

Thermal and Structural Analysis of the Blow Moulded Air Duct

by

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A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Applied Science
in
Mechanical Engineering

Waterloo, Ontario, Canada, 2013

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

In this study, one of the plastic automotive parts, Air Duct, manufactured through blow moulding process is reviewed and investigated with a practical process point of view using structural mechanics approach.

First, current blow moulding process was examined to find governing factors of the process which can be improved or adjusted for better quality control of finished product. Secondly, numerical analysis was conducted on the post-mould process in order to predict the deformation in the final products with properly assumed initial and boundary conditions.

The simulation results showed that the degree of warpage under current blow moulding process could be predicted at a reasonable accuracy. It was also discovered that the distortions of the holes are strongly dependent on its location and surrounding, and the current cooling method should be improved to improve the quality.

Based on the simulation results and literature survey, a better post-mould cooling method was suggested. In addition, the problem in cooling system was identified, and redesigning scheme was recommended.

Acknowledgements

I would like to thank my supervisor, Dr. HJ Kwon for entrusting me with this project. He guided me in the right direction throughout the project by providing not only his technical knowledge, but also encouragements and mental support throughout my pursuit for MASc degree. He played an impeccable role in the successful completion of this project.

I would also like to acknowledge some of my colleagues. Many thanks go to my lab colleagues, Bonghun Shin and Allan Rogalsky, who enriched my view of the project by suggesting many creative and practical ways of tackling engineering problems. I would like to thank my fellow MASc student, Jiwon Lee, for his help on various CAD modeling that were used for the finite element simulations. I would like to thank Hyunki Bae, who shared with me his valuable industry experience which provided valuable guidance throughout the project. All their help are greatly appreciated, and the completion of this project would have not been possible without them.

This acknowledgement would not be complete if I do not thank my family. I express my greatest thanks to my wife, Jenica Jung, and my children, Hojin Jung and Seoyun Jung, for their unconditional love, understanding, and moral support.

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Chapter 1

Introduction

1.1 Research Initiation

This study was initiated in September 2011 in collaboration with ABC Climate Control Systems Inc. (ABC). ABC is the leading manufacturer of plastic automotive systems and components in Canada. ABC's core business is the design, development, and production of plastic automotive systems and components. Being the second largest plastic auto parts manufacturing company after Magna International Inc. in Canada, their products and services are offered to many auto makers, such as General Motors, Ford, Toyota, etc.

They use blow moulding process to produce "Air Duct" that is the component placed between the air filter and engine intake. In blow moulding process, the consistency of the products' dimensions is a major concern. ABC have found that they have a large number of defective products due to these inconsistencies, and they need an innovative mould design method to prevent such inconsistencies and to reduce the production cost, which has motivated them to launch a collaborative research with MME department at University of Waterloo.

1.2 Background

After a product is manufactured through blow moulding, it is put through a process to be assembled with other products as shown in Fig. 1.1 (left). The products' dimensions should be consistent with other products to fit together. Dimension inconsistency causes the delay in assembly line and the increase of production cost. In many cases, the defective products are unable to be assembled, so consequently they are disposed [1].

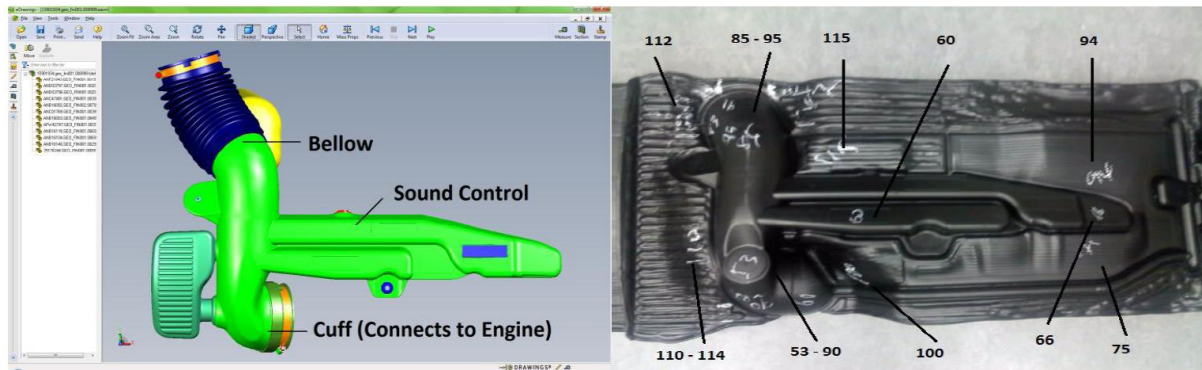


Fig. 1.1. CAD model (left) showing different parts assembled to the product and actual product (right) with different temperatures (°C) [1]

ABC have used exact dimensioned moulds for the blow moulding process, not considering the residual strain left in the product after moulding. Fig. 1 (right) shows the temperature distribution over the product right after the moulding process, which was measured before the project began. A collection of many factors caused dimension inconsistency problem and warping. Especially the round sections deform a lot to become oval, so frequently they cannot be assembled to other products in the subsequent process. Therefore, ABC has concluded that they had to redesign and optimize the moulds for the final product to have the correct dimensions and round sections.

Since the mould is extremely expensive and complicated, no errors are allowed. Therefore, they looked for an external help to develop an innovative method of determining how the moulds should be reshaped considering the thermal shrinkage.

1.3 Objectives

The main objective of this project is to investigate the moulding and related processes to identify factors which can cause defective products and to develop a method to accurately design the moulds, taking account of the thermal deformation during/after blow moulding process.

1.4 Approaches

To achieve the objective of the project, approaches from various kinds of points of view have been employed. First, related literatures were reviewed to find possible or potential factor which might lead to defective product. Second, current moulding process was carefully investigated to identify the parameters which could influence the quality of the products, including human factors and post-mould cooling methods. Last, finite element analysis (FEA) model of the product has been developed to simulate deformation after the moulding process considering deformation caused by heat transfer in the current product design. The schedule and major milestones are shown in Fig. 1.2.

