Also, Point 3 at the right hand side of the part is also affected by improper curvature. Figure 19 shows a sketch of the [art and the location of the three points studied.

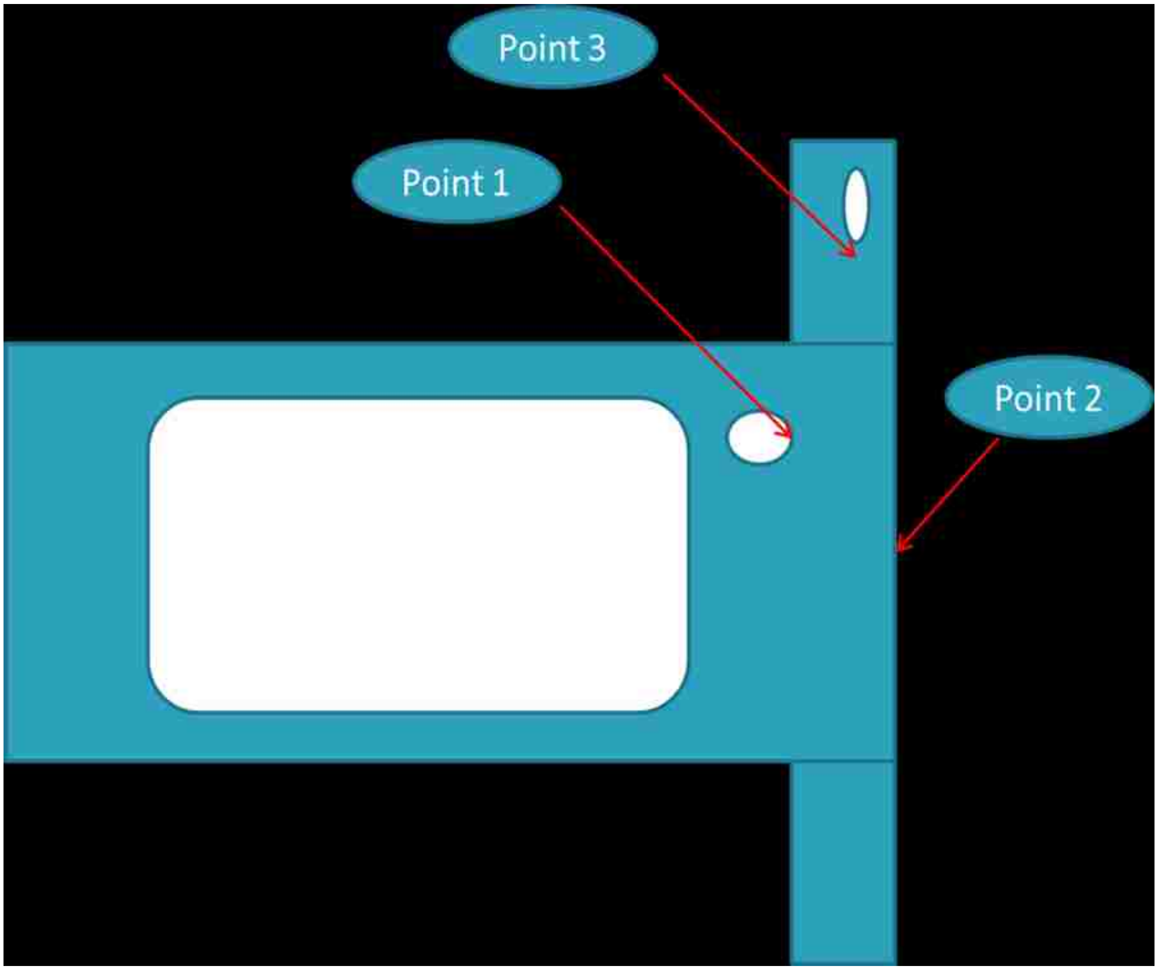


Figure 19: Sketch of the B surface of the part studied. Point 1, Point 2 and Point 3 are shown on the surface.

A table with the measurements shows a total of 108 measurements.

Table 11: Test results for forming for Point 1, Point 2 and Point 3 on the surface.

Repetition	Tool Temperature ºC	Time s	Point 1 mm	Point 2 mm	Point 3 mm
1	125	8.5	0.15	0.35	0.34
2	125	8.5	0.10	0.37	0.31
3	125	8.5	0.12	0.34	0.40
1	125	9.0	0.05	0.18	0.31
2	125	9.0	0.18	0.21	0.24
3	125	9.0	0.18	0.27	0.36
1	125	9.5	0.23	0.93	1.51
2	125	9.5	0.27	0.77	1.52
1	125	10.0	0.29	0.52	0.65
2	125	10.0	0.17	0.49	0.69
1	125	10.2	0.59	0.58	1.30
2	125	10.2	0.37	0.50	1.50
1	130	8.5	0.01	0.07	0.13
2	130	8.5	0.03	0.09	0.13
3	130	8.5	0.01	0.08	0.09
1	130	9.0	0.01	0.01	0.48
2	130	9.0	0.05	0.02	0.21

Table 11 (continued)

Repetition	Tool Temperature ºC	Time s	Point 1 mm	Point 2 mm	Point 3 mm
3	130	9.0	0.17	0.18	0.13
1	130	9.5	0.52	0.61	1.40
2	130	9.5	0.35	0.99	2.05
1	130	10.0	0.31	1.00	1.61
2	130	10.0	0.01	0.66	1.20
1	130	10.2	0.65	0.51	1.05
2	130	10.2	0.54	0.41	1.13
1	133	8.5	0.01	0.09	0.10
2	133	8.5	0.00	0.08	0.14
3	133	8.5	0.01	0.04	0.13
1	133	9.0	0.10	0.14	0.27
2	133	9.0	0.09	0.07	0.10
3	133	9.0	0.07	0.13	0.29
1	133	9.5	0.30	0.43	0.25
2	133	9.5	0.04	0.44	0.24
1	133	10.0	0.35	0.48	0.31
2	133	10.0	0.34	0.52	0.30
1	133	10.2	0.03	0.47	0.57
2	133	10.2	0.20	0.48	0.65

The first step in the analysis of the results was the analysis of variance (ANOVA). The step is important to understand how the data are consistent. The ANOVA allows one to understand if the variation in the results actually depends on the change of parameters or if it is due to some unknown effects that include all the parameters not accounted for in the analysis and considered as “error”. The analysis of variance was conducted using the software Minitab (State College, Pennsylvania).

4.1.1.1 Result analysis for forming, ANOVA (Point 1)

Table 12 is provided by the software Minitab as a result of the ANOVA test. It shows the value of degrees of freedom for each parameter included in the analysis and also provides a measure of their interaction. The major outcome is the measure of the p-value for all the parameters involved. The confidence level was chosen to be 95% because it is the more general value that is used for the ANOVA and in this case is considered to be sufficient for the purpose of the study. The p-value limit would be lower or equal to 0.05 for a parameter to be considered influential.

Table 12: ANOVA table for forming (Point 1).

Source	DOF	Sum of Squares (Deviance)	Variance	F-Value	P-Value	Corrected Sum of Squares	Percentage of Contribution
Tool temperature	2	0.08698	0.043488	5.27	0.014	0.070468	6.07%
Dwell time	4	0.58017	0.145042	17.57	0.000	0.547146	47.17%
Temperature *Dwell time	8	0.31949	0.039937	4.84	0.002	0.253442	21.85%
Error	21	0.17337	0.008256			0.288954	24.91%
Total	35	1.16001				1.16001	100%

It turns out that the p-value is sufficiently low (less than 0.05) for the three sources to be considered influential. The lower the p-value, the more a parameter can be considered influential.

The percentage of contribution was calculated using the corrected sum of squares for each parameter. The corrected sum of squares is calculated so that the deviance is not influenced by the sampling process and the system is randomized enough [42]. Any change to the randomness of sampling increases two quantities:

- The variance of the error;
- The degrees of freedom of each significant factor or interaction.

The corrected sum of squares is calculated with equation 2:

$$Q_{Ac} = Q_A - df_A\, s_e^2 \tag{2}$$

in which the corrected sum of squares of the parameter A is equal to the product of the sum of squares of the factor itself minus the product of the degrees of freedom relative to the factor and the squared variance of the error. This method is not extremely precise and the percentages found do not have to be taken as exact. It is nonetheless a good way to distribute the change and give an idea of which parameters are the most influential.

The dwell time, was found to have a very high influence on the deviation of Point 1, accounting for almost 50% of the change. The tool temperature instead was found to have a very low influence, its influence being just more than 6%. The error accounted for a quarter of the change. This value is moderate. It means that the selected parameters are able to account for three quarters of the change but not the remaining quarter which was due to:

- Tolerance of the process (forming, trimming)
- Inaccuracy of the measurement

Point 1 was set in a section of the part where the curvature does not really play a significant role. The area is basically among a very narrow flat section, just beside the hole and the beginning of the curvature towards the right of the part. The dwell time was found to be, in forming, the main source of changes for this specific location.

4.1.1.2 Result analysis for forming, ANOVA (Point 2)

Similar results were found for Point 2. The analysis of variance, conducted with a confidence interval of 95%, shows that also for Point 2 the parameters were influencing the result (Table 13)

Table 13: ANOVA table for forming (Point 2).

Source	DOF	Sum of Squares (Deviance)	Variance	F-Value	P-Value	Corrected Sum of Squares	Percentage of Contribution
Tool temperature	2	0.1901	0.095072	11.11	0.001	0.172988	6.50%
Dwell time	4	1.9394	0.484851	56.67	0.000	1.905176	71.55%
Temperature *Dwell time	8	0.3536	0.044199	5.17	0.001	0.285152	10.71%
Error	21	0.1797	0.008556			0.299484	11.25%
Total	35	2.6655				2.6628	100%

The three parameters considered and their interaction play an important role in this case as well. In this case, the dwell time had more influence on the deviation of the film. Its influence was above 70%, meaning that it was the main parameter to adjust in order to obtain different results. The percentage of contribution of the temperature, surprisingly, accounted for still around 6% of the total change. This means that also for Point 2, which represents a measure of how well the part was curved, the temperature was not a key factor and the dwell time is the parameter that mainly influences it. The error lowered compared to Point 1 to a value of about 11%. This confirms the parameters to be a good estimator of the deviation also for Point 2.

4.1.1.3 Result analysis for forming, ANOVA (Point 3)

The ANOVA performed with a confidence level of 95% gives the result shown in Table 14

Table 14: ANOVA table for forming (Point 3).

Source	DOF	Sum of Squares (Deviance)	Variance	F-Value	P-Value	Corrected Sum of Squares	Percentage of Contribution
Tool temperature	2	2.6569	1.32844	65.62	0.000	2.61642	23.08%
Dwell time	4	5.7079	1.42696	70.49	0.000	5.62694	49.69%
Temperature *Dwell time	8	2.5479	0.31849	15.73	0.000	2.38598	21.04%
Error	21	0.4251	0.02024			0.70846	6.25%
Total	35	10.7038				11.3378	100%

In this case the parameters were shown again to be very influential in the process. The p-values in this case were very low and all of them are below 0.001. The error for Point 3 was reduced to a very low value, just above 6%. This means that more than 93% of the change in the deviation of the part can be attributable to a change in the factors or to their interaction. For Point 3 the model was well able to predict the change of the deviation. The dwell time is confirmed to be the parameter that accounts for most of the change, almost 50%. The temperature in this case, which for other points was a minor influence, here contributed about 23% to the outcome. The tool temperature seemed have influenced the top right section of the part, close to the edge. This result could be considered in line with the operation use of the high pressure forming tool. The tool is expected to provide very tight tolerances for registration and for sections within the part, but the tolerances of the edges are slightly looser than the ones obtainable with thermoforming [30]. As previously mentioned, in thermoforming the temperature at which the plastic is formed is generally higher than high pressure forming.

4.1.1.4 Result analysis for forming, percentages of contribution and residuals

It is of particular interest to visualize through a graphical representation the effects of each of these on the deviation.

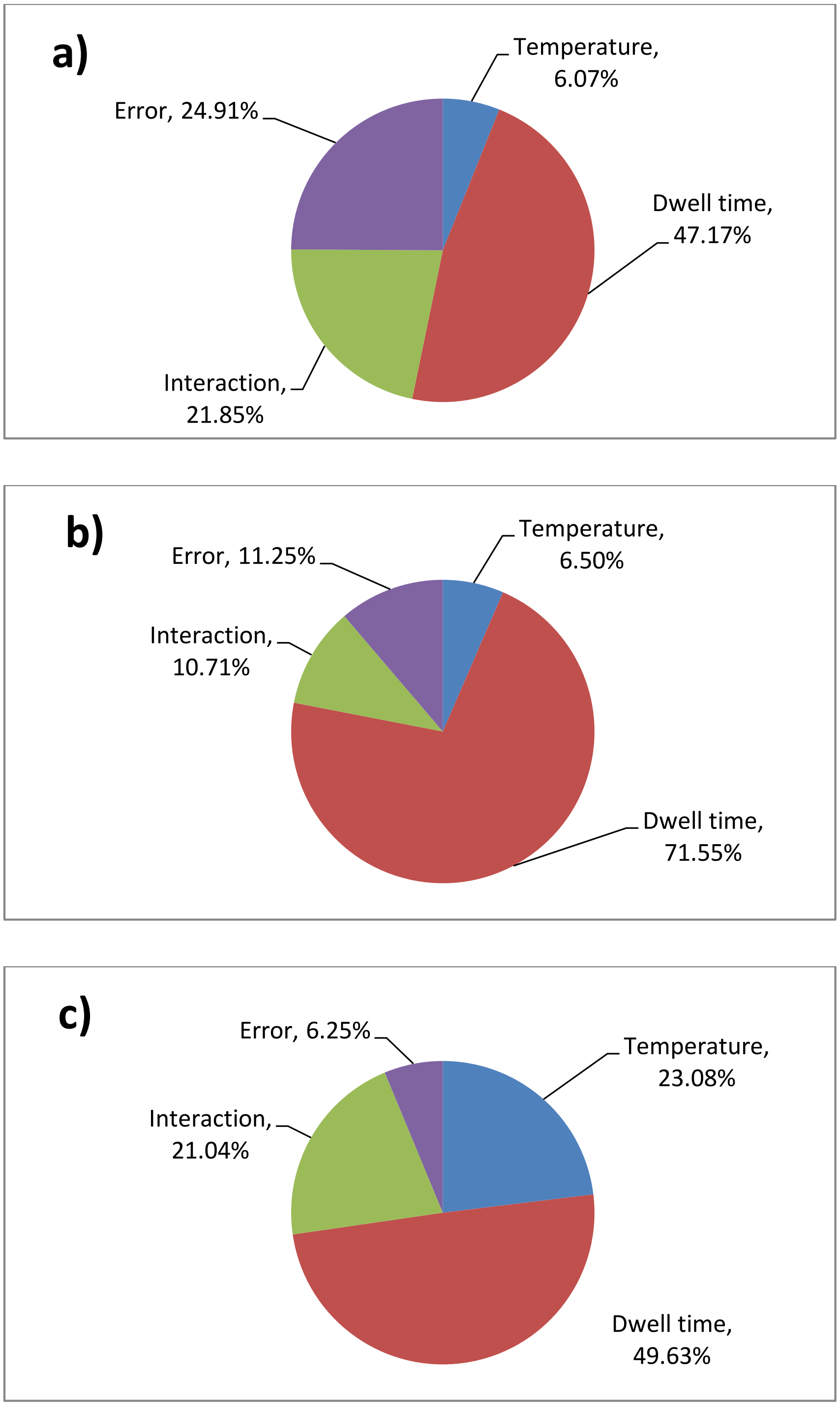


Figure 20: Percentages of contribution of factors and interaction in forming for the three points analyzed: a) Point 1, b) Point 2, and c) Point 3.

The analysis of residuals is a good indicator of the consistency of data measured. The two main tools that are used to make sure that the tests were performed correctly are a histogram of residuals and a graph showing the trend of residuals with the observation order. Both of these graphs for forming are shown in Appendix C, for all the points (Point 1, Point 2 and Point 3) analyzed. The histogram of residuals shows the distribution of them with respect to the frequency. If the histogram shows a normal distribution, it means that the error in the measurements is randomly distributed. The histograms of Figures C-1, C-3 and C-5 show normal distributions. About the graph representing the value of the residuals against observation order, the lines do not follow any particular pattern. This means that the order of the experiments was randomized enough; such is the case for Point 1, Point 2 and Point 3 as shown in Figures C-2, C-4, C-6

4.1.2 Result analysis for forming, influence of temperature and dwell time

Figure 21 shows the influence of each of the factors separately, by looking at the mean value of the deviation for a certain level of each factor. It is possible to see from Figure 21 how Point 1 was influenced by the temperature and the dwell time. The first part of the graph shows the effect of the temperature without considering the dwell time. An initial increase of the temperature led to a very slight, almost negligible increase in the deviation. A further increase, up to 133˚C caused a steeper decrease in the deviation. In the case of the dwell time, the increase of the deviation due to an increase of the dwell time is clear. The deviation was low at a low dwell time. However, once the time went up to 9.5 s the mean deviation reached values that would not be compatible with the acceptable range. A further increase of the temperature up to 10.2 s shows a further increase of the mean value of the deviation for Point 1. The reason for this is that the temperature of the film reached a value that was too high in the pre-heating phase. The point in consideration, beside the hole is on the side of the part that is heated more. According to Figure 18 for Point 1 the temperature at a dwell time value of 9 s was just above 180 ˚C, whereas just increasing the dwell time by half a second, the temperature of the film reached a value close to 195˚C. This may be considered an explanation to the phenomenon observed, so that for this specific film, a step difference in the pre-heating temperature between 9 s and 9.5 s would lead to a large difference in the average deviation.

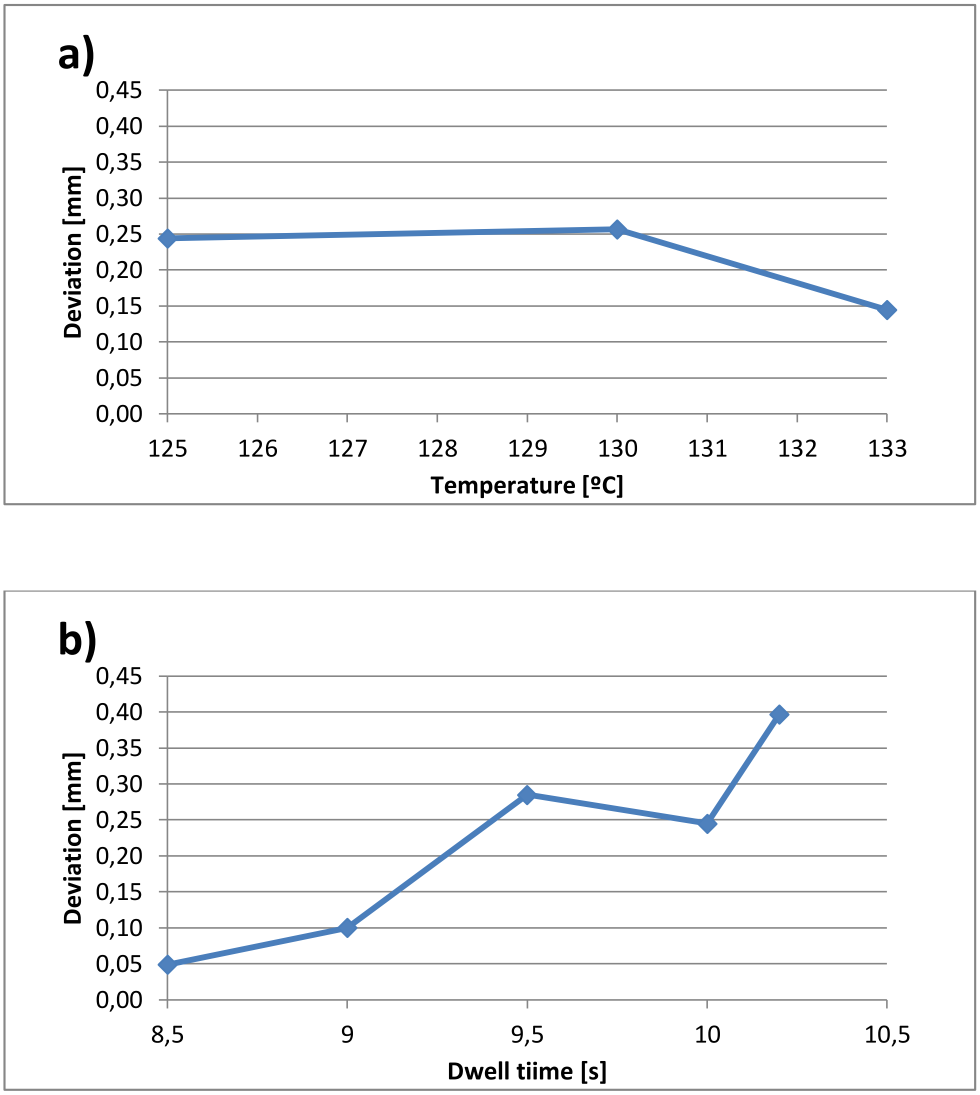


Figure 21: Mean of deviation of Point 1 for a) temperature change, and b) dwell time change.

A similar representation is shown in the case of the deviation of Point 2. Figure 22 shows a clearer dependence of the deviation on the temperature. The increase of the temperature to 133˚C implies a mean decrease of the deviation from 0.5 mm to 0.3 mm. Also in this case, as for Point 1, the decrease in the deviation was steeper for the step from the second to the third level of the factor temperature, suggesting that on average an higher temperature of the forming tool would lead to a lower measure of the deviation. Especially in the case of Point 2, which is located at the very end of the part on the rightmost edge, it is fundamental that a low deviation is achieved so that the correct curvature is ensured. It is evident that in this case, more than for Point 1, the tool temperature had a stronger influence in the determination of the correct curvature. The dwell time, on the other hand, shows a peculiar trend. The value of the average deviation was very low for low values of dwell time, whereas it increased a lot when the pre-heating time was higher than 9.5 s. The range of values for which dwell time is acceptable is the one below 9.0 s. Above 9.0 s dwell time, the values of deviation were unacceptably high.

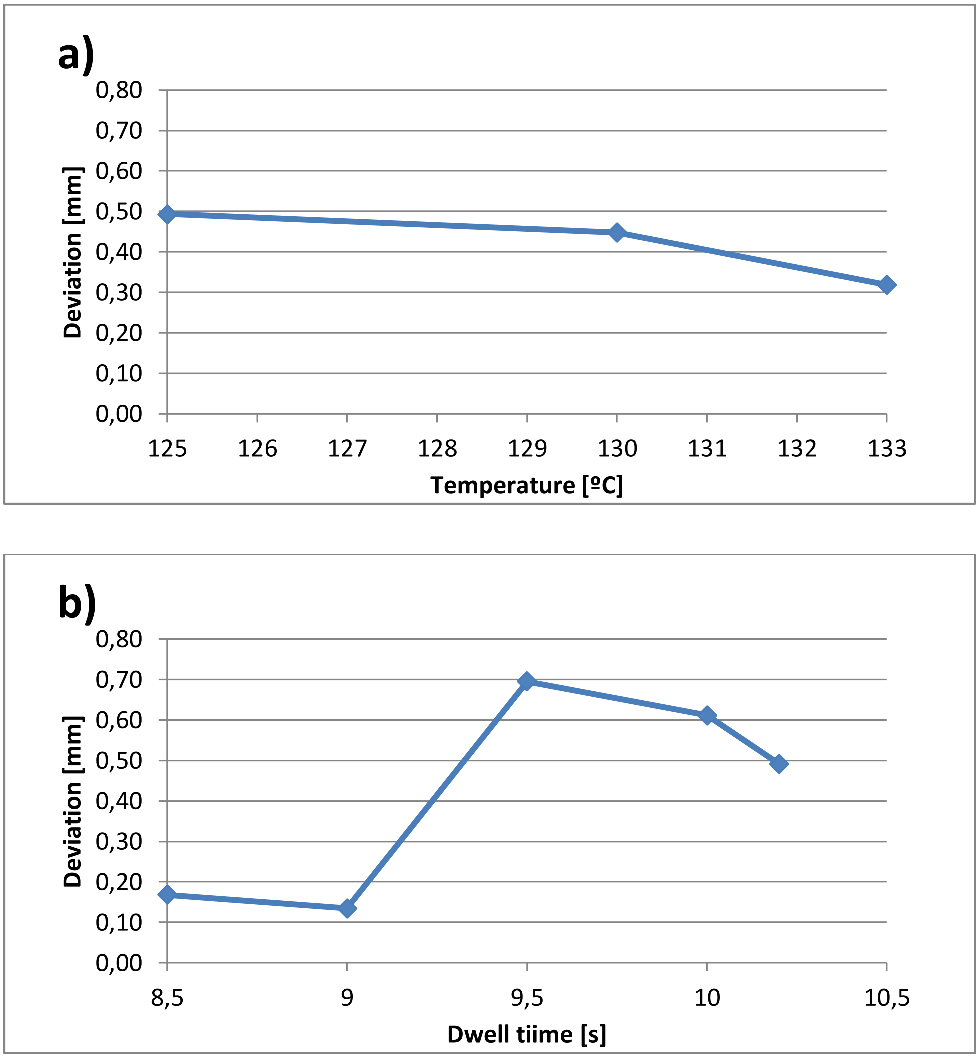


Figure 22: Mean of deviation of Point 2 for a) temperature change, and b) dwell time change.

In the case of Point 3, a very similar behavior to Point 1 was found. The effect of the temperature varies with the range (Figure 23). A first increase in the temperature, from

125˚C to 130˚C did not result in big differences in the deviation. The main difference in the deviation was seen when 133˚C was reached. At this highest level of temperature, the mean deviation was observed to go down a lot compared to the lower temperature factors. Point 3 is located at the top right position of the part, very close to a hole. The deviation of this point is influenced by the curvature and also warping of the part. It seems that the effects that caused the deviation of Point 3 were a mix of those that caused the deviation of Point 1: distortion and Point 2: curvature.

The effect of the dwell time was actually in line with the effect that the same factor had on the two other points. The deviation was kept low for values of dwell time (below 9 s), whereas it went up a lot for dwell time values higher than 9.5 s. Again, looking at Figure 18, the temperature that Point 3 reached on the surface of the film when the dwell time went above 9.5 s was higher than 195˚C. This may confirm that there is a threshold temperature that should not be exceeded when pre-heating the film. With the set of data available it is not easy to define the exact temperature at which this phenomenon happens, but it would be in the range of 190 ˚C to 195 ˚C.

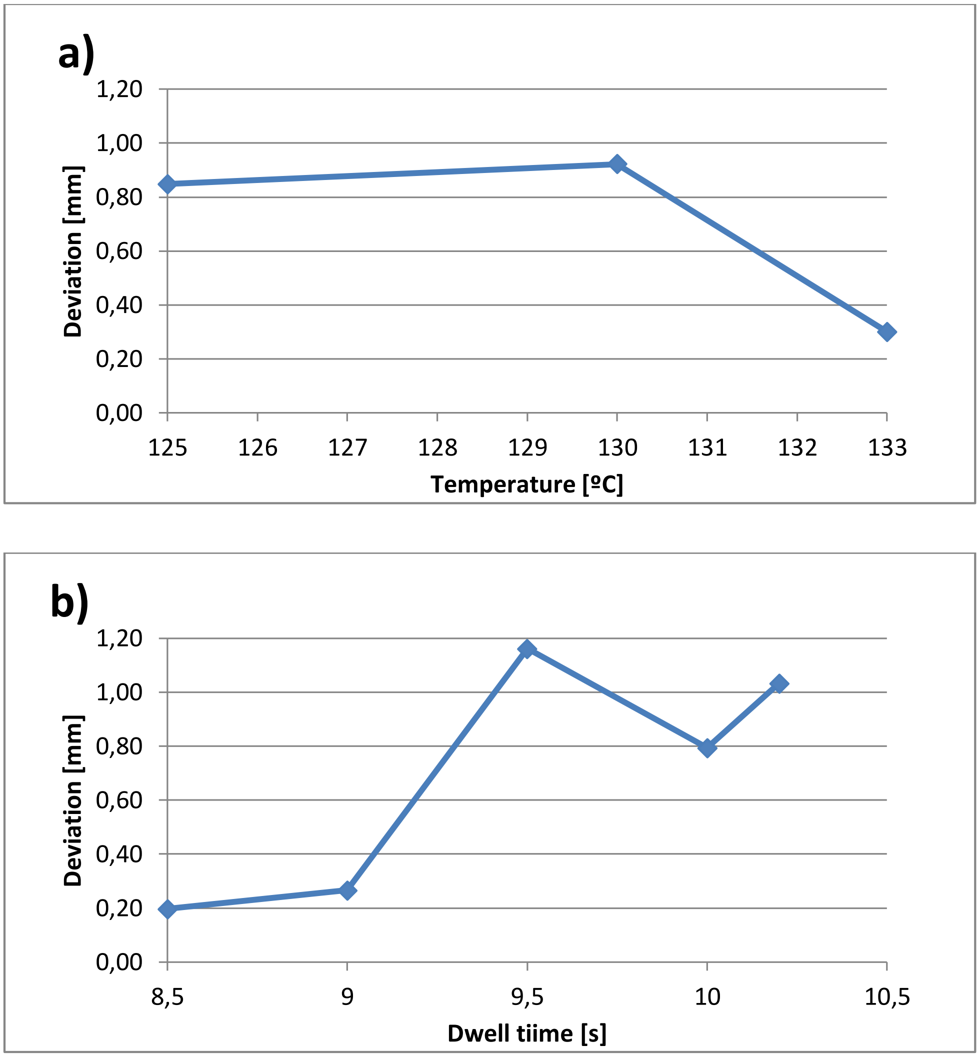


Figure 23: Mean of deviation of Point 3 for a) temperature change, and b) dwell time change.

The interaction between dwell time and temperature was also found to be influential in the ANOVA. Figure 24, Figure 25 and Figure 26 show the major effects of interaction by plotting the temperature on the x-axis and the deviation on the y-axis. The different curves represent the dwell time values. Note that x-axis in the interaction graphs is not kept in scale, as the slope of the curves is not an important parameter.

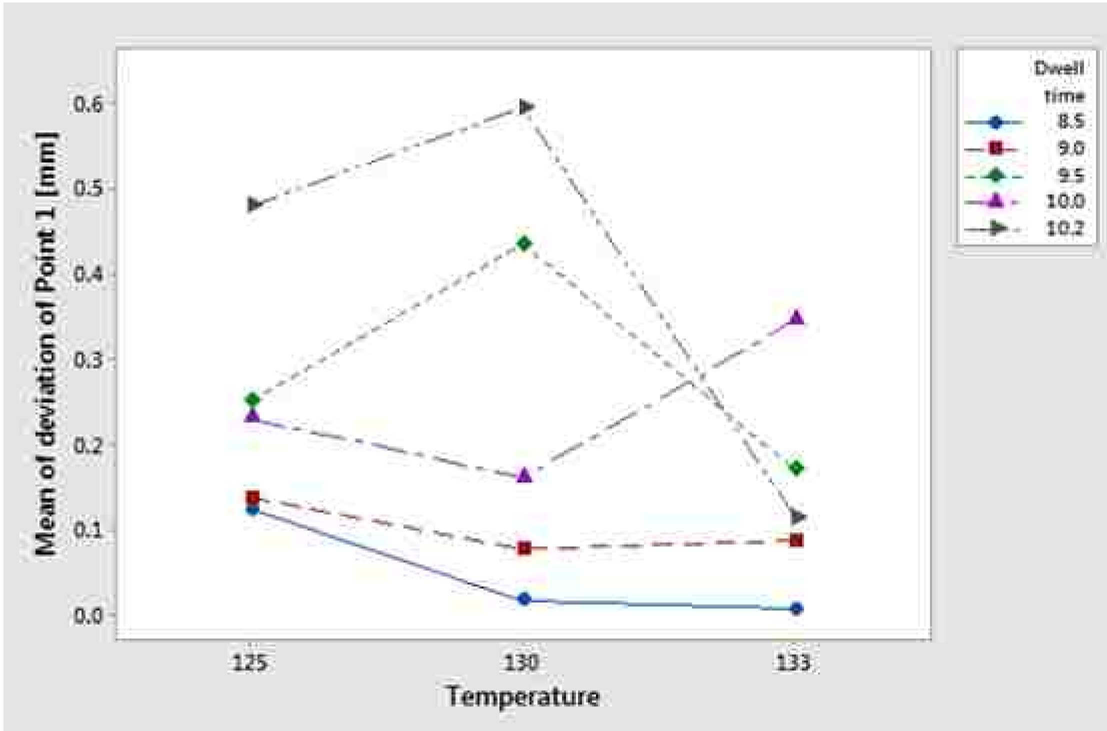


Figure 24: Interaction map for the deviation of Point 1 (forming).