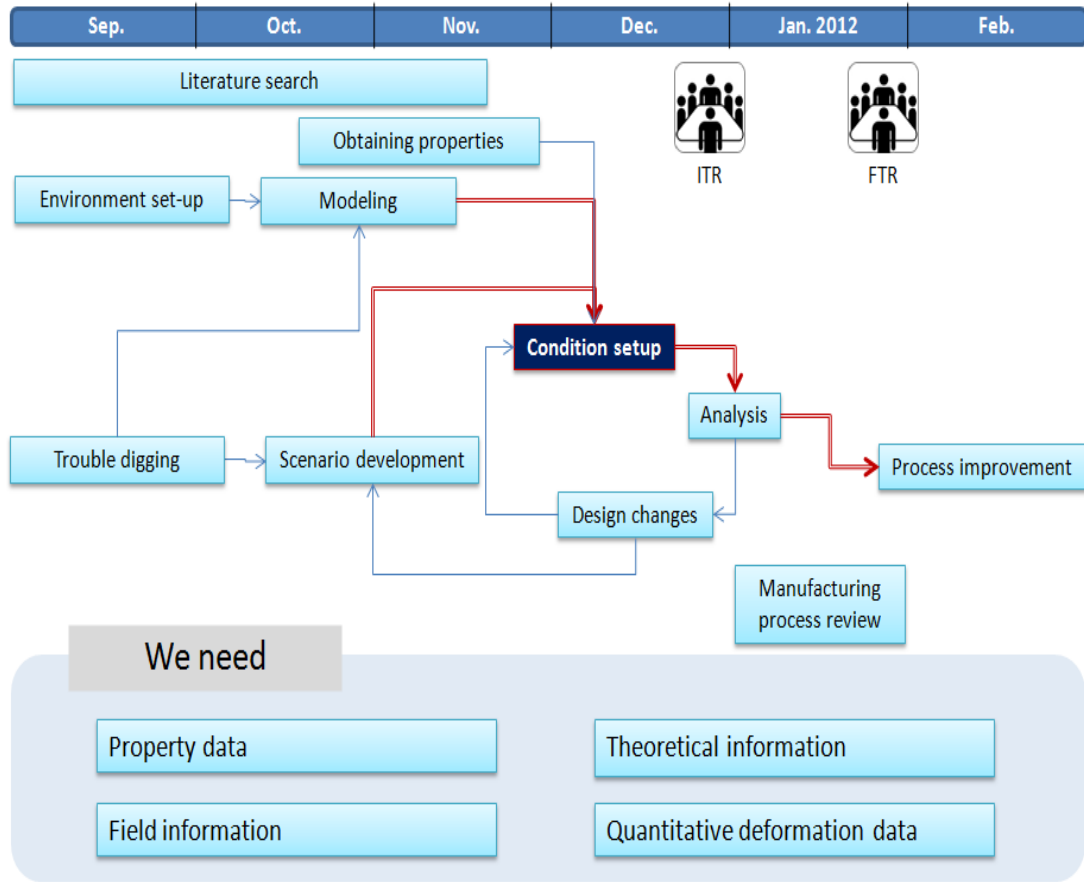


Figure 1.2. Project schedule and procedure

Chapter 2

Theoretical Background

2.1 Introduction

The considered product has a complicated shape having two open ends and a few holes on the surface, so it is very difficult to design, mesh, and analyze with engineering software. Especially, applying thermal analysis to the system requires many properties of the material and of interaction between the product and the air (a coolant). Moreover, the material, polypropylene, itself demonstrates extremely complicated mechanical and thermal behavior depending on various conditions.

Therefore, a wide variety of ground knowledge and supporting data are required to obtain the planned results. In this chapter, blow moulding process, including the types and cooling methods, and the material properties of polypropylene will be studied to find the available measures to resolve the defective product issue.

2.2 Blow Moulding

2.2.1 Blow Moulding

Traditionally very small portion of polypropylene has been processed by blow moulding. The combination of economy and good properties offered by polypropylene leads to its widespread use in films, fibers, and injection moulding. Polypropylene was not commercialized until the mid 1950s, so blow moulding technology was largely optimized on the requirements for polyethylene. Blow moulding is a relatively low pressure process, using less than 1% of the pressure levels employed in injection moulding. This requires a lot melt viscosity, produced by high shear rates and temperatures. The difficulty in polypropylene processing is that its viscosity is far more sensitive to temperature and shear rate than is the case with polyethylene, so there are problems in working polypropylene using the equipment designed for polyethylene [2].

Recently machinery and technology developed specifically for polypropylene, and developments in the polymer properties have made polypropylene a suitable material for the process. Also advances in polymerization technology have made it possible to produce grades with melt strengths and shear

dependencies that are more tolerant of the blow moulding process. Consequently, blow moulded polypropylene is one of the fast growing sectors in plastic industries. Its market share is currently small, but its growth rate is very high.

2.2.2 Blow moulding process

Blow moulding is a manufacturing process by which hollow plastic parts are formed. The process is discontinuous or batchwise, involving a sequence of operations which culminates in the production of a moulding. This sequence of cycle is repeated automatically or semi-automatically to produce a stream of moulded parts.

The blow moulded parts are formed in a mould that defines the external shape. As the name implies, the inner shape is defined by the pressure of fluid (normally compressed air). In this respect, blow moulding is quite different from many moulding processes where both inner and outer forms are determined by moulds. The major advantage of blow moulding is that the inner form is virtually free of constraints because there is no core to extract.

Blow moulding is now highly developed and has many variant forms. At its most basic, the process involves melt processing thermoplastic into a tube that is referred to as a parison. Parison is clamped between the halves of a cooled mould, so that the open top and bottom ends of the parison are trapped, compressed and sealed by the mould faces. A blowing tube is also trapped in one of the parison ends, creating a channel through which air pressure is introduced within the sealed parison. Air pressure causes the parison to expand, so that it takes up the form of the mould cavities. Contact with the cooled mould chills the thermoplastic to its solid state, so the form is retained after the mould is opened and the part removed [2].

Blow moulding can be categorized into three groups: injection stretch moulding, injection blow moulding, and extrusion [2].

2.2.3 Injection blow moulding

The injection blow moulding (IBM) is used to produce hollow glass and plastic objects in large quantities. In the IBM process, the polymer is injection moulded onto a core pin; then the core pin

rotates to a blow moulding station to be inflated and cooled. Although IBM is the least common among the three blow moulding processes, it is typically used to make small medical and single serve bottles. The process is divided into three steps: injection, blowing and ejection [2].

The injection blow moulding machine has an extruder barrel and screw assembly which melts the polymer. The molten polymer goes into a hot runner manifold where it is injected through nozzles into a hollow heated preform mould. The preform mould forms the external shape and is clamped around the core rod which forms the internal shape of the preform. The preform consists of a fully formed bottle neck with a thick tube of polymer attached, which will form the body.

The preform mould opens, and the core rod rotates and is clamped into the hollow chilled mould. The core rod opens to allow compressed air into the preform, which inflates it to the finished article shape.

After a cooling period the blow mould opens and the core rod rotates to the ejection position. The finished article is stripped off the core rod. The preform and blow mould can have many cavities, typically three to sixteen depending on the article size and the required output. There are three sets of core rods, which allow concurrent preform injection, blow moulding and ejection

2.2.4 Extrusion Blow Moulding Process

Various plastic parts are manufactured by extrusion blow moulding, from backpack frame and bottles to odd shaped overflow reservoirs used by automobiles. Plastic is heated in an extruder until the plastic becomes a fluid. This plastic fluid is extruded through a diehead to form a tube, called a parison. A mould containing a cavity is closed around the parison and air is blown inside the parison. The air pressure expands the parison against the cavity wall. The plastic is cooled by the mould. The air pressure is released. The mould opens and the moulded part comes out [2]. The major components of the extruder are hopper, barrel, barrel heaters, cooling system, and screw (Fig. 2.1). The hopper contains the raw plastic pellets of granules, and the barrel is the place where plastic is heated and pressurized. The barrel heaters melt the plastic before start-up. The cooling system is used to cool the plastic when excessive heating arises, and the screw rotates to melt, pressurize and transport the plastic forward.

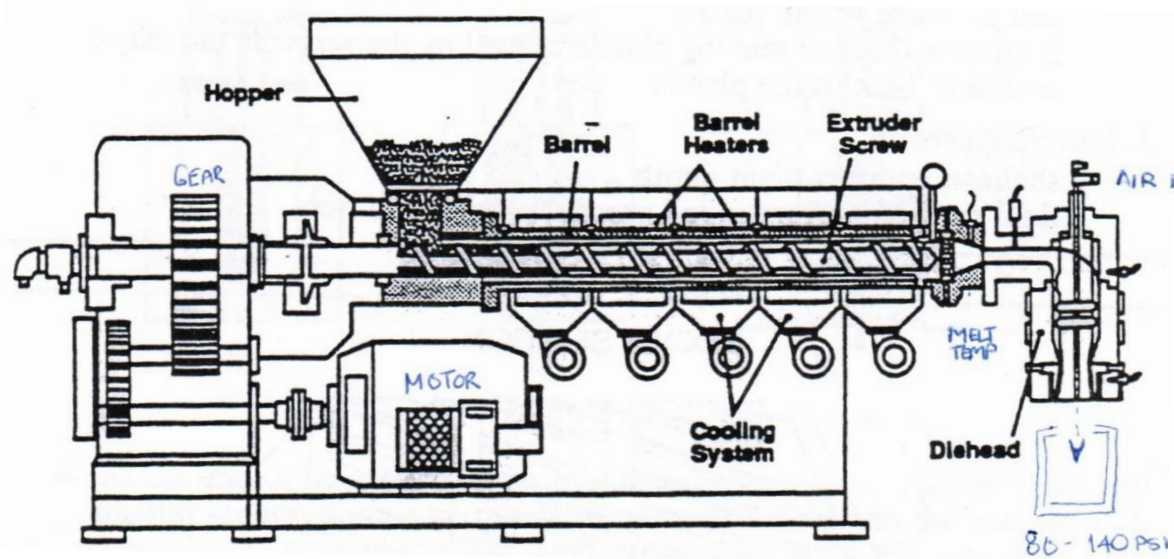


Figure 2.1. Cutaway of Extruder [3]