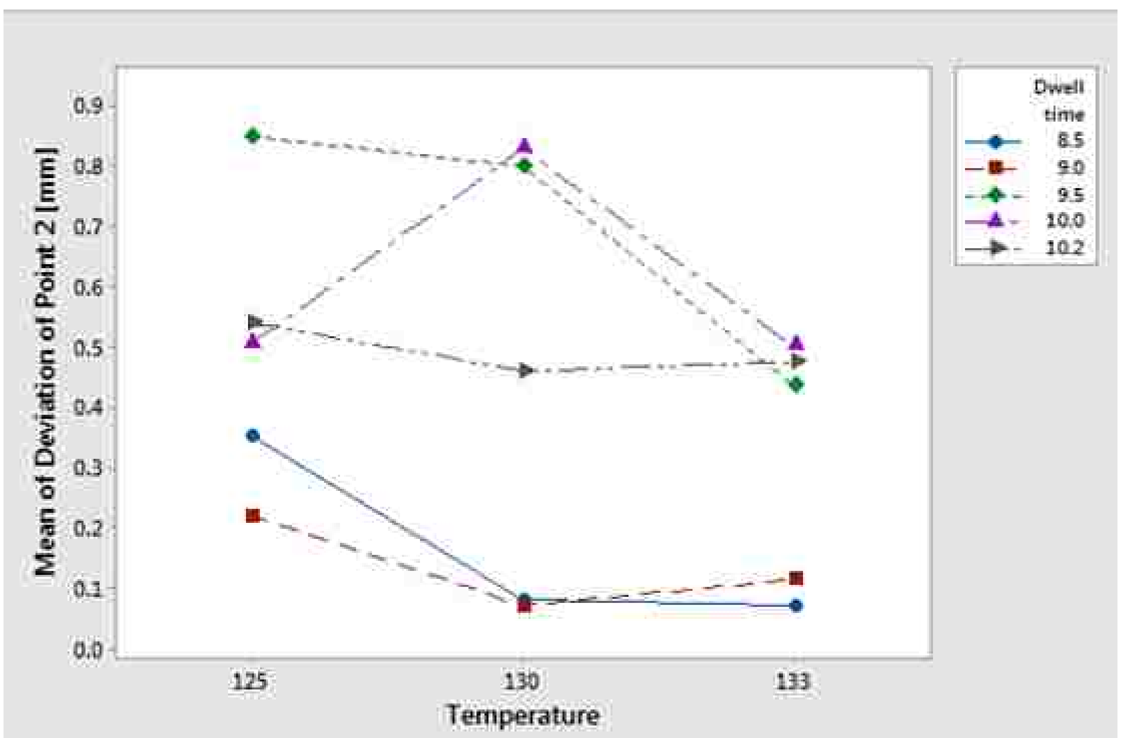


Figure 25: Interaction map for the deviation of Point 2 (forming).

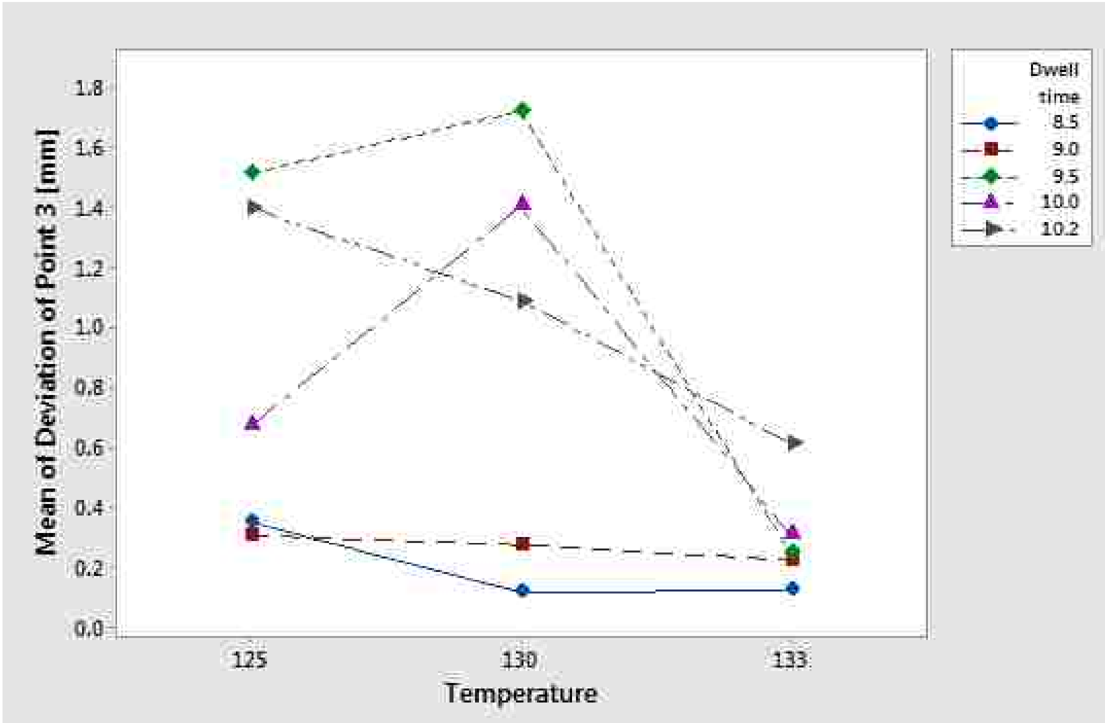


Figure 26: Interaction map for the deviation of Point 3 (forming).

Based on the graphs, it is not very easy and clear to provide an explanation of the interaction, especially because multiple levels were analyzed. It is interesting to note the interaction between pairs of levels of dwell time that show similar deviations. This was the case for values of dwell time of 8.5 s and 9.0 s. The range of deviation reached by these two levels was far less than deviation reachable with the other levels. In the case of Point 1, the red and the blue curve do not intersect and despite the fact that their initial value is very close, they have a diverging trend with the increase of the temperature. This means that there is a positive interaction between the two levels of the dwell time. A positive interaction occurs when the difference in the output of two different levels is increasing between the levels of the other factor. In other words, for this specific case, when the deviation increased between the curves of 8.5 s and 9.0 s with the increase in temperature, the interaction is said to be positive. This is not true in the case of Point 2. For Point 2 the interaction between the dwell time values of 8.5 s and 9.0 s is negative, as occurs when the lines intersect. This shows that the two curves had different trends when the temperature is increasing. Again, in the case of Point 3, the interaction is overall negative. In this case it can be split in two parts. The first part, from 125˚C to 130˚C shows a negative interaction, while the second part shows no interaction as the two curves the red and the blue one are almost parallel.

The boxplots of deviation for each point are given in Appendix D: Boxplot and confidence interval bars of deviation. The boxplot is a simple and clear representation of the range of values that the deviation assumes for a certain set of parameters.

A confidence interval is generally employed to predict future values. Obviously with few measurements it is not easy to have a strong statistical base to predict future values. So in this case the confidence interval for the temperature is moderately large, about 0.5mm for Point 2 and Point 3, whereas for Point 1 is smaller, about 0.2mm. Confidence intervals for the deviation with the variation of the temperature are reported in Appendix D: Boxplot and confidence interval bars of deviation.

4.1.3 Result analysis for forming, Analysis of the means

Table 15 summarizes the values of the means for the tests accomplished on forming.

Table 15: Representation of the means for forming calculated for each test for each point.

Test number	Temperature [ºC]	Dwell time [s]	Deviation of Point 1 [mm]	Deviation of Point 2 [mm]	Deviation of Point 3 [mm]
1	125	8.5	0.12	0.35	0.35
2	125	9	0.14	0.22	0.30
3	125	9.5	0.25	0.85	1.52
4	125	10	0.23	0.51	0.67
5	125	10.2	0.48	0.54	1.40
6	130	8.5	0.02	0.08	0.12

Table 15 (continued)

Test number	Temperature [ºC]	Dwell time [s]	Deviation of Point 1 [mm]	Deviation of Point 2 [mm]	Deviation of Point 3 [mm]
7	130	9	0.08	0.07	0.27
8	130	9.5	0.44	0.80	1.73
9	130	10	0.16	0.83	1.41
10	130	10.2	0.60	0.46	1.09
11	133	8.5	0.01	0.07	0.12
12	133	9	0.09	0.11	0.22
13	133	9.5	0.17	0.44	0.25
14	133	10	0.35	0.50	0.31
15	133	10.2	0.11	0.48	0.61

This is the set of that that will be used from now onward for all the measurements. The variation of the deviation with a fixed temperature and a variable dwell time are shown in Figure 27, Figure 28 and Figure 29. For all tool temperature values between 125ºC and 133ºC the change of dwell time between 8.5 s and 9 s did not create a big difference in the deviation. For the remaining dwell time values it is possible to notice a general increase of the deviation with dwell time. The biggest change occurred between the values of 9.0 s and 9.5 s. Also, it is interesting to notice how, when the temperature was set to the lower values of 125ºC or 130ºC, the deviation may go up to very high values, above 1.5 mm. Instead, considering a temperature of 133ºC, the deviation was always low, less than 0.6 mm.

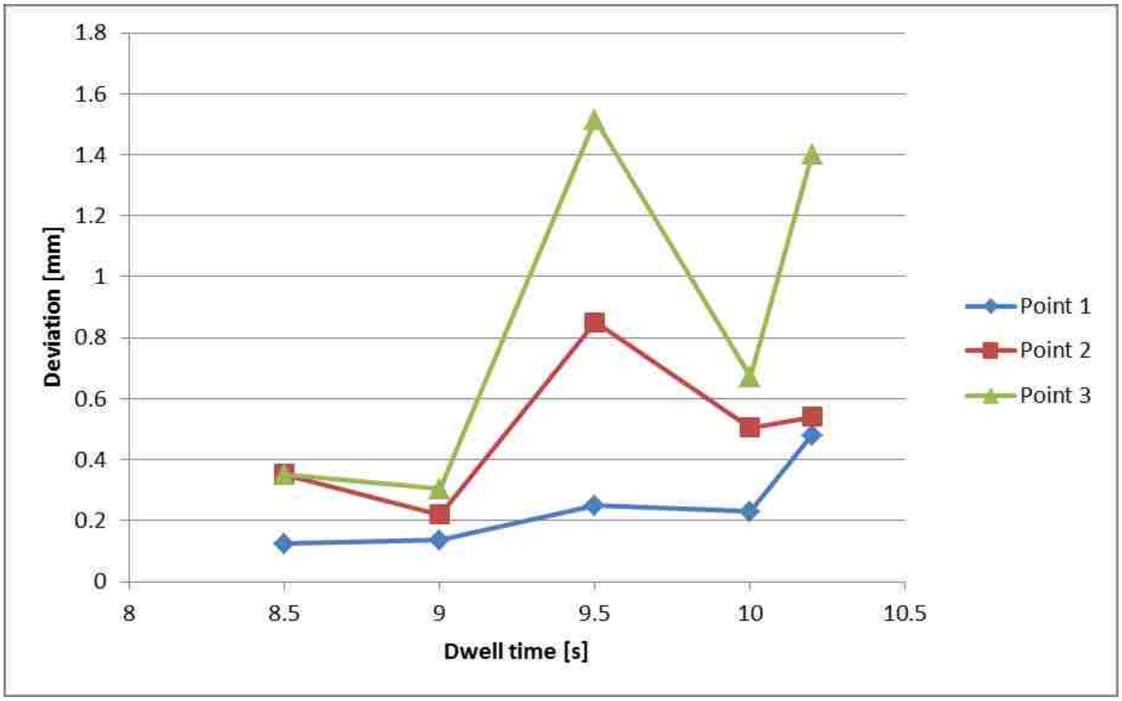


Figure 27: Graph of the deviation vs dwell time at a Temperature of 125˚C.

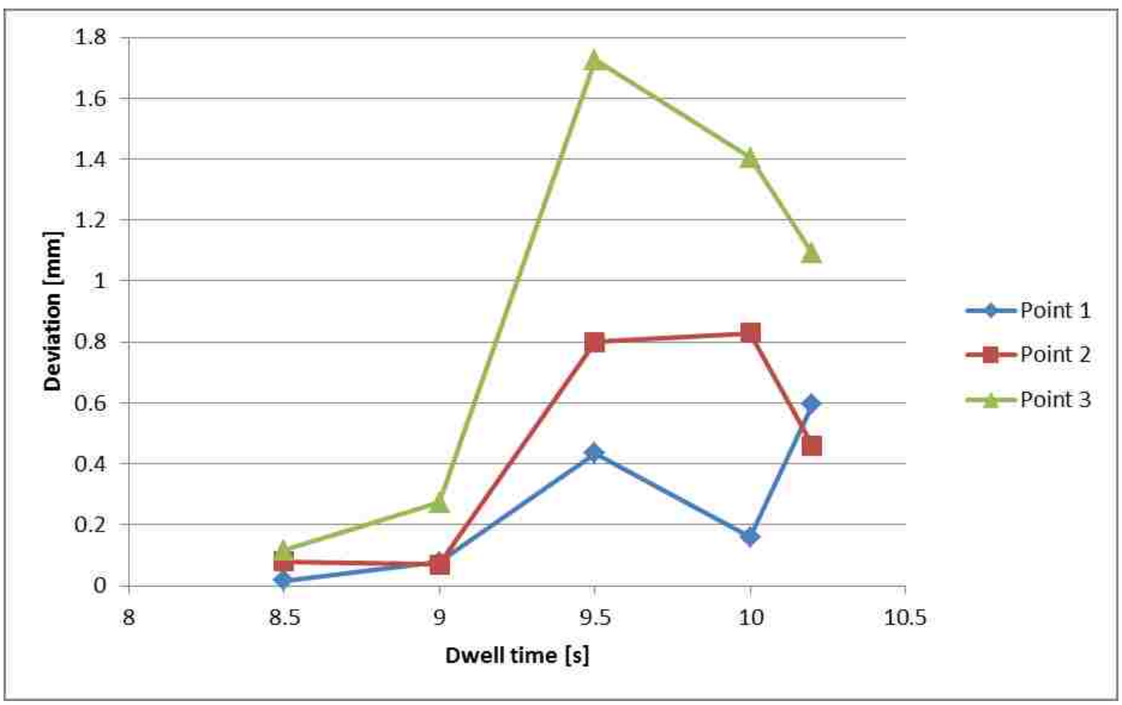


Figure 28: Graph of the deviation vs dwell time at a Temperature of 130˚C.

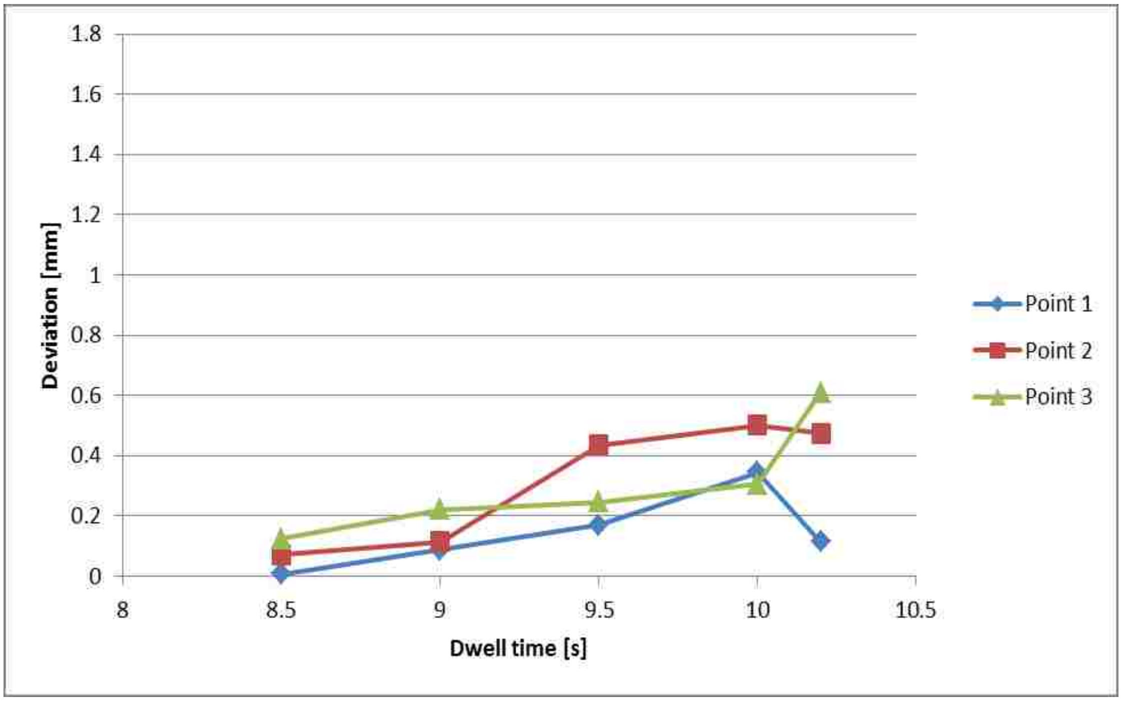


Figure 29: Graph of the deviation vs dwell time at a Temperature of 133˚C.

Once the trends are clear it becomes important to determine a good set of formation parameters that would make the deviation the smallest. It is important to consider for this analysis all of the three points studied. It is fundamental that the deviation is low for all the three points in order to find the set of parameters that would bring the deviation to the lowest value. Very clearly, it is possible to see that generally the left hand side of Figure 27, Figure 28 and Figure 29 show lower values of deviation, corresponding to dwell time values of 8.5 s and 9.0 s. After narrowing down the choice of the dwell time to these two lower values, the following step is to look at the temperature. Looking at the y-axes of Figure 27, Figure 28 and Figure 29 it is possible to see that for temperatures of 130 ºC and 133 ºC, the measure of the deviation was certainly lower than the deviation found for 125ºC. Having narrowed down the choice to the values of 130 ºC and 133 ºC for the tool temperature, it is not easy to distinguish for which value the deviation is the lowest: for both the values of temperature, the results are extremely similar and acceptable.