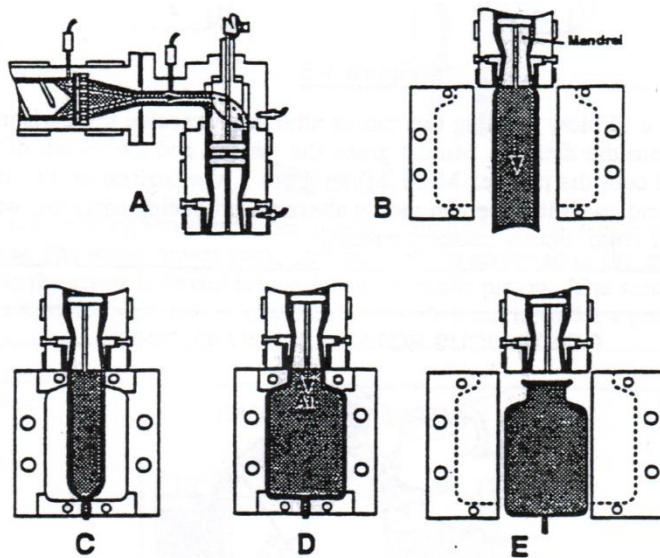


Figure 2.2. Plastic flow through the die: (a) At the end of the extruder, the plastic flows through the screen pack. Next, the plastic flows into the die body and around a center post called a mandrel. (b) The mandrel forms the flowing plastic into the hollow parison. (c) When the parison reaches its proper length the mould closes. (d) Air is then blown inside the parison from the top or bottom. The pressure of the air holds the plastic against the side walls of the cavity. The plastic then cools and solidifies. (e) When the plastic is cool enough to hold its shape [3]

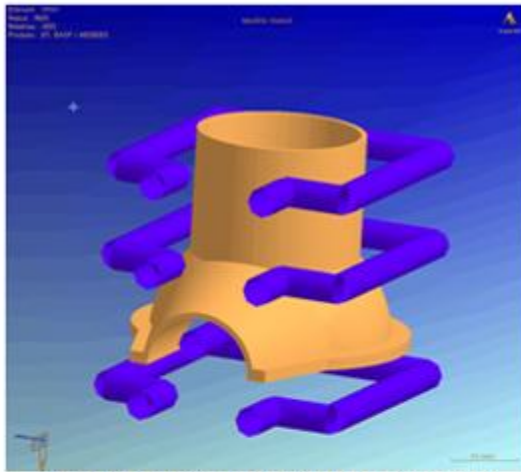
By the end of the extruder screw, plastic is thoroughly mixed at a uniform temperature and the desired pressure for flow through the die. Then, the melt goes into the die, and it is formed inside the die (Fig. 2.2).

2.2.5 Cooling system

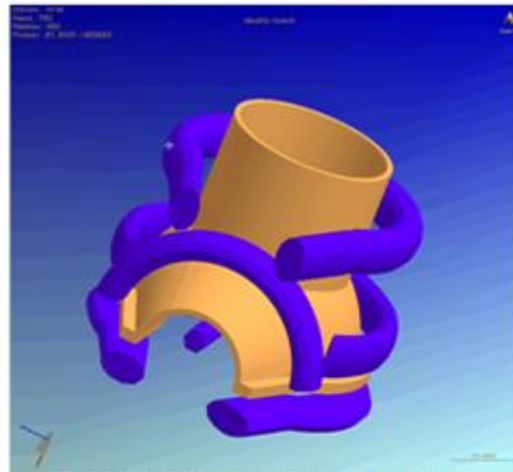
Cooling is one of the most important factors that influence the quality of blow moulded products. The temperature should be as uniform as possible all over the part. The temperature uniformity is a critical factor for the performance of blow moulding. Heat should be taken away from the material until the plastic becomes thermally stable, which enables proper demoulding. The time needed to accomplish this is called cooling time [4].

Cooling system has to be designed considering optimum heat transfer between the melted plastic and the moulds. This is achieved by creating several paths inside the moulds and flowing cooling fluid (i.e. water) to circulate and get rid of the excess heat from the plastic. The methods used for producing these holes rely on the conventional machining process such as straight drilling, which is incapable of producing complicated counter-like channels or anything vaguely in 3D space [2, 4, 6].

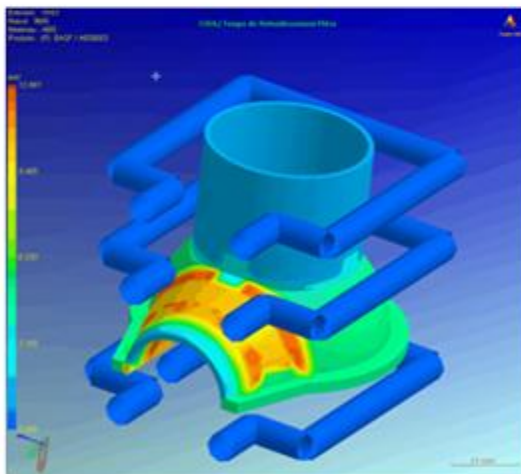
An alternative cooling method that fits to the shape of the cavity and core of the mould can provide better heat transfer in injection moulding process, and hence result in optimum cycle time. This alternative method uses contour-like channels, generally, of different cross-section, fitting very close to the surface of the moulds to increase the heat absorption away from the molten plastic, which ensures that the moulded part is cooled uniformly as well (Fig. 2.3). Nowadays, more efficient cooling systems are being designed and applied in the mould with more complex layout and cross-sections as prototyping technology (e.g. Direct Metal Deposition, Selective Laser Melting) and many advanced computer aided engineering (CAE) software are developed.



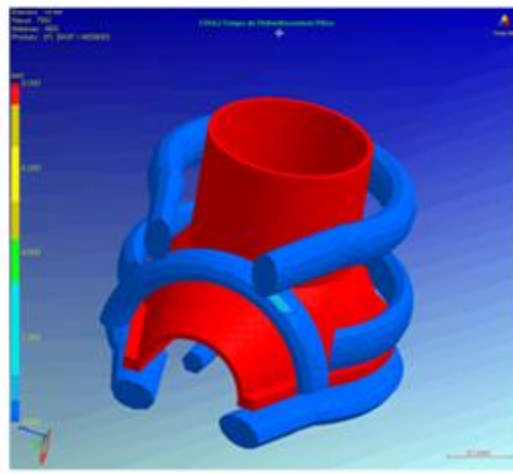
Part and traditional Cooling channels geometries.



Part and Laser Building Mould Manufacturing Cooling channels geometries (Conform Cooling).



Part cooling time : 12 seconds.



Part cooling time: 8 seconds.

(a)

(b)

Figure 2.3. (a) Traditional and (b) conformal cooling systems [4]

Many researches on cooling systems for injection moulding have been performed to improve the efficiency of cooling. A.B.M. Saifullah [4] and K. M. Au [5] presented a scaffolding architecture for conformal cooling design for rapid plastic injection moulding. Tang et. al. [6] have developed a methodology for optimal design of cooling channels for multi-cavity injection mould in terms of

channel size, location and coolant flow rate using FEA for solving the transient heat transfer problem. Li [6] has described a feature based design synthesis approach to develop cooling system design by first decomposing complex part shape into simpler shape elements and then developing an algorithm to generate cooling channels. Lam et. al. [7] have proposed an method to optimize cooling channel design and process parameter selection simultaneously using genetic algorithm. Research in conformal cooling system has mainly focused on fabrication and testing of prototype conformal cooling moulds using freeform fabrication techniques. Sach et al. [8] described the production of injection moulding tooling with conformal cooling channels using the Three Dimensional Printing (3DP) process. They compared the effectiveness of conformal and conventional cooling by experimental testing and also by finite difference approach. They concluded that the conformal mould was able to maintain a more uniform temperature. Xu et. al. [9] have studied fabrication of conformal cooling channels using 3DP and proposed a systematic modular approach to design of conformal cooling channels.