When it comes to decide which are the best values found for forming, the choice falls upon the lower values of dwell time and tool temperature. A dwell time of 8.5 s allows a saving of 0.5 s on the cycle time with respect to a dwell time of 9.0 s, which does not lead to significant changes in the deviation of the film. Also, the lower value of the temperature, 130 ºC, has to be preferred to the higher value because the deviation is nearly the same, less energy is required to heat the tool and heating the tool to the set temperature would take less time. The outcome of the first part of the analysis is that the set of parameters that best reduce the deviation in the formation process is

- Dwell time : 8.5 s
- Tool temperature 130 ºC

4.2 Results for UV curing

The second phase of the process is the UV curing phase. The tests related to this phase of the process were accomplished with the set of parameters of forming that was found to result in the lowest deviation (see Section 4.1.3 Result analysis for forming, Analysis of the means)

In the case of UV curing, the parameters considered for the analysis were the UV oven conveyor speed and the ink size. Three samples were made for each set of parameters considered. The total number of tests was 18 for a total of 54 measurements of the deviation. As in the case of forming, the deviations were measured at three points. The three points corresponded exactly to the ones analyzed for forming; the first one being beside the hole, the second at the rightmost end of the part and Point 3 being on the upper right side of the part beside a hole.

Table 16 shows the results of the measurements. The data are sorted by repetition, UV oven conveyor speed and ink size.

Table 16: Test results for UV curing for Point 1, Point 2 and Point 3 on the surface.

Repetition	UV oven conveyor speed [fpm]	Ink size	Point 1 mm	Point 2 mm	Point 3 mm
1	30	Regular	0.22	0.21	0.14
2	30	Regular	0.22	0.16	0.14
3	30	Regular	0.26	0.15	0.12
1	30	Larger	0.18	0.11	0.04
2	30	Larger	0.11	0.09	0.04
3	30	Larger	0.16	0.19	0.14
1	40	Regular	0.13	0.08	0.06
2	40	Regular	0.19	0.09	0.07
3	40	Regular	0.08	0.09	0.18
1	40	Larger	0.09	0.04	0.03
2	40	Larger	0.06	0.2	0.07
3	40	Larger	0.05	0.15	0.10
1	45	Regular	0	0.11	0.09
2	45	Regular	0.03	0.11	0.08
3	45	Regular	0.05	0.1	0.1
1	45	Larger	0.17	0.13	0.1
2	45	Larger	0.12	0.09	0.04
3	45	Larger	0.12	0.07	0.11

In order to understand if the data are different because of the change in parameters an analysis of variance was conducted.

4.2.1.1 Result analysis for UV curing, ANOVA (Point 1)

Table 17 shows the results obtained from the ANOVA calculation.

Table 17: ANOVA table for UV curing (Point 1).

Source	DOF	Sum of Squares (Deviance)	Variance	F-Value	P-Value	Corrected Sum of Squares	Adjusted Percentage of Contribution
Conveyor speed	2	0.041678	0.020839	18.48	0.000	0.039422	43.59%
Ink size	1	0.000800	0.000800	0.71	0.416	-0.000328	0%
Conveyor speed* Ink size	2	0.034433	0.017217	15.27	0.001	0.032177	35.58%
Error	12	0.013533	0.001128	-	-	0.019173	20.84%
Total	17	0.090444	-	-	-	0.090444	100%

From the table it is evident that only one of the two investigated parameters was influential in the change of the deviation. The conveyor speed was an influencing parameter since its p-value is considerably below 5%. The ink size can be considered a non-influential parameter. The reason is that its p-value is above the value of 5%. The risk of error of considering ink size as an influential parameter is high at the confidence interval of 95% considered for this analysis. An option that could be considered is pooling. Pooling would allow removing any factor from the ANOVA table that is regarded as non-significant and adding its contribution to the error. In this way a more robust analysis would be provided, avoiding non-influential parameters to be included in the percentage of contribution. Pooling is a process that has to be used with extreme caution because it may bring to misleading results. Pooling in this case cannot be performed because the parameter ink size is not influential itself, but it is fundamental in order to calculate the interaction, which is instead significant. As in the case of forming, the corrected sum of squares has been calculated. In this case, following the same procedure and the same approximate technique used for forming to find the percentage of contribution of each factor, a negative value was found for the ink size (-0.000328). Obviously a negative percentage of contribution makes no sense, so the negative value was subsequently adjusted to 0. In order to have the same total, the corrected sum of squares for Ink size was combined with the corrected sum of squares for Error (0.019173) to give the final value of 0.018845 which when normalized gave the adjusted percentage of contribution of 20.84%..

It is curious to notice how the interaction between the two parameters actually has an influence which is very high compared to the other points. The interaction between ink size and conveyor speed accounts for at least 35% of the total deviation of the shape for Point 1. So the curing factors that influenced the shape of the film in Point 1 were the conveyor speed and the interaction between the conveyor speed and the ink size. The error for Point 1 accounts for about 20% of the total deviation. Again, it means that the method used to detect deviations leaves one fifth of the change to unknown factors.

4.2.1.2 Result analysis for UV curing, ANOVA (Point 2)

Considering the ANOVA for Point 2, Table 18 shows the results:

Table 18: ANOVA table for UV curing (Point 2).

Source	DOF	Sum of Squares (Deviance)	Variance	F-Value	P-Value	Corrected Sum of Squares	Adjusted Percentage of Contribution
Conveyor speed	2	0.008844	0.004422	2.30	0.143	0.005	13.26%
Ink size	1	0.000050	0.000050	0.03	0.875	-0.001872	0%
Conveyor speed* Ink size	2	0.005733	0.002867	1.49	0.264	0.001889	5.01%
Error	12	0.023067	0.001922	-	-	0.032677	81.72%
Total	17	0.037694	-	-	-	0.037694	100%

The deviations observed are not likely due to the parameters shown in the table. The p-values for both the conveyor speed and the ink size are very high (higher than 0.1) and the risk of error to consider them influential in the deviation of the part at Point 2 is too high. Their interaction also does not show a low p-value so that it cannot be regarded as influential. The column of corrected sum of squares has been calculated and the adjusted percentage of contribution following the same procedure of the previous case for Point 1. It confirms that the error in this case and so the uncertainties of measurements play an important role in the deviation of Point 2. The error in this case accounts for more than 80%. The tested factors play a very limited role in the changes in the deviation of the film. This is an important result. It means that UV curing parameters did not influence the curvature of the part when forming parameters are set to a value that makes the deviation small. The change in Point 2 detected in this phase of the analysis for UV curing was very limited and related mostly to unknown effects. It is possible to affirm that the only process stage that affects the curvature of the part is the forming stage.

4.2.1.3 Result analysis for UV curing, ANOVA (Point 3)

Table 19 shows the results for Point 3.

Table 19: ANOVA table for UV curing (Point 3).

Source	DOF	Sum of Squares (Deviance)	Variance	F-Value	P-Value	Corrected Sum of Squares	Adjusted Percentage of Contribution
Conveyor speed	2	0.001154	0.000577	0.32	0.734	-0.002486	0%
Ink size	1	0.006188	0.006188	3.40	0.090	0.004386	13.84%
Conveyor speed* Ink size	2	0.002383	0.001191	0.65	0.537	-0.001257	0%
Error	12	0.021841	0.001820			0.030941	86.16%
Total	17	0.031566				0.031566	100%

In this case, such as in the case of Point 2 the high p-value indicated that it is nearly impossible to consider the parameters in the table influential. The ink size is the parameter that potentially could play an influence on the phenomenon, but the p-value related to the ink size 0.090 is above the threshold of 0.05.

The column of the adjusted percentage of contribution shows that the error played a major role in the differences in the deviation of the film, accounting for more than 86%. As in the case of Point 2, there is extremely limited influence of UV curing parameters on the deviation of the film. For this section, the influence of the UV oven conveyor speed and the interaction on Point 3 are null. The ink size accounts for about 14% of the change. These results confirm what has been stated before: so that the curvature of the part is only influenced by forming parameters.

4.2.1.4 Results analysis for UV curing, percentages of contribution and residuals

Differently from forming, in the UV curing stage, it turned out that not all the factors were significant for each point. Point 1 was the only one for which a certain degree of significance was found. Point 2 and Point 3, according to the ANOVA calculations, do not show significant changes in their deviation with a variation of factors C and D. A representation to summarize the results achieved with the ANOVA is represented in Figure 30

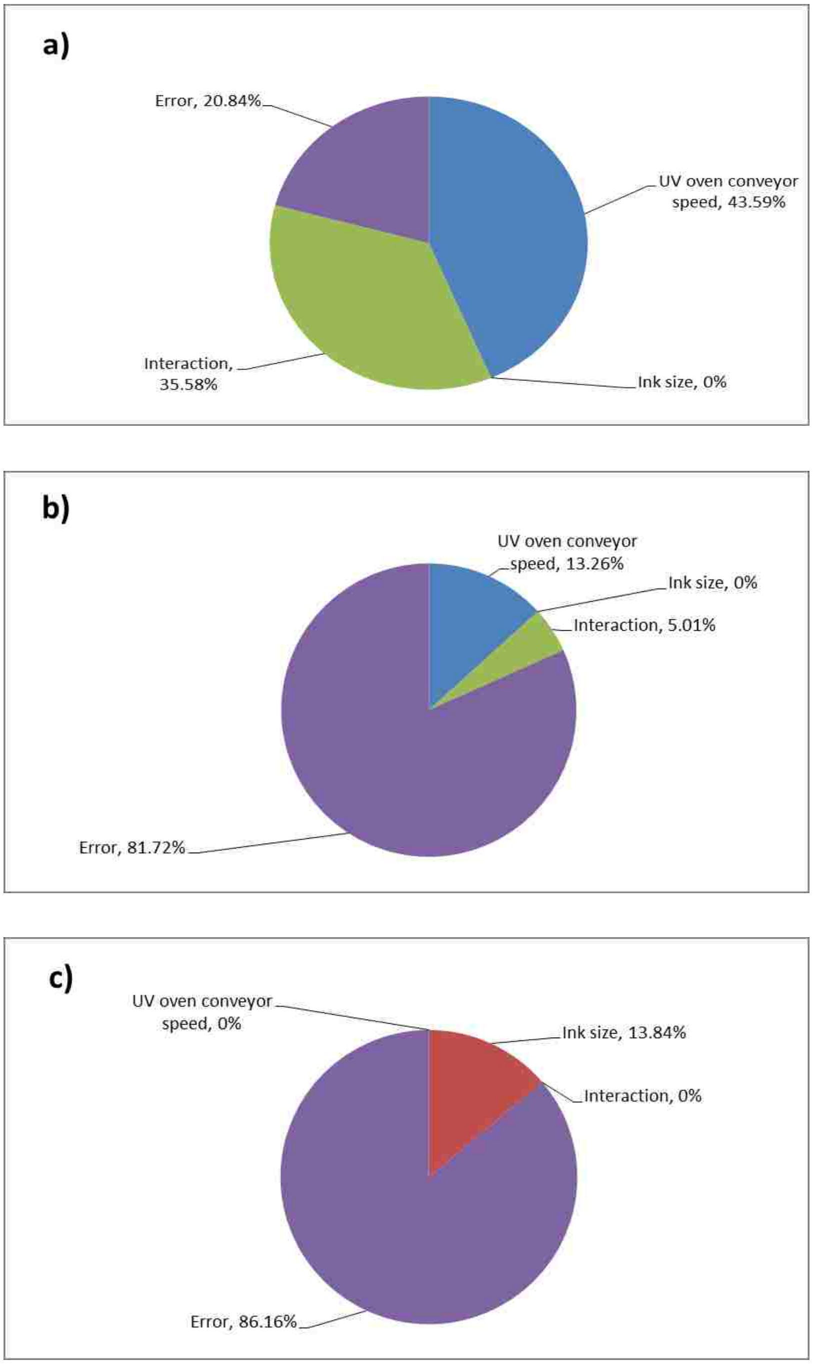
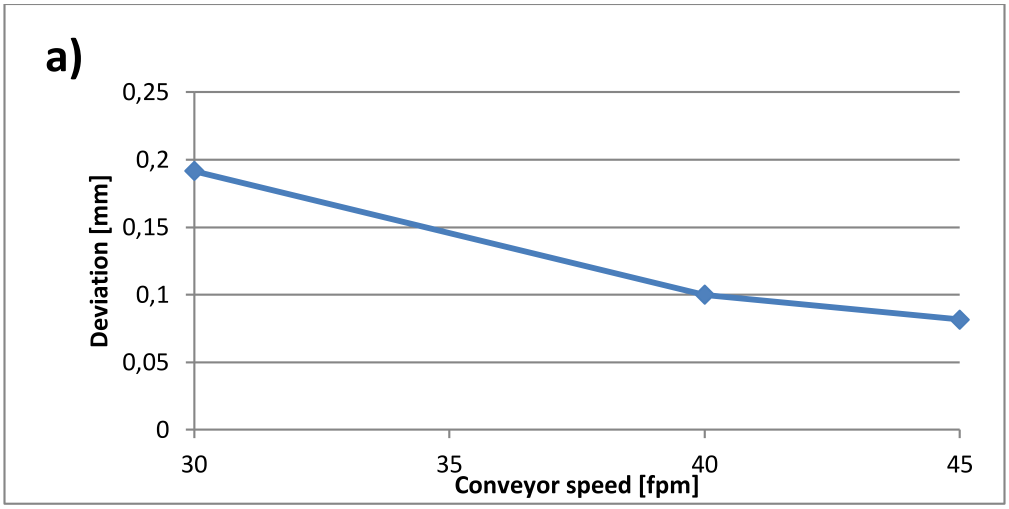


Figure 30: Pie graphs representing the percentages of contribution of factors and interaction in UV curing for the three points analyzed.

As it was first pointed out in the case of forming, also in the case of the UV curing stage, an analysis of residuals was performed in order to verify that the experiments were carried out correctly. The histogram of residuals and the graph showing the residuals versus the observation order have been employed for this purpose. In Appendix E, Figures E-1, E-3, E-5 show a shape of the histogram which can be compared to a normal distribution. Also looking at Figures E-2, E-4, E-6 it is possible to see that the residuals do not show any particular pattern and so it can be affirmed that the tests and the samples were randomized enough also in the case of experiments conducted for the UV curing stage.

4.2.2 Result analysis for UV curing, Influence of UV oven speed

Since from the ANOVA it was found that the only Point 1 the parameter Conveyor speed was significant, the analysis of the means is limited just to Point 1. Figure 31 shows the main effects of the variation of parameters. It is possible to notice a clear decreasing trend of the mean deviation with the increase of the conveyor speed. It means that for an higher conveyor speed, the part was kept less long in the UV oven and so it was deformed less. A slower conveyor speed, while on the one hand would provide a better curing of the part, ensuring superior mechanical resistance, on the other hand would cause a little deformation of the part itself. A way to solve the issue of curing was thought to be the variation of the ink size. It comes out from the ANOVA that ink size was not an influential parameter. This is also clear by looking at of Figure 31b. The difference in average deviation for Point 1 between a regular and a larger ink size is in the order of 0.02 mm and so almost null.



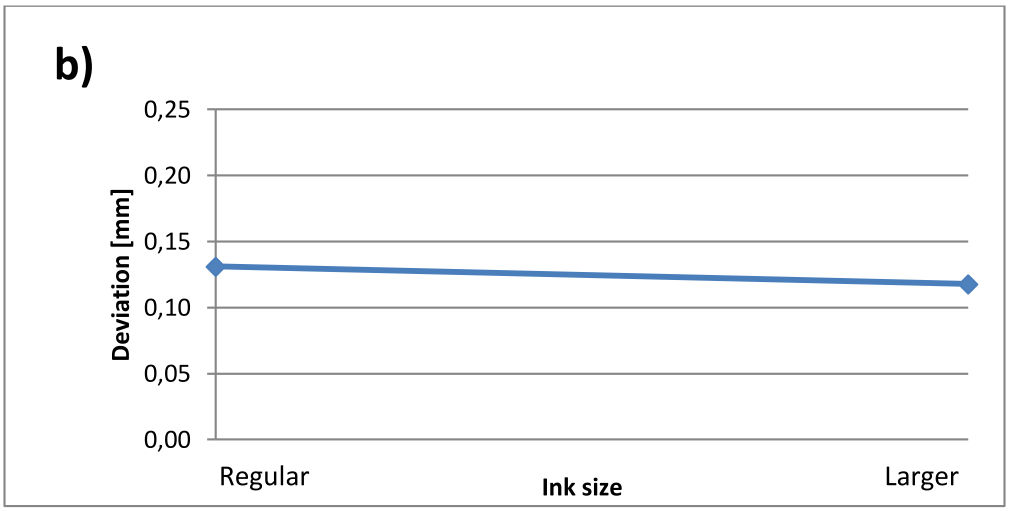


Figure 31: Mean of deviation of Point 1 for a) UV conveyor speed change, and b) ink size change.

It is interesting also to consider the interaction of the two factors, as the interaction was found to be a significant parameter. It is shown in Figure 32. On the y-axis the mean deviation is represented, whereas on the x-axis the UV conveyor speed is plotted. The blue and the red curves represent respectively the larger and the regular ink size. It is evident that from 30 fpm to 40 fpm there was no interaction among the two factors: the two lines are almost parallel. From 40 fpm up to 45 fpm the two lines show completely different trends. The red one, that shows regular ink size, keeps decreasing, whereas the blue line representing larger ink size has a slight increasing trend. From 40 fpm onwards the interaction between the two levels is considered to be negative, as the lines show opposite trends and eventually cross.

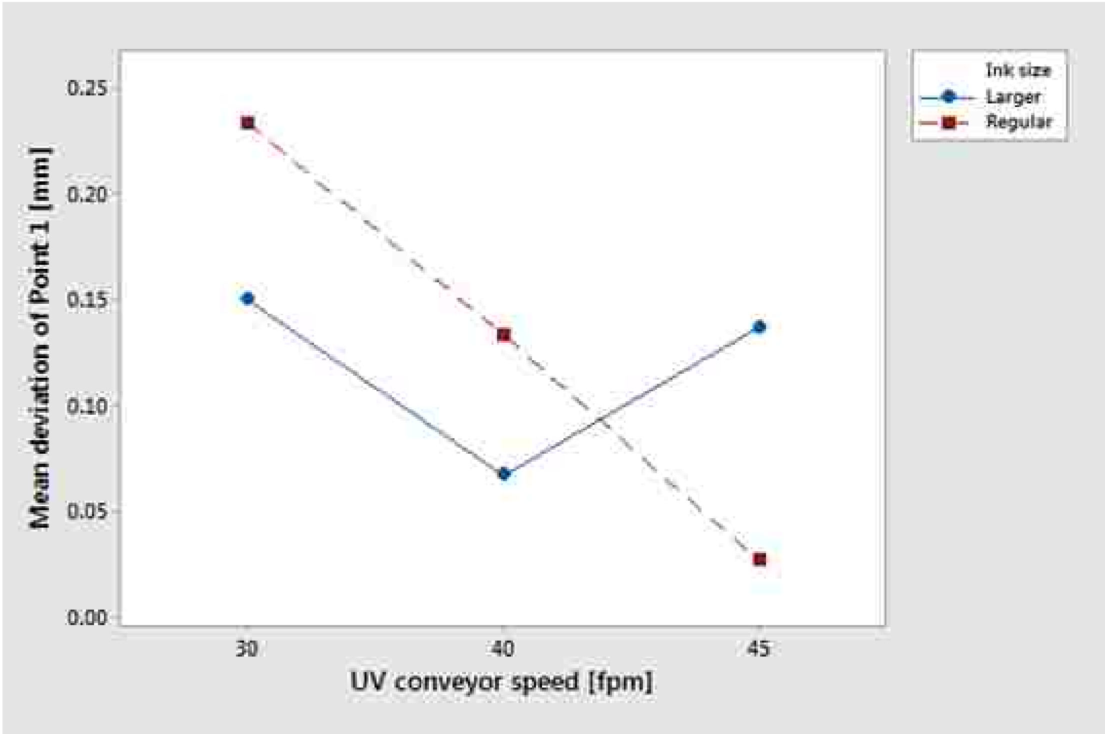


Figure 32: Interaction map for the deviation of Point 1 (UV curing).

As the only parameter that influences the results, the UV oven conveyor speed is the only parameter for which a boxplot is provided. It is shown in Figure F-1 in Appendix F: Boxplot and confidence interval bars of deviation for UV curing.

The graph in Figure F-2 shows the confidence interval for Point 1, which might look broad looking at the graph but taking into account the scale on the y-axis the range is regularly large. It seems that the values of the deviation had a decreasing trend with increasing the UV oven conveyor speed, but the confidence interval of 95% does not allow one to say that their difference is statistically significant without a high risk of error. Graphs related to Point 2, Point 3 and to the ink size would be meaningless, because their confidence intervals would be strongly overlapped.

4.2.3 Result analysis for UV curing, Analysis of the means

Since the deviation for Point 2 and Point 3 did not go above the value of 0.2 mm while varying cure parameters, they are not considered critical for the fitting of the film into the mold cavity. Moreover the parameters of UV curing conveyor speed and ink size are not influential for Point 2 and Point 3. For this reason an analysis of the mean using the results at Point 1 was performed. For completeness, Table 20 reports the means of all the measurements, for all three measured points for the two factors.

Table 20: Mean deviations for UV curing for each test for each point.

Test #	Conveyor speed [fpm]	Ink size	Point 1 mm	Point 2 mm	Point 3 mm
1	30	Regular	0.23	0.17	0.14
2	30	Larger	0.15	0.13	0.07
3	40	Regular	0.13	0.09	0.11
4	40	Larger	0.07	0.13	0.07
5	45	Regular	0.03	0.11	0.09
6	45	Larger	0.14	0.10	0.09

In Figure 33, a clear representation of the situation for Point 1 is shown. The graph is basically an interaction diagram between the two factors considered. It is also a good check on the behavior of the deviation for all the parameters involved in the analysis. From the graph it is possible to note the slightly decreasing trend of the deviation passing from a regular ink size to a larger ink size for the two lower conveyor speed values. In the case of higher conveyor speed, the trend is increasing. The deviation slightly increased.

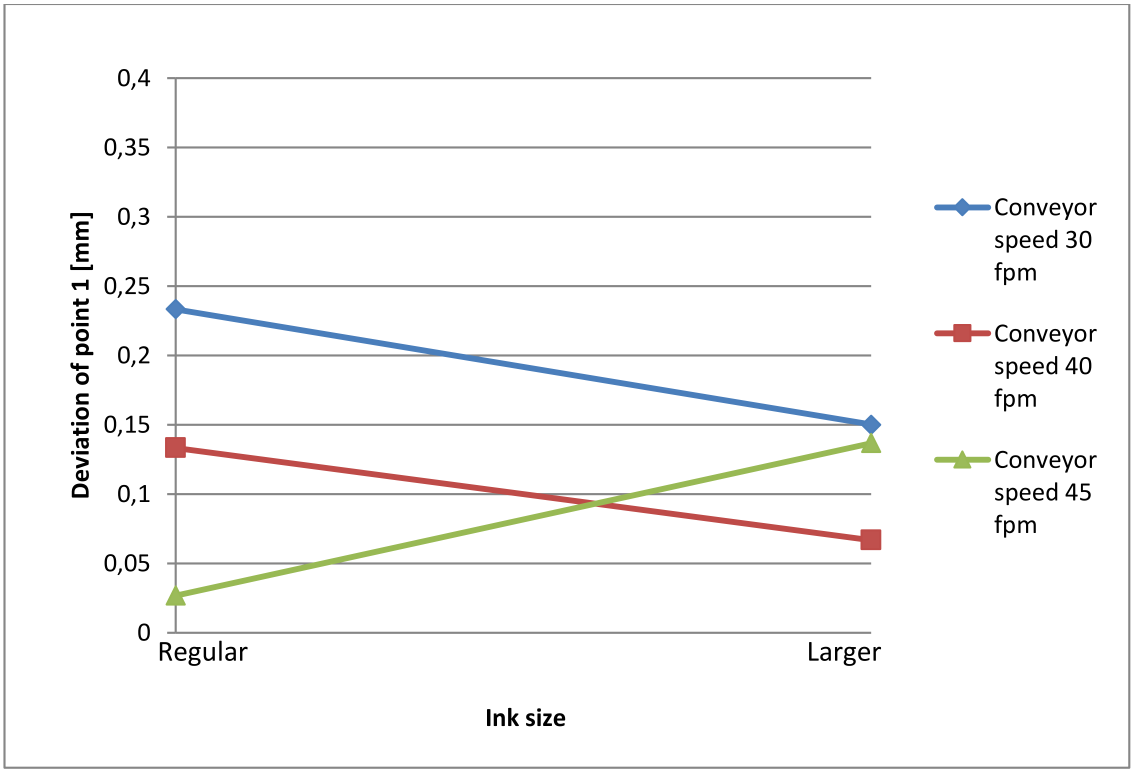


Figure 33: Variation of the deviation of Point 1 vs Ink size for different Conveyor speed values.

Two further diagrams are also important to clarify the effects of the conveyor speed on the deviation. They are bar diagrams shown in Figure 34 and Figure 35. On the y-axis a measure of the deviation of Point 1 is plotted, and the three bars represent the three different levels of conveyor speed. The two diagrams represent the case of regular ink size and larger ink size. From the graphs, it is possible to draw information about the condition for which the deviation is the lowest, among the set of parameters tested. The lowest deviation is reached for a conveyor speed of 45 fpm with a regular ink size.

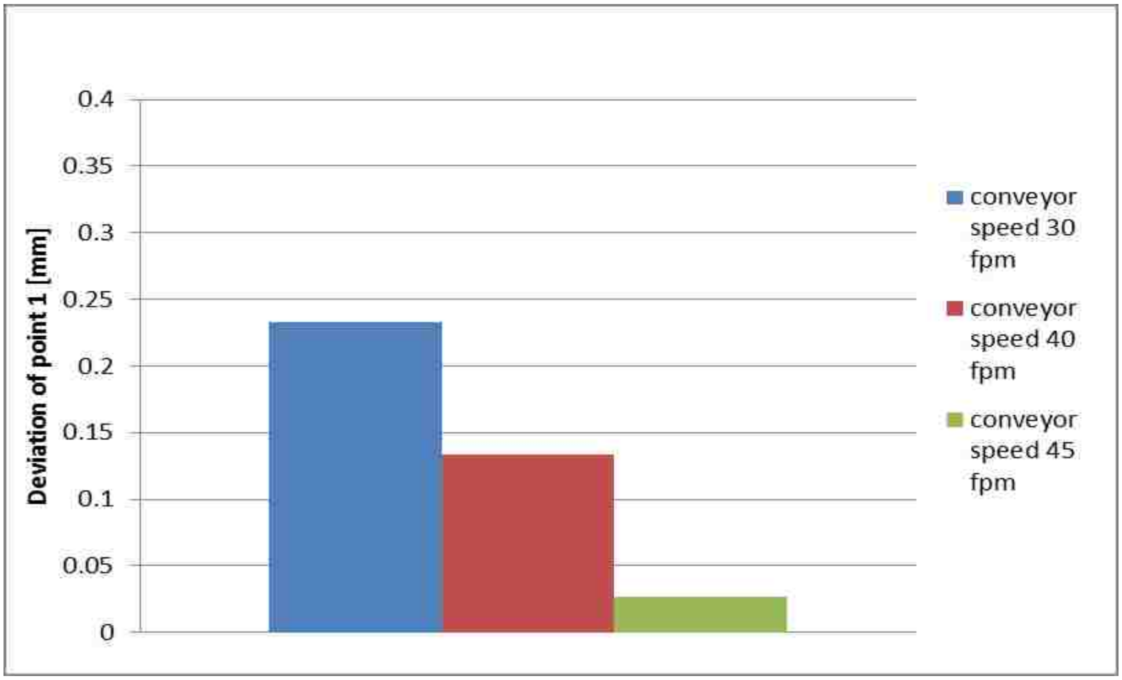


Figure 34: Variation of the deviation of point 1 for different conveyor speed values with regular ink size used.

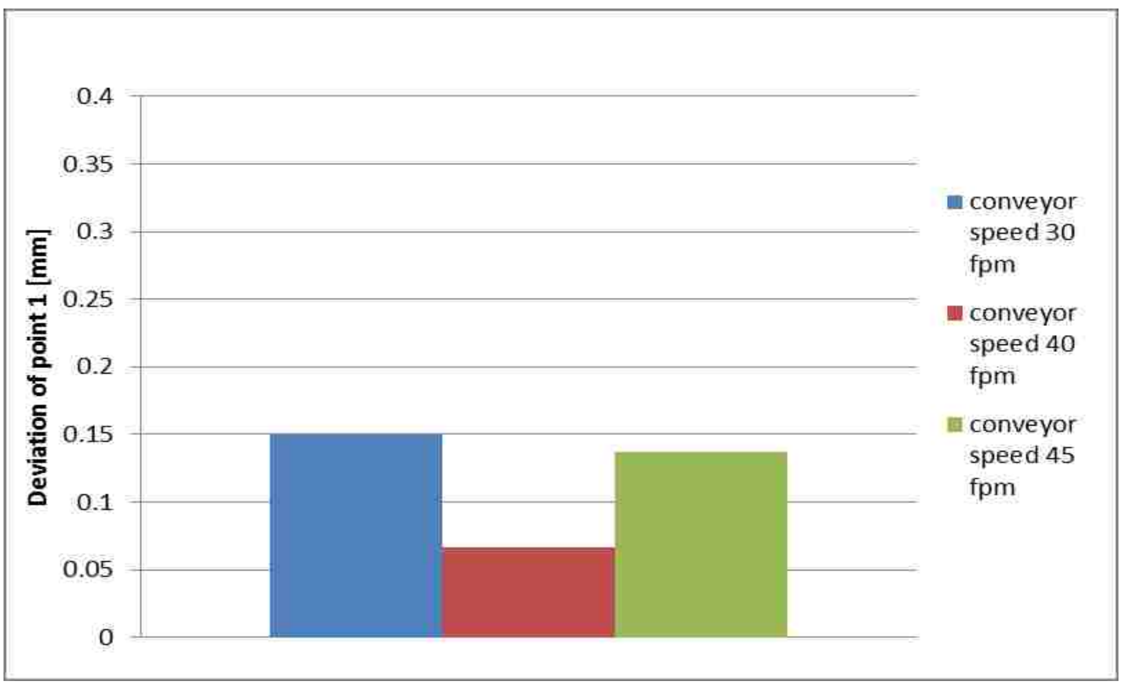


Figure 35: Variation of the deviation of point 1 for different conveyor speed values with larger ink size used.

The major outcome of the analysis concerning UV curing stage of the process is that this stage does not influence the process as much as forming does. The two parameters conveyor speed and ink size had a very low and limited influence on the process. Even with statistically significant differences in deviation for conveyor speed, the deviation does not change enough to be of relevance. The variation of factors in forming has led to high differences in the deviation of the film from the nominal CAD model, up to more than 1.5 mm. In the case of UV curing, once the forming stage was set so that the deviation is minimized, the deviation range was much smaller. The highest deviation was found to be below 0.25 mm for a UV curing conveyor speed of 30 fpm which was thought (prior to these tests) to cause the major deformations. A value of deviation of 0.25 mm is considered a “warning” in the process, because it may lead in some cases to pinching, but in any case it is not as worrying as some values reached for varied forming parameters. Basically, the main outcome of the analysis for the UV curing stage is that, if the parameters of forming are properly set, whichever parameter is chosen for UV curing – within the range of acceptable ones- the deviation of the film will not be influenced much.

Another point that has to be considered is that the lowest value of deviation found in the second part of the analysis, related to UV curing was for a conveyor speed of 45 fpm. The value of 0.03 mm average deviation can be certainly compared to the value found during the first part of the analysis for forming. For forming, the UV curing conveyor speed was set to 35 fpm which was certainly able to provide more curing to the part. The deviation in the case of conveyor speed set at 35 fpm was only 0.02 mm. It means that there is basically no difference between the deviations caused by the two conveyor speed values. The recommendation in this case is to use whichever UV curing conveyor speed would be more suitable for the optimization of other parameters not related to the deviation. If the part is able to pass mechanical and chemical tests provided by car manufacturers with a lower cure and a higher conveyor speed, then the higher conveyor speed is preferred as the cycle time would be slightly reduced.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study described the main characteristics of FIM technology, describing its uses in the automotive field. A set of performance standards for vehicle displays has also been provided. One of the main issues encountered in production, pinching of the film in the mold, and its causes and effects has been explained. Through experimental work and analysis it was found that in the film forming stage of the process, the parameters of pre-heating time and temperature, and their interaction, are influential in the determination of the shape and the distortion of the film. Contrary to what was expected, dwell time was shown to have the greatest contribution to the deviation of the shape of the film for the three points analyzed. Dwell time was shown to contribute at least 50% to the deviation of the film, whereas tool temperature, even though it was found to be influential and statistically significant, was shown to contribute less than 25% to the deviation for the set of parameters tested. Dwell time was found to have a greater influence on the curvature of the part, since its influence on Point 2 was higher than 70%. The tool temperature reached its highest percentage of contribution (23%) for Point 3, which is at the edge of the part.

The factors in the UV curing phase were found not to be very influential on the film deviation from the process using the values of dwell time and tool temperature that gave the lowest deviation in forming. The UV curing parameters are shown to have a very low influence on the deviation compared to forming parameters. The main source of differences in the deviation was found to be the error, which means differences in the replicates and variances in the production process of parts. From the ANOVA calculation, UV curing parameters were identified to be influential just for Point 1; in particular the UV oven conveyor speed and the interaction between it and ink size. This shows that UV curing may slightly influence warping of the part, not its curvature.

It was found that, in order to minimize the deviation with the set of factors and levels available, the preheating dwell time had to be set to a value not higher than 9.0 s. Actually dwell times of 8.5 s and 9.0 s led to very similar results, but a lower value of dwell time, 8.5 s, was considered to be best as it would keep the cycle time shorter. The level of temperature that led to the smallest deviation was 130˚C. From the UV curing, it turned out that the parameters for which the deviation is the lowest were a conveyor speed of 0.18 m/s (35 fpm) and a regular ink size.

Another point that has not been clearly demonstrated through the study but is possible to claim is that the influence on the deviation of the other parameters in Table 7 is limited as it was originally thought. This has not been shown directly through experiments, but the fact that a way to lower the deviation of the part was found, by keeping the other parameters at their original values and by changing only two of the forming parameters, suggests that it is not necessary to change those parameters as well.

Also, it is possible to update the Ishikawa diagram of Figure 12. The yellow box, indicating "Ink area" and "B surface of the film" should be colored grey, indicating "cause discarded", whereas the ones indicating "Improper film shape", "Distortion" and "Forming and UV curing" should be colored in red, which means "cause confirmed".