2.3 Polypropylene

2.3.1 Polymers

A polymer is a chemical compound or mixture of compounds consisting of repeating structural units created through a process of polymerization [10]. The terms polymer and polymeric material encompass very large, broad classes of compounds, both natural and synthetic. Because of the extraordinary range of properties of polymeric materials, they play essential and ubiquitous roles in everyday life, from those of familiar synthetic plastics and other materials of day-to-day work and home life, to the natural biopolymers that are fundamental to biological structure and function [11].

An important micro-structural feature of a polymer is its architecture, which relates to the way branch points lead to a deviation from a simple linear chain [12]. A branched polymer molecule comprise a main chain with one or more substituent side chains or branches. Types of branched polymers include star polymers, comb polymers, brush polymers, etc (Fig. 2.3) [11]. There exist also two-dimensional polymers which are composed of topologically planar units. A polymer's architecture affects many of its physical properties including from melt viscosity to glass transition temperature and the size of individual polymer coils in solution.

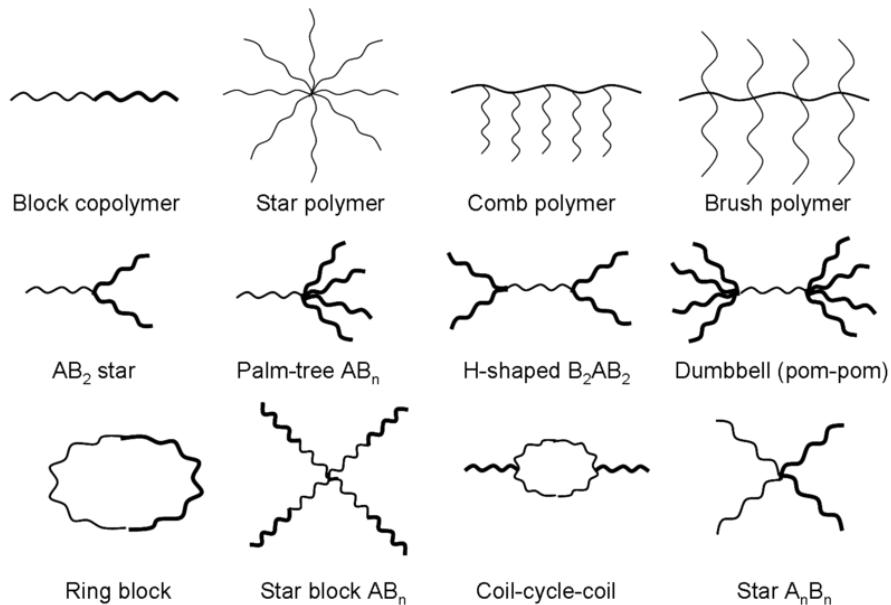


Figure 2.3 Various polymer architectures [11]

As mentioned above, polymers' physical properties significantly depend on their micro-structure. The tensile strength is very important in applications that rely upon a polymer's physical strength or durability. In general, tensile strength increases with polymer chain length and cross-linking of polymer chains. Similarly, Young's Modulus which is highly relevant in polymer applications is strongly dependent on temperature.

2.3.2 Glass Transition Temperature

The term melting point (T_m) suggests not only a solid-liquid phase transition but a transition from a crystalline or semi-crystalline phase to a solid amorphous phase [14]. Among synthetic polymers, crystalline melting is discussed only with regards to thermoplastics, as thermosetting polymers will decompose at high temperatures rather than melt. A parameter of particular interest in synthetic polymer manufacturing is the glass transition temperature (T_g), which describes the temperature at

which amorphous polymers undergo a transition from a viscous amorphous liquid, to a brittle, glassy amorphous solid.

Many researches have been performed in order to determine T_g . One of them is using generalized expressions for diffusion and viscous flow of polymers by assuming that T_g occurs at a universal value of the available free volume in a material. T_g can be modeled as following by normalization using the variable, X (external degree of freedom per polymer molecule) [14],

$$p(V, T,) = \left(\frac{\partial \ln Q}{\partial V} \right)_T \quad (1)$$

$$T^* = \frac{s\varepsilon^*}{2kv^*c} \quad (2)$$

$$T_{gX}^* = \frac{s_m \varepsilon_{mm}^*}{2kv^*c_m} \frac{\left[1 + (s_e / s_m)(\varepsilon_{ee}^* / \varepsilon_{mm}^*)^{1/2} \frac{1}{X} \right]^2}{\left[1 + (c_e / c_m)(1/X) \right] \left[1 + (s_e / s_m)(1/X) \right]} \quad (3)$$

$$\frac{T_{gX}^*}{T_{g\infty}^*} = \frac{T_{gX}}{T_{g\infty}} = \frac{s_m \varepsilon_{mm}^*}{2kv^*c_m} \frac{\left[1 + (s_e / s_m)(\varepsilon_{ee}^* / \varepsilon_{mm}^*)^{1/2} \frac{1}{X} \right]^2}{\left[1 + (c_e / c_m) \frac{1}{X} \right] \left[1 + (s_e / s_m) \frac{1}{X} \right]} \quad (4)$$

$$\frac{T_{gX}}{T_{g\infty}} = 1 - \left(\frac{c_e}{c_m} + \frac{s_e}{s_m} \left(1 - 2 \left(\frac{\varepsilon_{ee}^*}{\varepsilon_{mm}^*} \right) \right)^{1/2} \right) \frac{1}{X} \quad (5)$$

Table 2.1. Experimental $T_g - 1/X$ Values at High Molecular Weight [13]

Polymer	T_g (K)	$\frac{C_e}{C_m} + \frac{S_e}{S_m} \left[1 - 2 \left(\frac{\epsilon_{ee}^*}{\epsilon_{mm}^*} \right)^{1/2} \right]$	Sites/monomer	Reference
Polystyrene	373	5.16	2	12
Poly(α -methylstyrene)	446	13.67	2	25
Poly(propylene oxide)	213	0.00	3	13
Poly(butylene oxide)	213	0.00	4	13



Figure 2.4. DSCs of TA instruments [14]

The glass transition temperature (T_g) is generally measured by Differential Scanning Calorimetry (DSC) (Fig. 2.4) which is a device which measures the temperatures and heat flows associated with transitions in materials as a function of time and temperature. DSC is widely used to determine the thermal transitions of polymeric materials. The observed thermal transitions can be used to compare materials. However it should be noted that the transitions do not uniquely identify composition. The percent crystalline content of a polymer can be estimated from the crystallization peaks of the DSC graph as reference heats of fusion can be found in the literature [15]. DSC can also be used to study thermal degradation of polymers using an approach such as Oxidative Onset Temperature/Time (OOT).

The operational procedures of typical DSC devices follow the applicable standards such as ASTM E967. The calibration materials can be chosen among the materials listed in the standards. The typical procedures are: (1) Select two calibration materials with melting temperatures, one above and one below the temperature range of interest, (2) Determine the apparent transition temperature for each calibration material, (3) Place a 5 to 15 mg into a specimen holder, (4) Load the specimen into the instrument chamber, (5) Purge the chamber with nitrogen (or other inert gas) at a flow rate of 10 to 50 cm³/min, (6) Heat or cool the calibration material rapidly to 30 °C below the calibration temperature and allow to stabilize, (7) Heat the calibration material at 10 °C/min through the transition until baseline is reestablished above the transition, and (8) From the resultant curve, measure the temperatures for the desired points [16].