5.2 Implementation

In this work, a reduction of the Risk Priority Number for a top-rated issue in the PFMEA was found. Completion of the PFMEA shown in Table 21 is based on the new set of process parameters utilized in production. The current pre-production values used are: dwell time = 8.5 s, tool temperature = 130˚C, regular ink size and 35 fpm UV conveyor speed. The actions taken to correct the RPN were identified by the use of an appropriate control technique, with the use of a laser scanner to measure results. This characteristic led to a reduction of the Detection value from the high value of 8, representing 100% visual inspection, to a lower value of 6. The value of Occurrence decreased from the value of 5 previously found to the value of 1. Once the process parameters were properly set, the Occurrence of pinching became very low since the new process parameters were implemented, leading to zero part scraps due to pinching in the last three weeks of processing, during which time more than 4000 parts were produced. This leads to the new value of 1 in the FMEA. The Severity value is kept the same because the study was not aimed at decreasing the severity of the issue. In any case, a value of 5 for Severity is not a concern and so it can be left as it is. The re-evaluated RPN for the issue is now 30 as the product of the new calculated values of Severity, Occurrence and Detection. The value is low enough so that the issue should not be considered anymore as a top-rated one in the PFMEA.

Table 21: Updated PFMEA for pinching

Current situation									
Process Function	Potential Failure Mode	Potential Effect(s) of Failure	Sev	Class	Potential Cause(s)/ Mechanism(s) of Failure	Occur	Current Process Controls	Detec	RPN
Forming – UV curing	Improper Shape and Distortion. Pinching of the film in the mold	Flash of the resin. Ripped film	5	HIC (High Impact Characteristic)	Improper parameters of forming and curing	5	Visual Inspection	8	200

Countermeasures		Actions taken				
Recommended Action(s)	Responsibility and Target Completion Date	Action Results				
		Actions Taken	Sev	Occ	Det	RPN
Optimization of forming and UV curing parameters, Use of laser scanner	End of pre-production phase	Adoption of laser scanning. Modification of process parameter values	5	1	6	30

5.3 Recommendations

This study could be considered as a starting point for further studies regarding the same technology and the characteristics of the film in the process of FIM. It would be of a particular interest to analyze the distortion of the film in some other applications where a different shape of the part (a different curvature or a different film thickness is used) as the parameters to lower the deviation might have to be set on other values. Also it would be interesting to study how a film made with a different material such as PMMA or a combination of PC and PMMA would be influenced by the process parameters. The upper limitation in dwell time seems to be related to keeping the surface of the film below 195˚C. In order to do so, the dwell time can be estimated using the calculations shown in Appendix B, considering a h value of 21.6 W/m^2K. It would be of a particular interest to measure the core temperature of the film prior to forming, which may be slightly different for different thicknesses of the three layers of which the film is composed.

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APPENDICES

Appendix A: PFMEA charts

Effect	Criteria: Severity of Effect: This ranking results when a potential failure mode results in a final customer and/or manufacturing/assembly plant defect. The final customer should always be considered first. If both occur, use the higher of the two severities.		Ranking
	(Customer Effect)	(Manufacturing/Assembly Effect)	
Hazardous - without warning	Very high severity ranking when a potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulation. Failure will occur *without* warning.	Or may endanger (machine or assembly) operator without warning.	10
Hazardous - with warning	Very high severity ranking when a potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulation. Failure will occur with warning.	Or may endanger (machine or assembly) operator with warning.	9
Very High	Vehicle/Item inoperable (loss of primary function).	Or 100% of product may have to be **scrapped**, or vehicle/item repaired in repair department with a repair time greater than one hour.	8
High	Vehicle/Item operable, but at reduced level of performance. **Customer very dissatisfied.**	Or product may have to be sorted and a portion (**less than 100%**) **scrapped**, or vehicle/item repaired in repair department with a repair time between half an hour and one hour.	7
Moderate	Vehicle/Item operable, but Comfort/Convenience item(s) inoperable. **Customer dissatisfied.**	Or a portion (**less than 100%**) of the product may have to be **scrapped** with no sorting, or vehicle/item repaired in repair department with a repair time less than half an hour.	6
Low	Vehicle/Item operable, but Comfort/Convenience item(s) operable at a reduced level of performance. **Customer somewhat dissatisfied.**	Or **100%** of product may have to be **reworked**, or vehicle/item repaired off-line but does not go to the repair department.	5
Very Low	Fit & Finish/Squeak & Rattle item does not conform. Defect noticed by most customers (greater than 75%).	Or the product may have to be sorted, with no scrap, and a portion (**less than 100%**) **reworked**.	4
Minor	Fit & Finish/Squeak & Rattle item does not conform. Defect noticed by 50% of customers.	Or a portion (**less than 100%**) of the product may have to be **reworked** with no scrap, on-line but out-of-station.	3
Very Minor	Fit & Finish/Squeak & Rattle item does not conform. Defect noticed by discriminating customers (less than 25%).	Or a portion (**less than 100%**) of the product may have to be **reworked** with no scrap, on-line but in-station.	2
None	No discernable effect.	Or slight inconvenience to operation or operator, or no effect.	1

Figure A-1: Ranking chart - Severity

Detection	Criteria	A	B	C	Suggested Range of Detection Methods	Ranking
Almost Impossible	Absolute certainty of non-detection.			X	Cannot detect or is not checked.	10
Very Remote	Controls will probably not detect.			X	Control is achieved with indirect or random checks only.	9
Remote	Controls have poor chance of detection.			X	Control is achieved with visual inspection only.	8
Very Low	Controls have poor chance of detection.			X	Control is achieved with double visual inspection only.	7
Low	Controls may detect.		X	X	Control is achieved with charting methods, such as SPC (Statistical Process Control).	6
Moderate	Controls may detect.		X		Control is based on variable gauging after parts have left the station, OR Go/No Go gauging performed on 100% of the parts after the parts have left the station.	5
Moderately High	Controls have a good chance to detect.	X	X		Error detection in subsequent operations, OR gauging performed on setup and first-piece check (for setup causes only).	4
High	Controls have a good chance to detect.	X	X		Error detection in-station, OR error detection in subsequent operations by multiple layers of acceptance: supply, select, install, verify. Can not accept a discrepant part.	3
Very High	Controls almost certain to detect.	X	X		Error detection in-station (automatic gauging with automatic stop feature). Can not pass discrepant part.	2
Very High	Controls certain to detect.	X			Discrepant parts can not be made because item has been error proofed by process/product design.	1

Inspection Types: **A. Error Proofed** **B. Gauging** **C. Manual Inspection**

Figure A-2: Ranking chart - Detection

Occurance – Probability of Failure – Rankings

Probability of Failure	Likely Failure Rates*	Ranking
Very High: Persistent failures	100 per thousand vehicle/items	10
	50 per thousand vehicle/items	9
High: Frequent failures	20 per thousand vehicle/items	8
	10 per thousand vehicle/items	7
Moderate: Occasional failures	5 per thousand vehicle/items	6
	2 per thousand vehicle/items	5
	1 per thousand vehicle/items	4
Low: Relatively few failures	0.5 per thousand vehicle/items	3
	0.1 per thousand vehicle/items	2
Remote: Failure is unlikely	≤ 0.01 per thousand vehicle/items	1

Figure A-3: Ranking chart – Occurrence

Appendix B: One-dimensional model for the determination of the dwell time

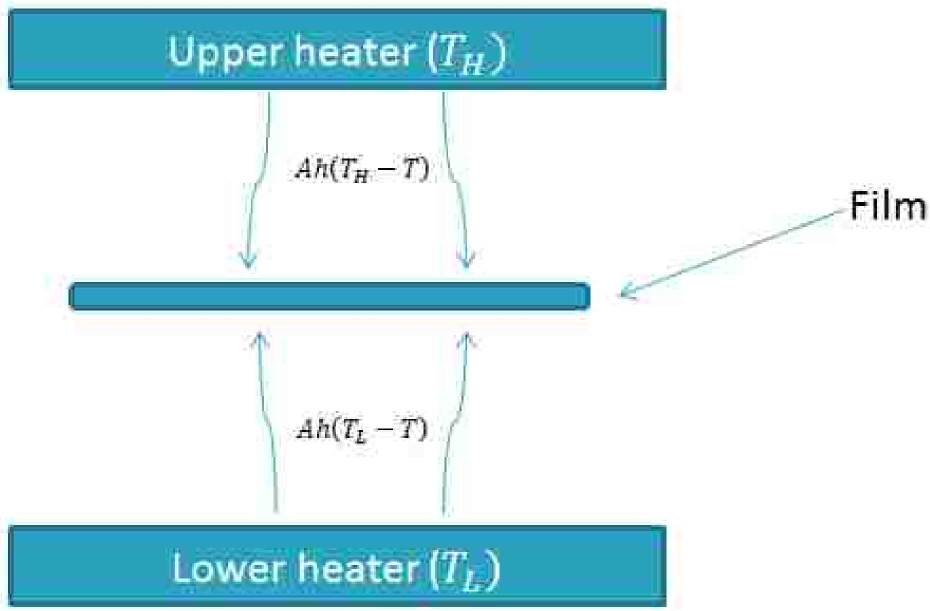

Figure B-1: Schematic of the pre-forming process

$$mc_P \frac{dT}{dt} = Ah[(T_L - T) + (T_H - T)]$$

$$mc_P \frac{dT}{dt} = 2Ah(T_M - T)$$

Where: $$T_M = \frac{T_H + T_L}{2}$$

Solving:

$$\int_{T_i}^{T_f} \frac{dT}{T_M - T} = 2Ah \int_0^{t_D} dt = 2Aht_D$$

$$\ln\left(\frac{T_M - T_f}{T_M - T_i}\right) = -\frac{2Aht_D}{mc_P} = -\frac{2ht_D}{\rho t c_P}$$

$$h = -\frac{\rho t c_P}{2t_D} \ln\left(\frac{T_M - T_f}{T_M - T_i}\right)$$

Different values of *h* have been calculated using as a reference the temperature values of heaters available and the calculated average temperature of the film for a certain dwell time Figure 18. *t* is the thickness of the film, equal to 380 µm, ρ is the density of polycarbonate, equal to 1200 kg/m^3, c_p is the specific heat capacity of polycarbonate, equal to 1200 J/Kg-K. T_i is the initial temperature of the film, assumed to be at room temperature at 20ºC; T_f is the final temperature of the film. T_M is the average temperature of heaters. It was calculated first for the left heaters and second for the right heaters. Corresponding values of T_f were used to calculate *h*, the value of convective heat transfer coefficient for a different set of dwell time values. The calculations were performed twice for each value of dwell time so as to simulate the behavior on both sides of the film, heated differently. Calculations are shown in Table B-1:

Table B-1: values of *h* for each combination of T_M and dwell time.

T_M [ºC]	Dwell time [s]	T_{final} [ºC]	ln [f(T)]	h [W/m^{2}K]
355	8.5	176.4	-0.62898	20.25
355	9.0	184.8	-0.67716	20.59
355	9.5	193.4	-0.72901	20.99
355	10.0	196.0	-0.74523	20.39
300	8.5	161.9	-0.70681	22.75
300	9.0	165.8	-0.73546	22.36
300	9.5	173.0	-0.7906	22.77
300	10.0	176.0	-0.81451	22.28

The average value of *h* from the table is: 21.6 W/m^{2}K.

Appendix C: Analysis of residuals for forming

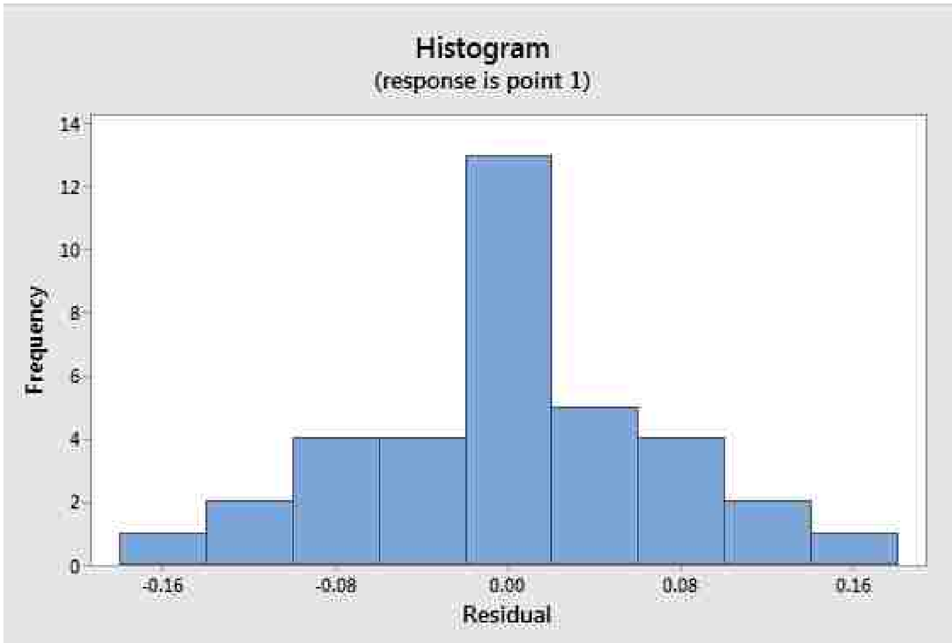

Figure C-1: Histogram of residuals for Point 1 (forming).

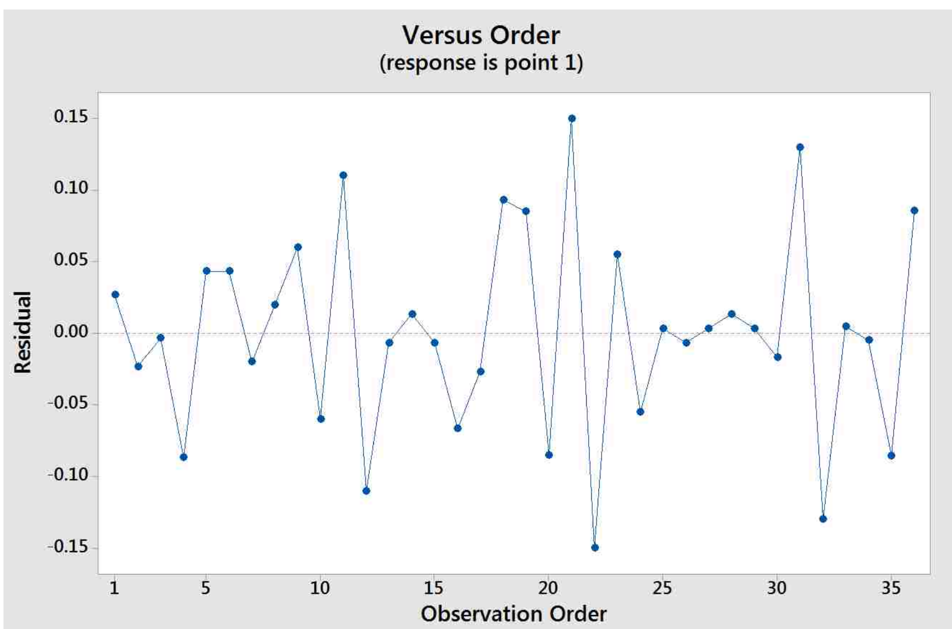

Figure C-2: Graph of the distribution of residuals vs observation order for Point 1 (forming).

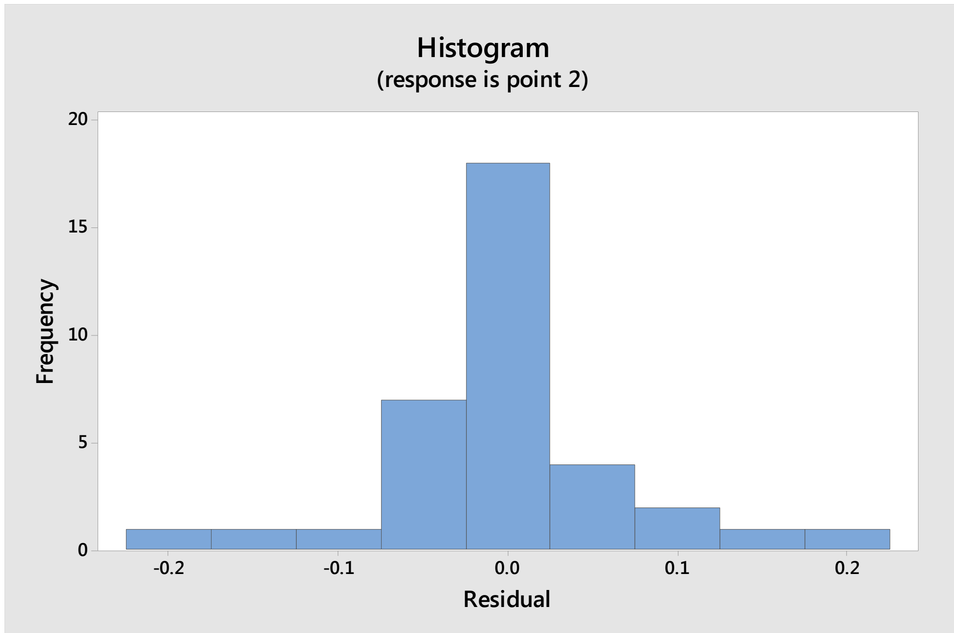

Figure C-3: Histogram of residuals for Point 2 (forming).

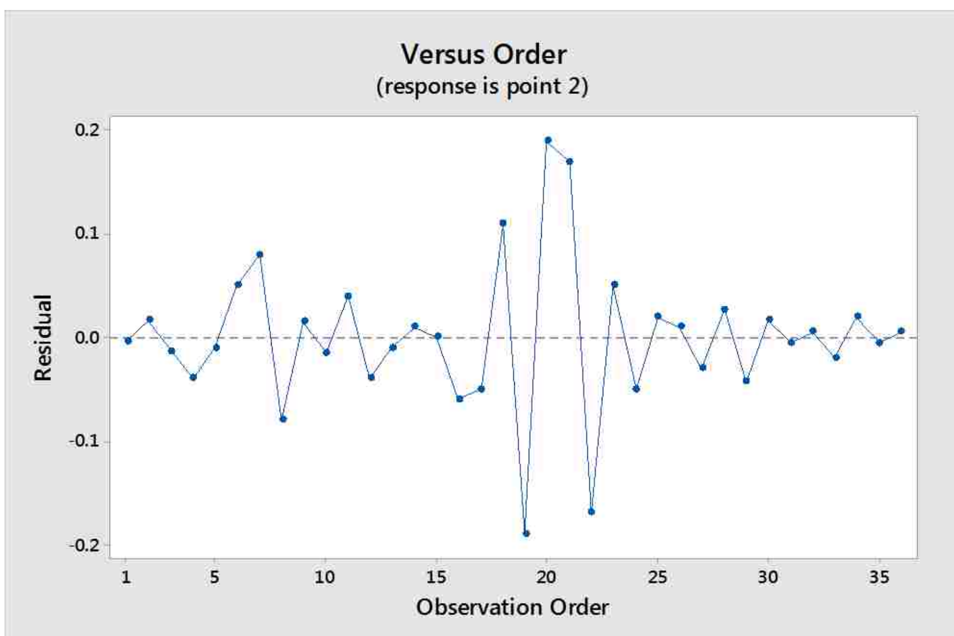

Figure C-4: Graph of the distribution of residuals vs observation order for Point 2 (forming).

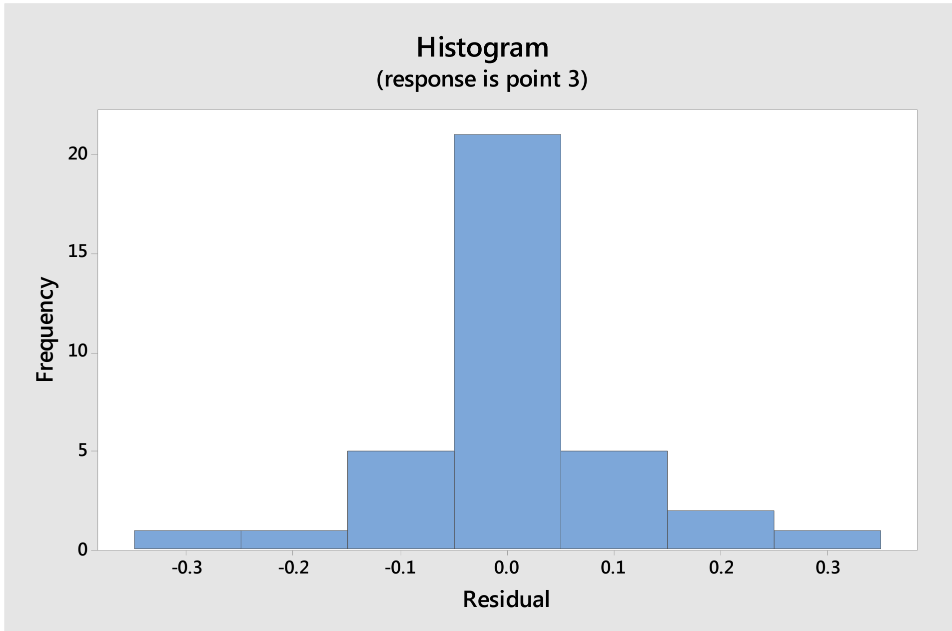

Figure C-5: Histogram of residuals for Point 3 (forming).

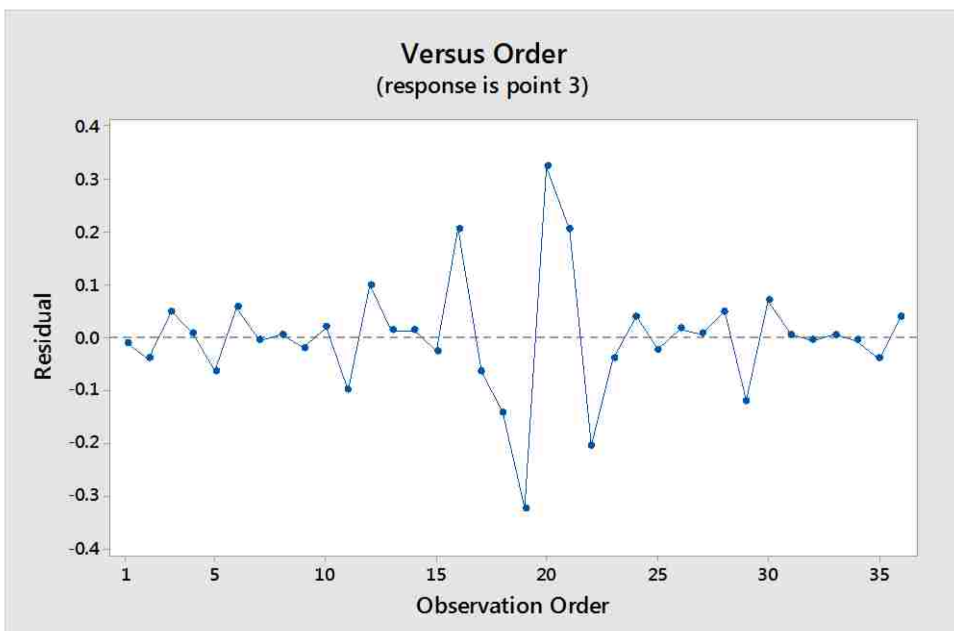

Figure C-6: Graph of the distribution of residuals vs observation order for Point 3 (forming).