Polymers for injection molding can be classified as semi-crystalline or amorphous. Both have complex thermo-rheological behavior which has a bearing on the molding process. Thermoplastics typically have a viscosity that decreases with shear and increasing temperature while increasing with pressure. Their thermal properties are temperature dependent and may depend on the state of stress [17]. In the case of semi-crystalline materials, properties also depend on the rate of temperature change. In injection molding simulation, it is needed to incorporate an equation of state to calculate density variation as a function of temperature and pressure. The equation of state relates the material's specific volume (inverse of density), pressure and temperature. This is referred to as the material's PVT (Pressure-Volume-Temperature) characteristic. It is very complex and depends on the type of material.

Polymer PVT data are very important in their value in material science. The excess usage of PVT data can be summarized in several major areas [18, 19]: (1) Prediction of polymer-polymer miscibility, (2) Prediction of service performance and service life of polymeric materials and components on the basis of free volume concepts, (3) Correlation of the reducing parameters of equations of state (EOS) with molecular structures, (4) Evaluation of start and progress of chemical reactions in polymer melts, (5) Investigation of the nature of phase transitions, and (6) Optimizing of processing.

Many polymers' properties are necessary in order to simulate an injection moulding of polymers such as PVT, thermal conductivity, heat capacity, and viscosity over wide range of temperatures and pressures. It is believed that the PVT is one of important properties to predict final shape and size of

moulded polymer products. So, many researches have been performed to obtain PVT correlation for various polymers through many experiments and theoretical approaches (Fig. 2.5). However, it should be noted that the data for the same material do not agree with each other because of the difference in methods and samples used in the experiments.

Degradation is also important, which means a change in the properties such as tensile strength, shape, or molecular weight by the influence of environmental factors [20], such as light, heat, etc. It is often due to the scission of polymer chain bonds via hydrolysis, leading to a decrease in the molecular mass of the polymer. Such changes are mostly undesirable because it causes shape change, which can lead to warpage, even though the change generally occurs over a long period of time (decades).

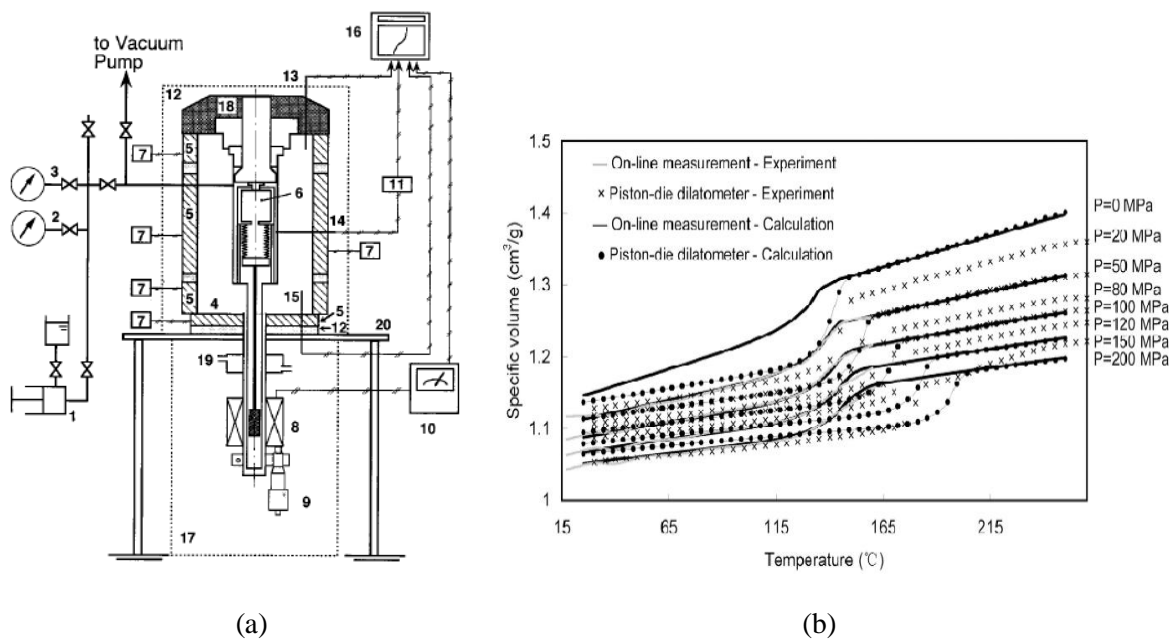


Figure 2.5. Examples of (a) Schematic diagram of the PVT apparatus and (b) correlation PVT diagrams of PP [21]

2.3.3 Crystallization

Many crystallizing thermoplastics show a remarkable change in mechanical properties during post-moulding aging at room temperature [22]. Although this phenomenon is well known, it is not properly understood. It is natural to look for morphological or structural changes occurring on aging that correlates with changes in mechanical behavior, and this is the approach used by many researchers in a study of polypropylene. They have attributed the observed differences in mechanical behavior to changes occurring in the amorphous phase to which their methods of structural and morphological characterization would be relatively insensitive.

Many researches have been performed on morphology of injection-molded polymers [23]. Four crystalline forms are known. The monoclinic α -modification is predominant in a structure formed during slow cooling from the melt. Higher content of trigonal β -modification can be obtained during fast cooling of the melt [24].

For moulding process, skin morphology is especially important because polymer melt is immediately solidified near a cold wall of molds. Crystallization of polymer can also cause minimal shear stress and hardness in the proximity of walls [25].

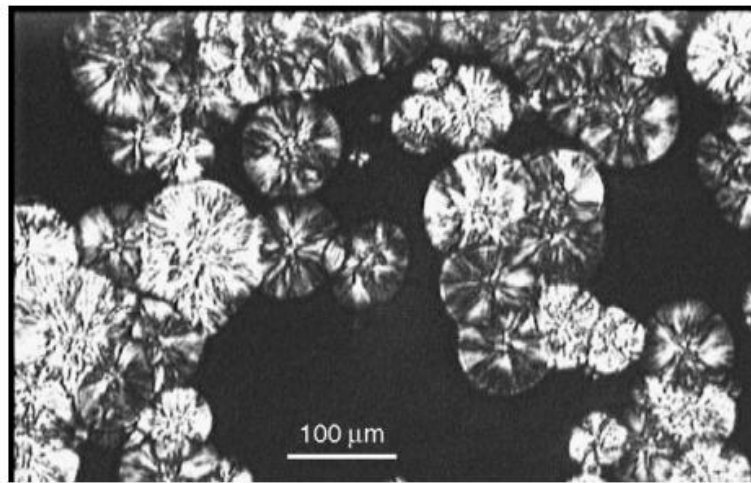


Figure 2.6. Micrograph of crystallization of pure i-PP at cooling rate 5K/min (temperature 117°C)

[26]

Detailed knowledge on micro-structure or morphology of polymers is one of important factors to understand polymers' physical characteristics. A great tool which can be used for characterization of the morphology of polymers, is Atomic force microscopy (AFM) [26, 27]. AFM (or scanning force microscopy (SFM)) is scanning probe microscopy with high resolution, generally more than 1000 times higher than the optical diffraction limit. The topology (Fig. 2.6) and other information are gathered by a combination of a mechanical probe and laser reflection of AFM. An AFM model is shown in Fig. 2.7. The effect of various conditions of polypropylene (PP) crystallization, such as the fraction of amorphous to crystalline phases, the shape, size, and structure of crystals can be measured by AFM. However, it should be noted that it is very challenging to consistently obtain correct and precise data.