Appendix D: Boxplot and confidence interval bars of deviation for forming

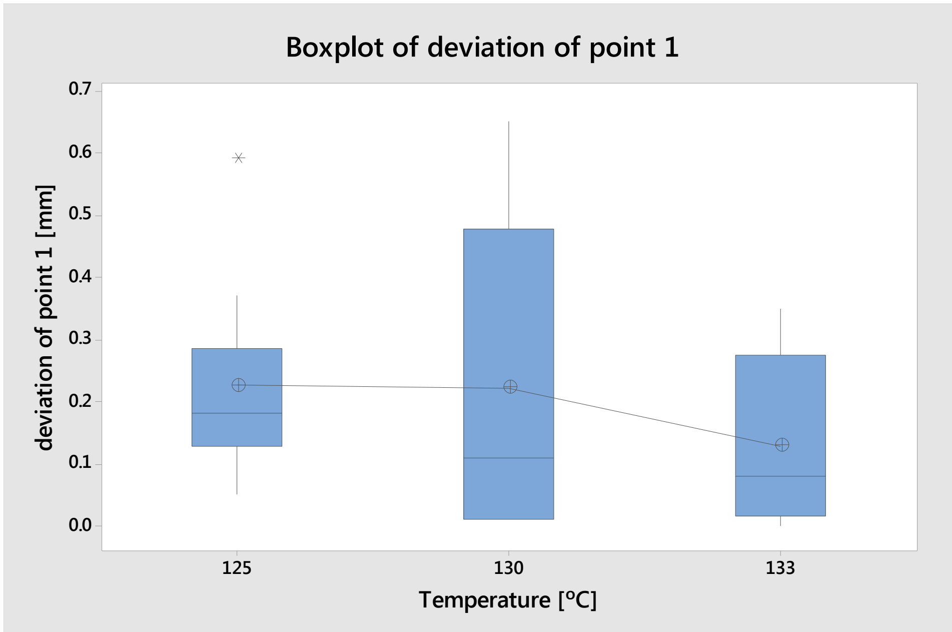

Figure D-1: Boxplot of deviation of Point 1 vs Temperature

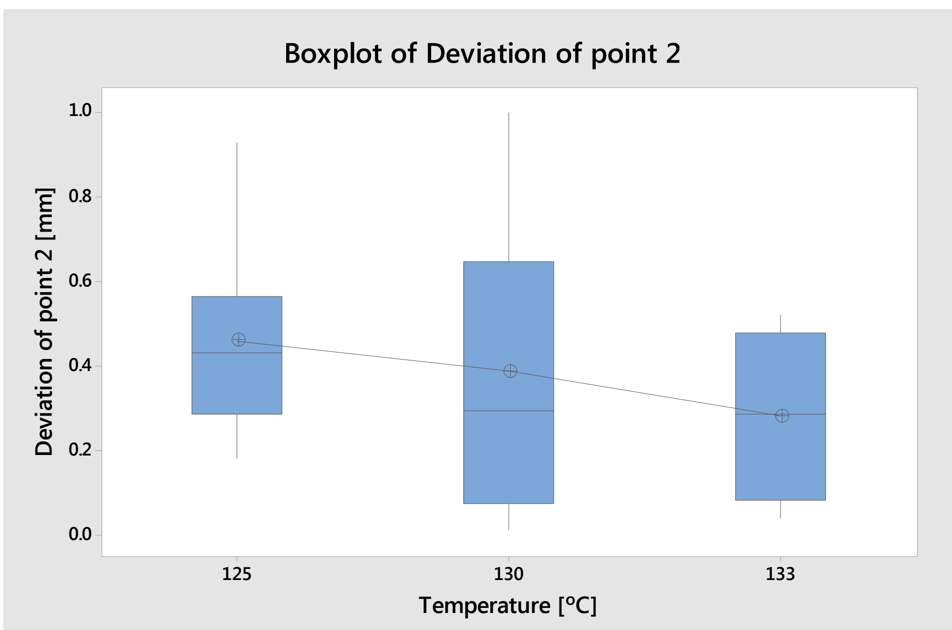

Figure D-2: Boxplot of deviation of Point 2 vs Temperature

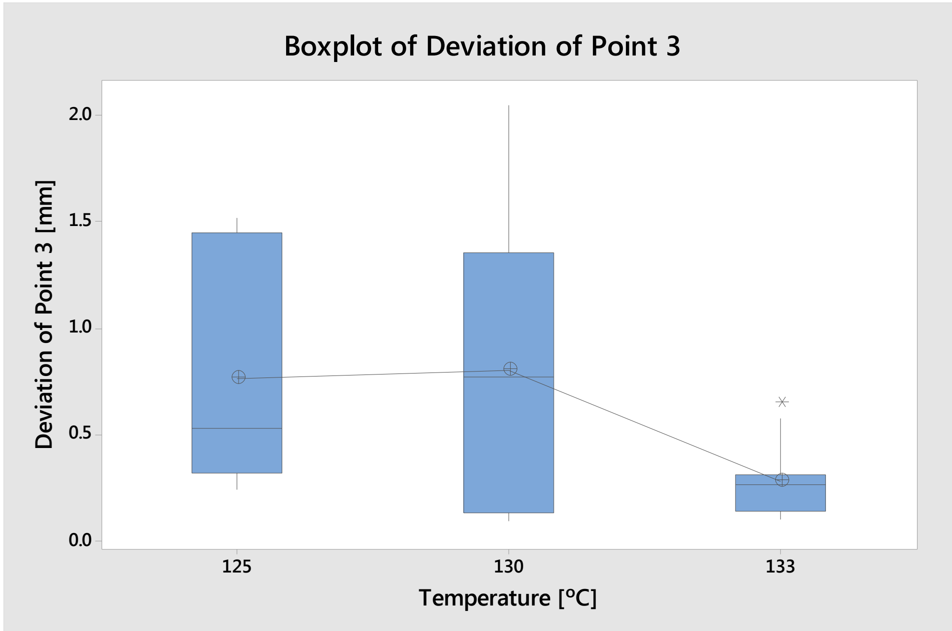

Figure D-3: Boxplot of deviation of Point 3 vs Temperature

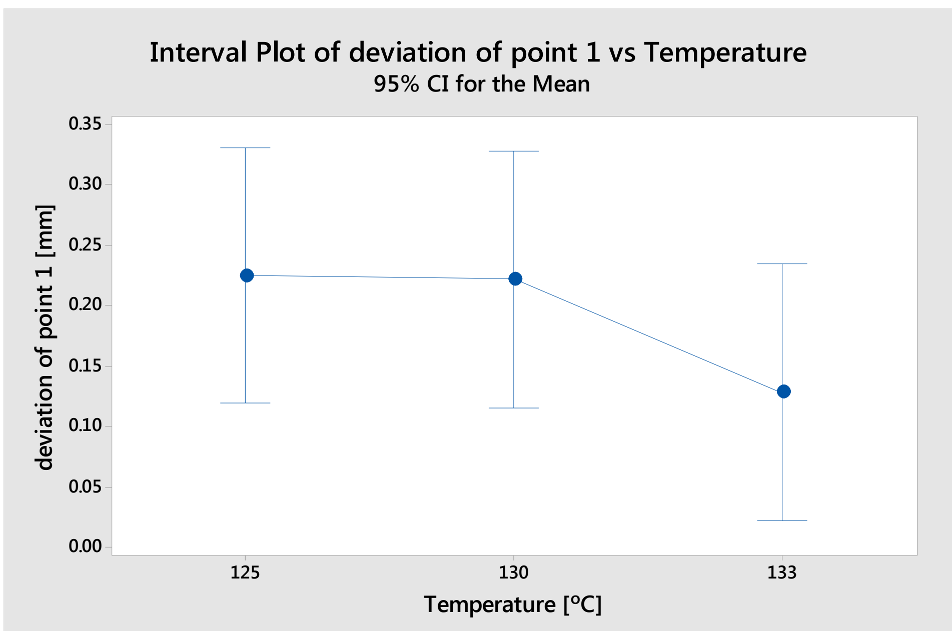

Figure D-4: Confidence Interval bars for deviation of Point 1 vs Temperature

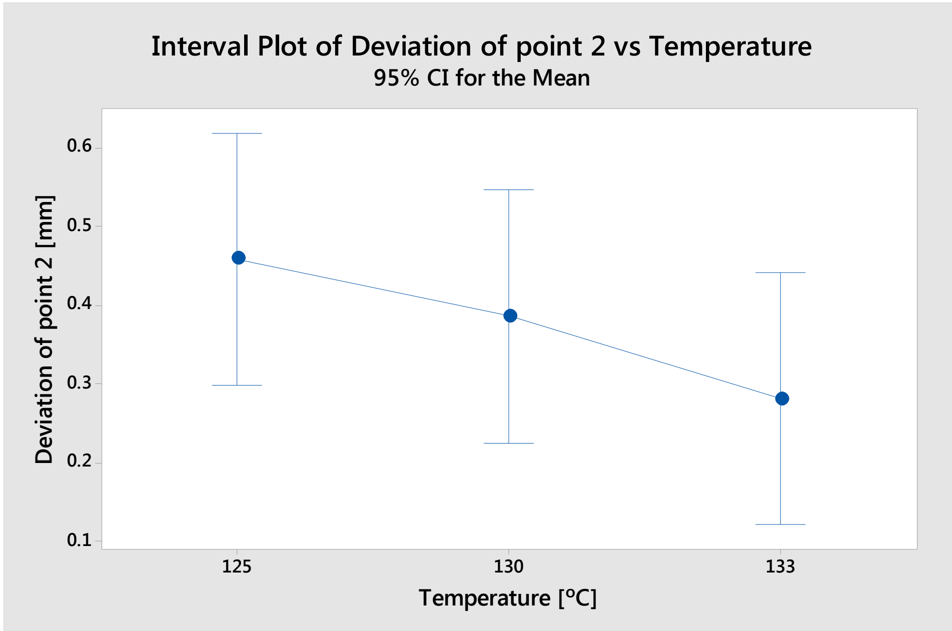

Figure D-5: Confidence Interval bars for deviation of Point 2 vs Temperature

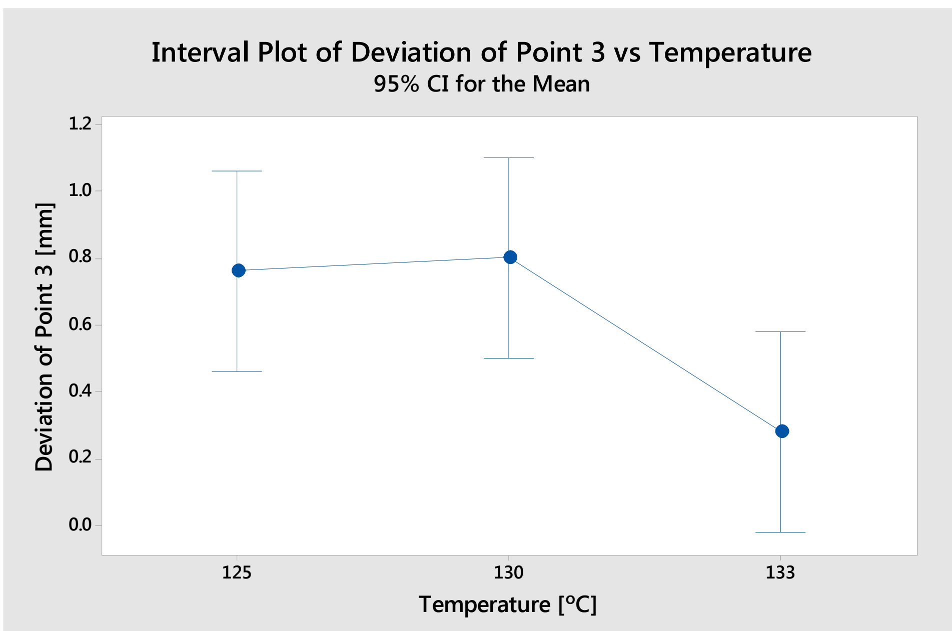

Figure D-6: Confidence Interval bars for deviation of Point 3 vs Temperature

Appendix E: Analysis of residuals for UV curing

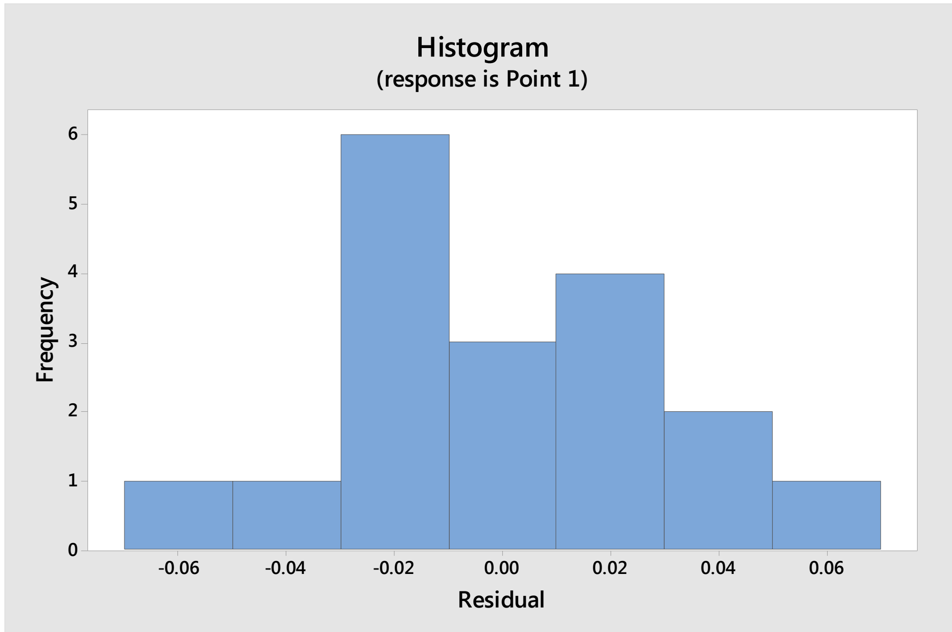

Figure E-1: Histogram of residuals for Point 1 (UV curing).

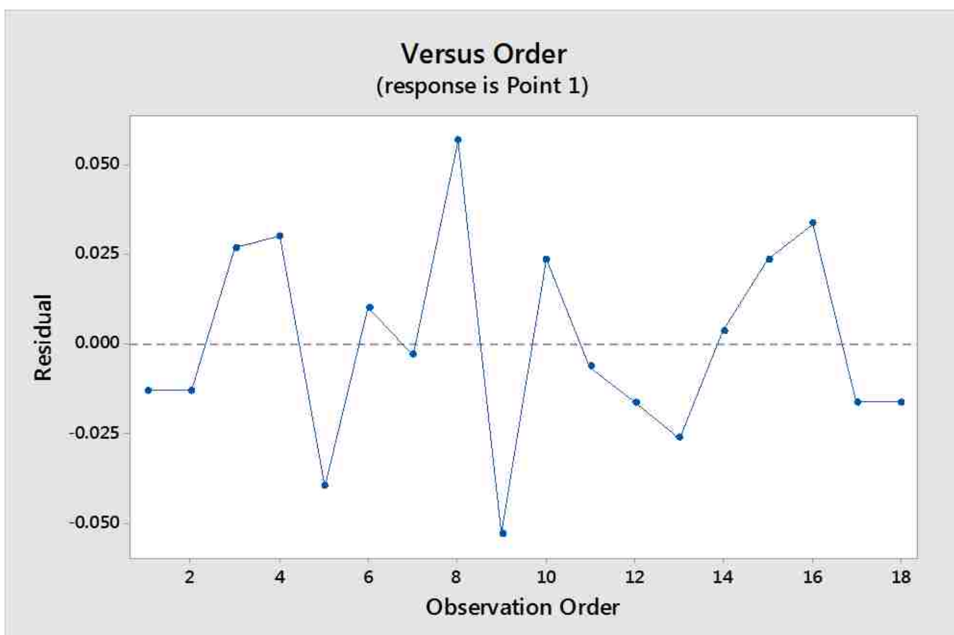

Figure E-2: Graph of the distribution of residuals vs observation order for Point 1 (UV curing).

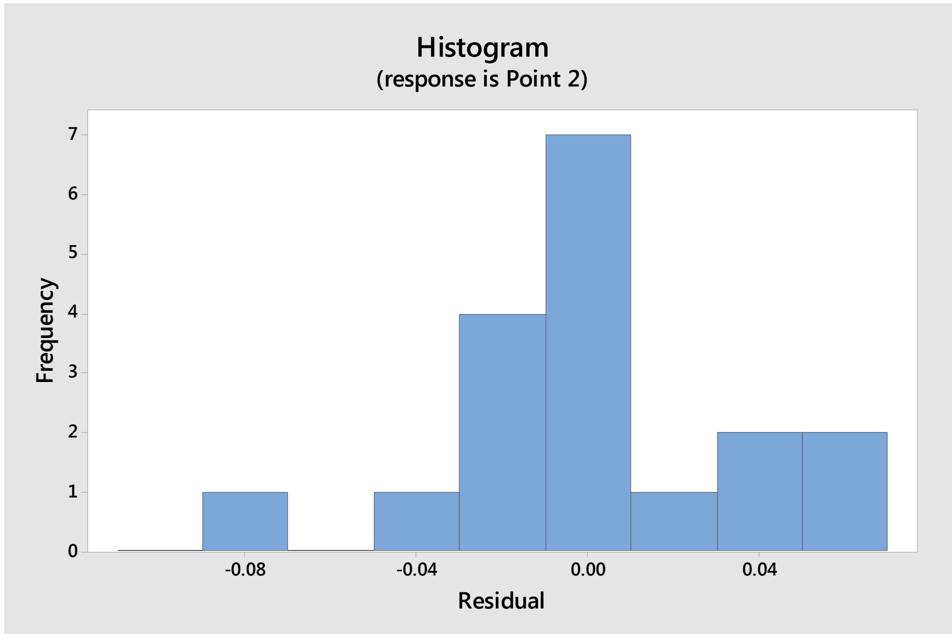

Figure E-3: Histogram of residuals for Point 2 (UV curing).

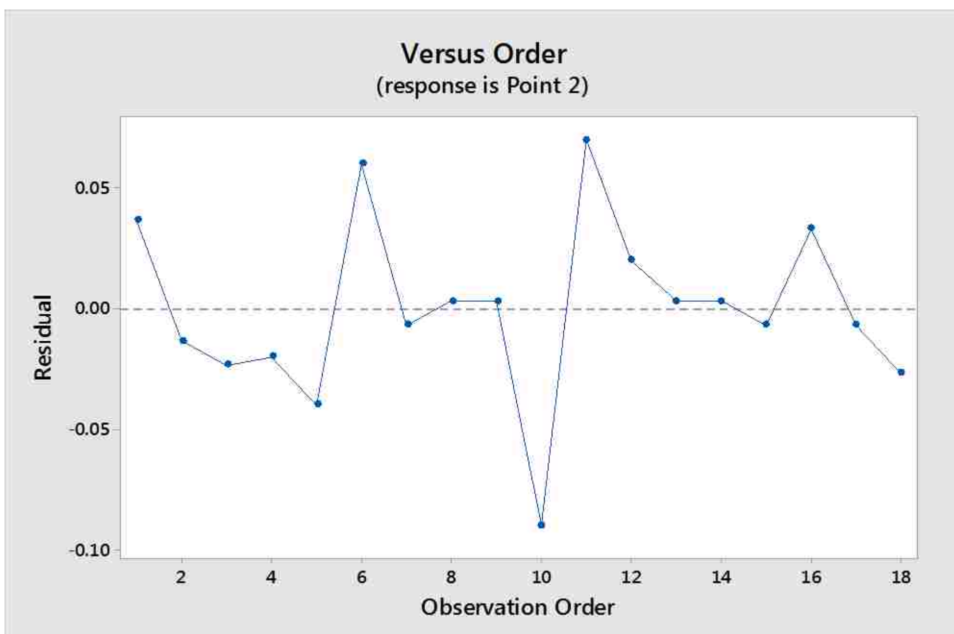

Figure E-4: Graph of the distribution of residuals vs observation order for Point 2 (UV curing).

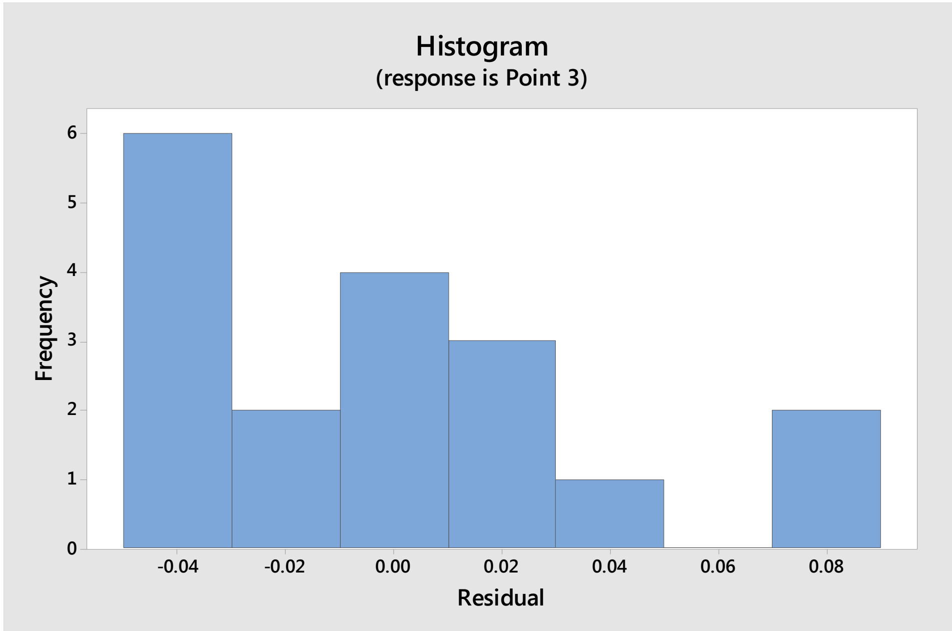

Figure E-5: Histogram of residuals for Point 3 (UV curing).

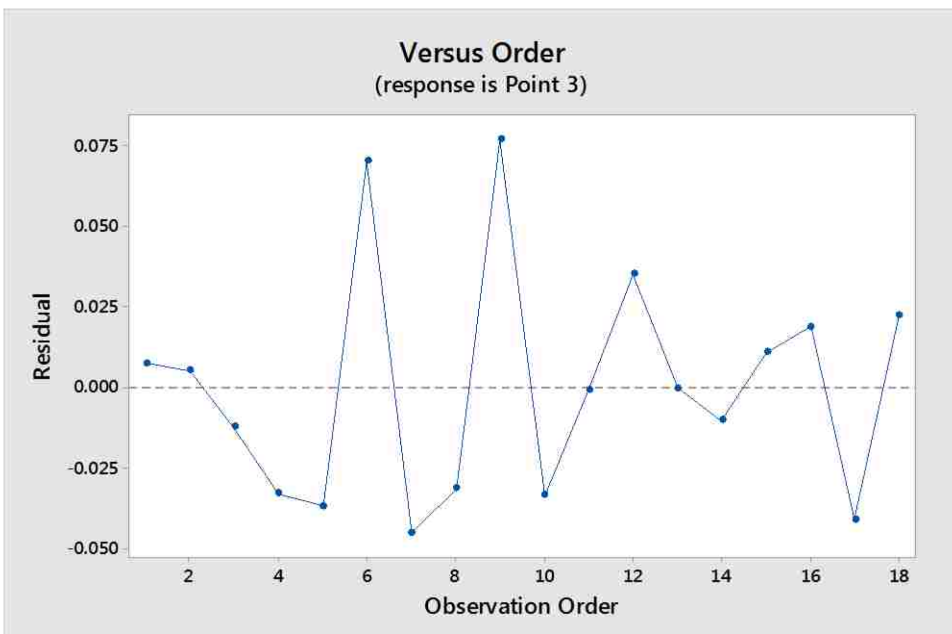

Figure E-6: Graph of the distribution of residuals vs observation order for Point 3 (UV curing).

Appendix F: Boxplot and confidence interval bars of deviation for UV curing

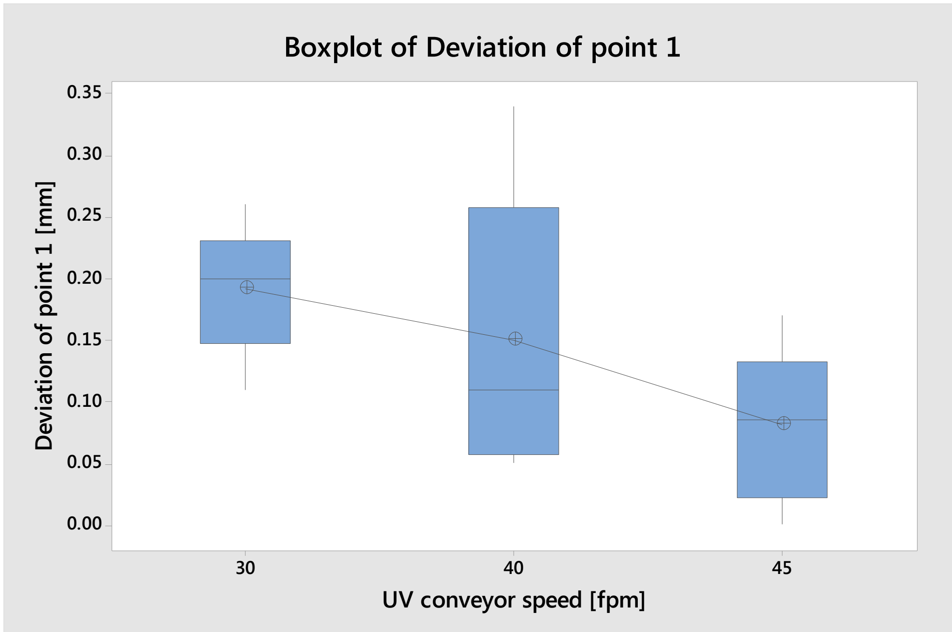

Figure F-1: Boxplot of deviation of Point 1 vs UV conveyor speed.

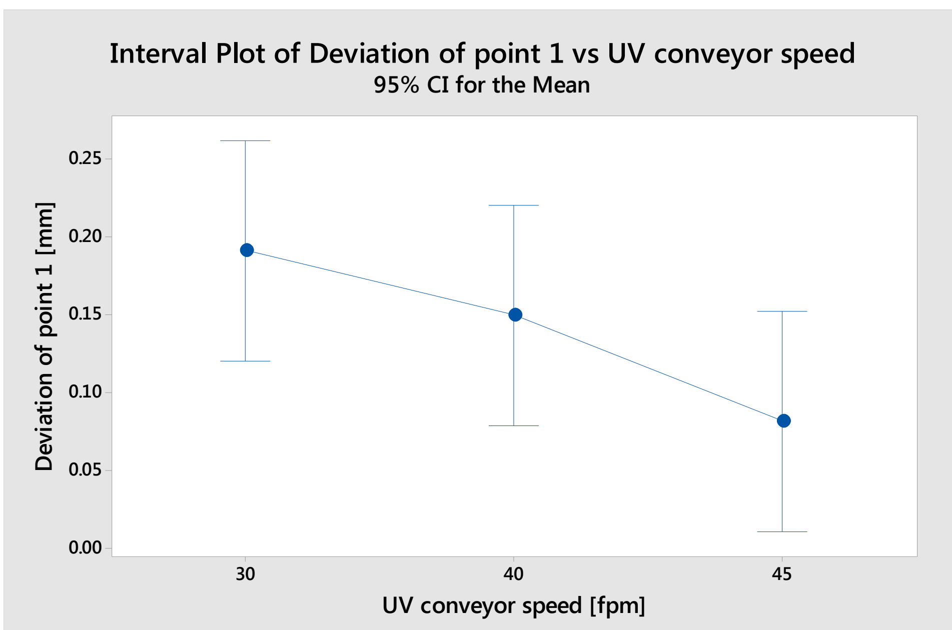

Figure F-2: Confidence interval bars for the deviation of Point 1 versus UV conveyor speed

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