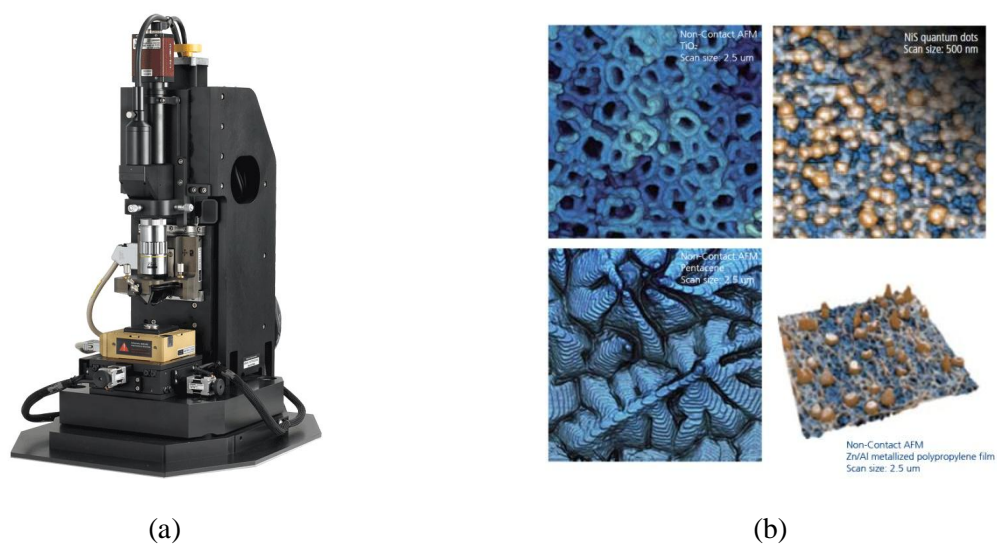


Figure. 2.7. A model of (a) AFM and (b) its images [28]

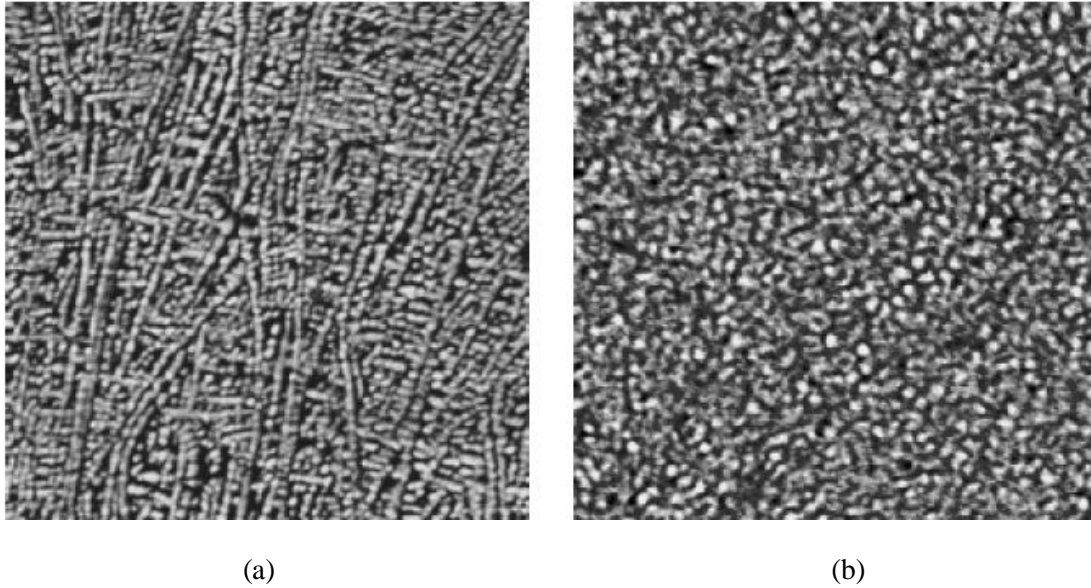


Figure 2.8. AFM images of (a) semicrystalline and (b) semimesomorphous iPP [26]

2.3.4 Shrinkage

In manufacturing processes including blow moulding, thermoplastic materials that undergo a phase change experience a decrease in specific volume, which results in shrinkage. A certain amount of shrinkage is unavoidable in any process that involves cooling from elevated temperature, and this must apply to blow moulded polymers [29]. The shrink rate, S , is used to scale mold dimensions to compensate for shrinkage. With perfectly isotropic shrinkage assumption, the total volumetric shrinkage rate of a material, S_v , is related to the linear shrinkage rate S by the relationship

$$S = 1 - (1 - S_v)^{1/3} \quad (6)$$

A simplification of this relationship, neglecting higher order terms of the binomial theorem expansion of $(1 - S_v)^{1/3}$, is

$$S \approx \frac{S_v}{3} \quad (7)$$

Hence, a material exhibiting 3% volumetric shrinkage should shrink in all directions by 1.01% after cooling [29]. Determining a single shrinkage compensation factor using either of the preceding equations for S is suitable for most applications. Tables of S values for commonly used thermoplastic materials are quite common in many specifications and standards (Table 2.2).

Even though linear shrinkage rates are available for a wide range of plastics, the reported values are usually given as a range. Shrinkage varies due to a lot of factors such as material, processing, part geometry, etc. Furthermore, shrinkage may vary in the direction of flow versus transverse direction (anisotropic shrinkage).

Table 2.2. Shrinkages of various thermoplastic materials [29]

Material	Shrinkage in inches/inch
ABS- High Impact	.005 - .007
ABS- Medium Impact	.005 - .008
ABS-High Heat	.004 - .006
ACETAL	.020 - .035
ACRYLIC- General Purpose	.002 - .009
ACRYLIC- High Flow	.002 - .007
ACRYLIC- High Heat	.003 - .010
ACRYLIC- Impact	.004 - .008
NYLON- 6,6	.010 - .025
NYLON- 6	.007 - .015
NYLON- Glass Reinforced	.005 - .010
POLYCARBONATE	.005 - .007
POLYESTER .025 - .050 thick	.006 - .0012
POLYESTER .050 - .100 thick	.012 - .017
POLYESTER .100 - .180 thick	.016 - .022
POLYETHERIMIDE	.005 - .007
POLYETHYLENE- LDPE	.015 - .035
POLYETHYLENE- HDPE	.015 - .030
POLYPROPYLENE	.010 - .030
PPO®/HIPS (NORYL®)	.005 - .007
POLYSTYRENE- Crystal	.002 - .008
POLYSTYRENE- Impact	.003 - .006
POLYURETHANE	.010 - .020
PVC-RIGID	.002 - .004
PVC-FLEXIBLE	.015 - .030
SAN	.002 - .006

2.3.5 Residual Stress

Residual stress is the stress that remains after the original cause of the stress has been removed. Residual stresses occur for various reasons, including inelastic (plastic) deformations, temperature gradients or structural changes (phase transformation) [27]. Residual stress in polymer moulding generally means the stress that remains inside of moulded parts after moulding process. The residual stress is the major factor which causes warpage. Fig. 2.9 shows one of residual stress analysis results solved by Moldflow, one of widely-used commercial codes.

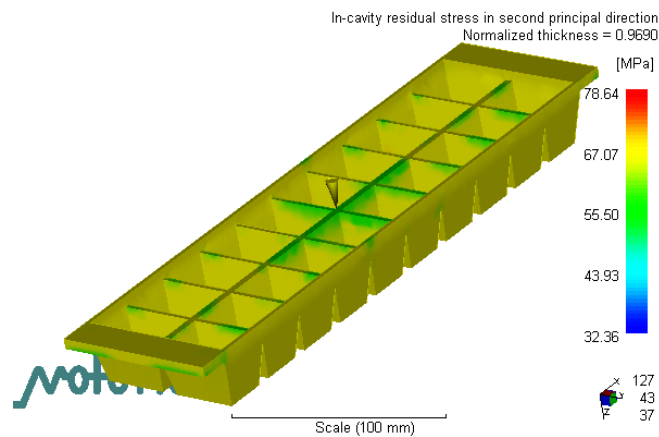


Figure 2.9 An example of residual stress analysis by Moldflow [28]

It is well known that injection moulded parts often contain residual stresses that are caused by non-uniform cooling rates and that are dependent on the pressures applied during solidification and therefore also on the time at which gate freeze-off (solidification before filling is completed) occurs [29]. The presence of such stresses causes the change in mechanical properties, and change in their magnitude and distribution during post-moulding aging is important [30].

Residual stresses in moulding process can be categorized into two groups [27, 30, 31]. First, there is, so-called, thermal stress which develops by temperature difference during cooling process, and the other residual stress is flow residual stress which occurs due to shear stress and normal stress differences due to high strain rates [29].

In practice, the dimensions can change by a variety of material, part, geometry, tooling, and process related factors, which causes warpage (out- of-plane distortion). Warpage is very unpredictable while shrinkage can be considered to be linear. Even though warpage is very difficult to overcome in many cases, it is noteworthy that a number of factors regarding warpage are related to process control (melt and mould temperatures, filling pressure and time, and ejection temperature) and tooling or mould design (Gate, mould cooling layout, and ejection system design) while other factors such as wall thickness and its variations, overall part dimensions, can be considered at the design stage (Table 2.3). These process control and mould design factors need to be considered even from the beginning of part design phase with caution because these factors significantly influence the change and the change rate of residual stress which resultantly causes warpage.

Table 2.3. Warpage factors [32, 33]

Category	Factors
Material	Amorphous vs. Semi-crystalline Filler or reinforcement content Degree of moisture absorption
Part Geometry	Nominal wall thickness Wall thickness variations Overall part dimensions Shrinkage restricting features
Tooling	Gate locations Types and sizes of gates Runner systems Mould cooling layout Ejection system design Elastic deformation of tool
Processing	Melt temperatures and uniformity Mould temperatures and uniformity Filling, packing and holding pressures Filling, packaging, and holding times Part temperature at ejection Clamp tonnages Post mould fixturing/annealing

2.3.6 Polypropylene

Polypropylene (PP) is one of thermoplastic polymers used in many applications: packaging and labeling, stationery, and liquid containers, automotive components, and polymer banknotes [11]. In 2008, the global PP market recorded a volume of 45.1 million metric tons, which led to a turnover of about \$65 billion [34].

Most commercial PP is isotactic and has an intermediate level of crystallinity between those of low-density polyethylene (LDPE) and high-density polyethylene (HDPE) [35]. PP is normally tough and flexible, especially when copolymerized with ethylene. This allows PP to be used as an engineering plastic, competing with materials such as ABS. PP is reasonably economical, and can be made translucent when uncolored but is not as readily transparent as polystyrene, acrylic, or certain other plastics. It is often opaque or colored using pigments. PP has good resistance to fatigue [11].

The melting point of PP occurs at a range, so a melting point is determined by finding the highest temperature of a differential scanning calorimetry chart. Perfectly isotactic PP has a melting point of 171 °C (340 °F). Commercial isotactic PP has a melting point that ranges from 160 to 166 °C (320 to 331 °F), depending on atactic material and crystallinity. Syndiotactic PP with a crystallinity of 30% has a melting point of 130 °C (266 °F) [35, 36].

The melt flow rate (MFR) or melt flow index (MFI) is a measure of molecular weight of PP. The measure helps to determine how easily the molten raw material will flow during processing. PP with higher MFR will fill the plastic mold more easily during the injection or blow-molding production process. As the melt flow increases, however, some physical properties, like impact strength, will decrease.

There are three general types of PP: homopolymer, random copolymer, and block copolymer. The comonomer is typically used with ethylene. Ethylene-propylene rubber or EPDM added to PP homopolymer increases its low temperature impact strength. Randomly polymerized ethylene monomer added to PP homopolymer decreases the polymer crystallinity and makes the polymer more transparent.

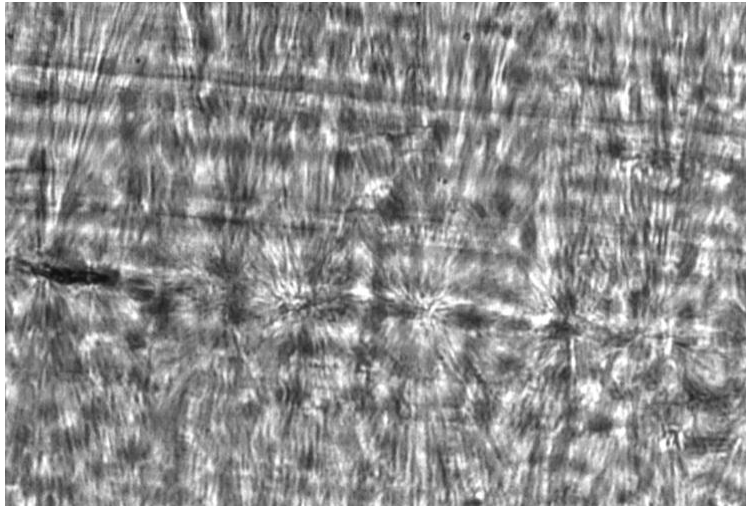


Figure 2.10. Micrograph of PP [11]

PP is liable to chain degradation from exposure to heat and UV radiation such as that present in sunlight. Oxidation usually occurs at the tertiary carbon atom present in every repeat unit. A free radical is formed here, and then reacts further with oxygen, followed by chain scission to yield aldehydes and carboxylic acids. In external applications, it shows up as a network of fine cracks and crazes that become deeper and more severe with time of exposure [11].

For external applications, UV-absorbing additives must be used. Carbon black also provides protection from UV. The polymer can also be oxidized at high temperatures, which is a common problem during molding operations. Anti-oxidants are normally added to prevent polymer degradation.

The properties of PP can vary depending on additional components which are normally glass fiber filler. In general, unfilled PP has relatively low impact and stiffness properties. Therefore PP resins are often modified to improve their mechanical properties. Adding elastomer to PP can have an adverse effect on the stiffness of PP, so PP is often compounded with glass fiber to be a glass reinforced PP (GF PP). The glass fiber that is added to PP is, generally categorized by its length: Long glass fiber reinforced PP is called LGF PP, and short glass fiber reinforced, SGF PP [35]. It is certain that they show differences in their mechanical properties (Fig. 2.10). The mechanical properties of SGF PP and LGF PP can also be modified by controlling the amount of glass fiber compounded with PP [35].

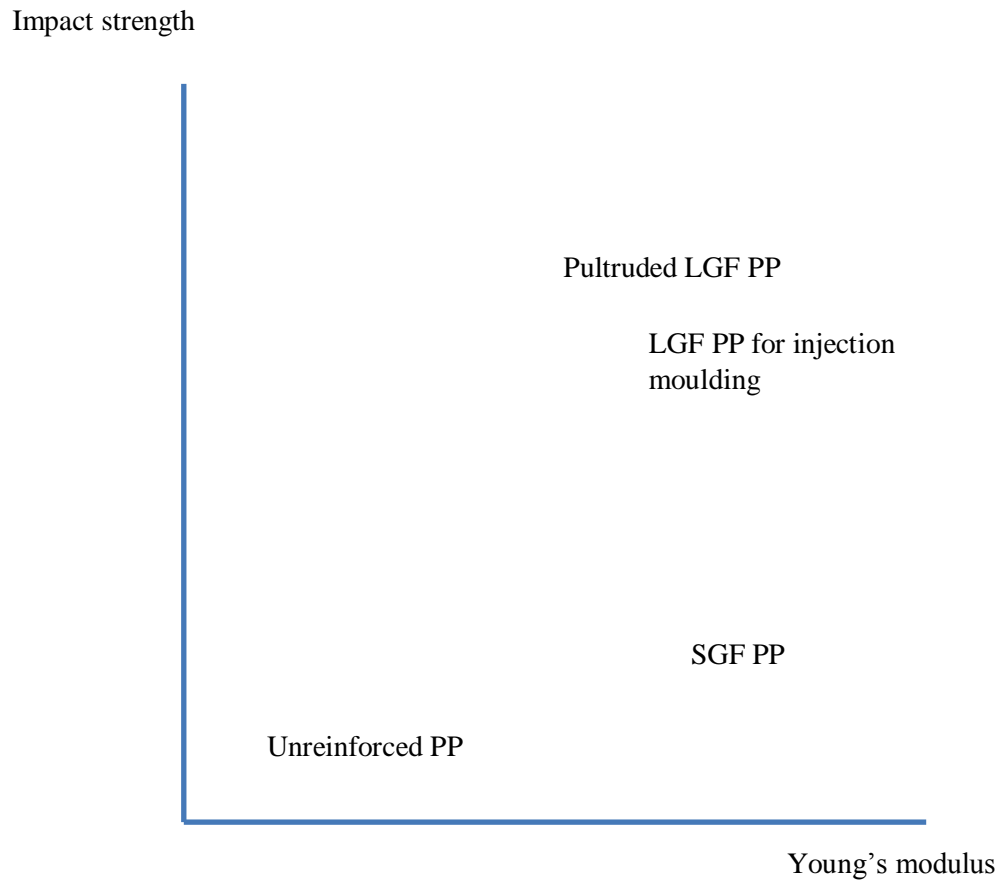


Figure 2.10. Impact behaviors of glass fiber reinforced PP

The properties of PP can vary depending to additional components which are normally glass fiber filler. In general, unfilled PP has relatively low impact and stiffness properties. Therefore PP resins are often modified to improve their mechanical properties. Adding elastomer to PP can have an adverse effect on the stiffness of PP, so PP is often compounded with glass fiber to be a glass reinforced PP (GF PP). It is evident that the particle size has a large effect on composite properties [37]. Strength and Young's modulus increase, and deformability and impact strength decrease as glass fiber pellet size decreases. The pellet size distribution is as important as the pellet size itself is [37].

Large pellets usually have a strong adverse effect on the deformation and failure characteristics of the compounded PP.

Chapter 3

Process Investigation

3.1 Problem definition

First, in order to set the study scope, the problem has to be set, and then the main goal of the study can become definite. The major issue in the production line was that the part (Part No. 15901934) (hereafter the Part) deformed after blow-moulding, resulting in uneven welding surfaces and noncircular cuff and bellow holes. This had been regarded as the main cause of dimensional inconsistency.

ABC had considered a design change of the mould to remedy this problem. However, since the mould was highly expensive and complicated structure, this should be carefully examined before putting into practice. Also, the moulding process and post-mould cooling process should be studied from various points of view.

3.2 Manufacturing process

The whole manufacturing process has many sub-processes. Once the raw material (PP) passes the acceptance inspection, this new material goes into a blender, and it is blended with the repro which is made of defective parts by grinding. This mixture is dried and then transferred to the blow mould machine. Among them, this study particularly focuses on two processes; moulding and post-mould cooling. These two processes are indicated by a rounded square in Fig. 3.1. In cooling process, the moulded parts are cooled on a metal frame by cooling fans. After cooling, the part is conveyed to the following process to be machined, welded, assembled and tested.

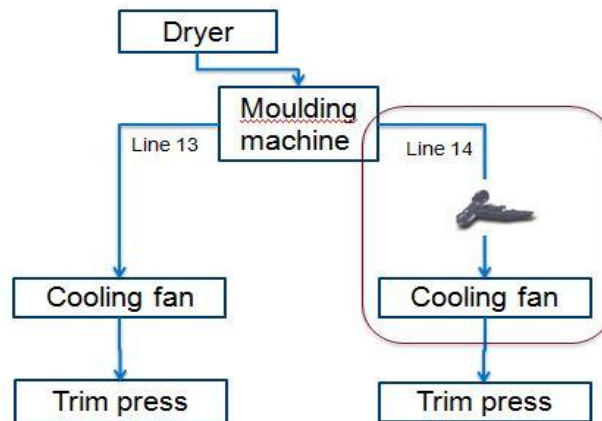


Figure 3.1 Moulding and cooling processes

3.3 Common Problems and Solutions

In extrusion blow moulding, the machine conditions at each step in the process determine the PP conditions and hence the part properties. These part properties should be controlled to meet the quality requirements. Narrowing the focus on making a good parison and reshaping the parison into a good blow moulded product, critical factors affecting the part quality can be identified as follows:

(1) Factors for parison formation: plastic flow rate, plastic pressure, melt viscosity and flow passage dimensions (die gap)

(2) Factors for reshaping parison: parison stretch, parison sealing, inflation rate, plastic cooling rate.

There are so many factors to be considered when a bad part problem arises. However, only a limited number of actions are practically available in the manufacturing plant, such as eliminating any pressure difference around the die gap circumference, correcting diehead gap variation, or reducing temperature differences around the diehead. All these remedies are to resolve the issue of uneven flow rate [3].

There are some more measures which can be conducted for correcting the problems. For example, if misalignment occurs, it means that parison expansion was incomplete due to inefficient venting or uneven cooling. In this case, when poor venting is the problem, all the vent system might need to be redesigned. Or if the uneven cooling is caused by thickness variation of the part, the part should be redesigned.

It means there is no other effective way if there have been critical problems in the designs of the part and the mould. Therefore, the process should be designed when the part is designed. Table 3.1 shows some possible causes of defective part and suggested solution for each cause, excerpted from literature and rearranged.

Table 3.1. Possible causes and suggested remedies [32, 33]

Problem	Possible cause	Suggested remedy
Warping	Melt temperature too low	
	Incorrect part design	Redesign part
	Overpacking near gate	
	Sharp variation in wall thickness	Redesign part
	Flow length too great	
	Part ejected too hot	
	Inadequate or badly located ejectors	
	Temperature variation between the mold halves	Redesign mould

The causes and remedies can be rearranged as shown in Fig. 3.2. The causes can be categorized into the three groups, part design, mould design and process control. Taking a look at the figure, it can be concluded that the more attention should be given to mould design and process control than the other causes. In order to reduce the number of defective parts and secure the consistency in dimensions, the following design flow should be followed: (1) Design part minimizing thickness variation, (2) Design mould locating the gates to minimize the flow length, and (3) Design process, which should be optimized through trial runs.

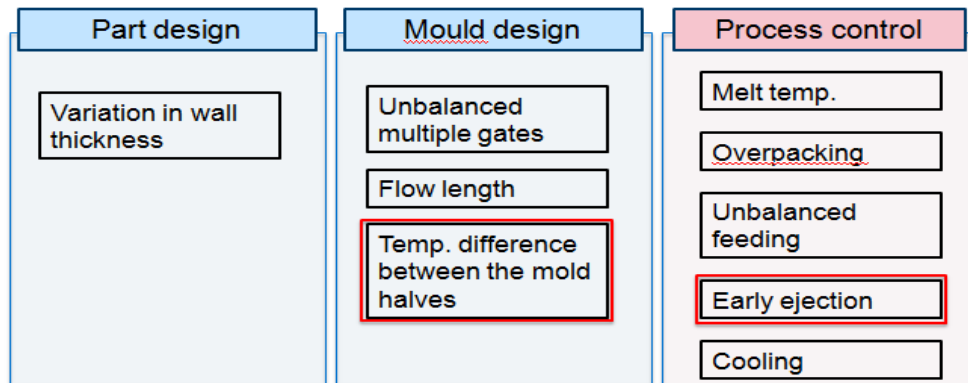


Figure 3.2 Possible causes categorized by development and production phases

3.4 Cooling process investigation

Through the investigation on post-mould cooling process, one important factor which might produce a significantly different result in warping phenomenon was identified. It was the way how the part cooling was conducted. After moulding, the part was ejected and placed on a metal frame rack. The part was then cooled by a big fan located underneath the fan. It can be considered as a forced convection cooling which might cause warping behavior different from that in natural convection mode (Fig. 3.3).

It was also found that the cooling process was not fully reviewed from the point of view of engineering and optimization, so it can be improved to reduce the number of defective parts. Consequently, assuming that is no problem in moulding process, the cooling process can be a major target of the process investigation even if mould machine - specifically cooling system - might need to be redesigned using collected information after all.

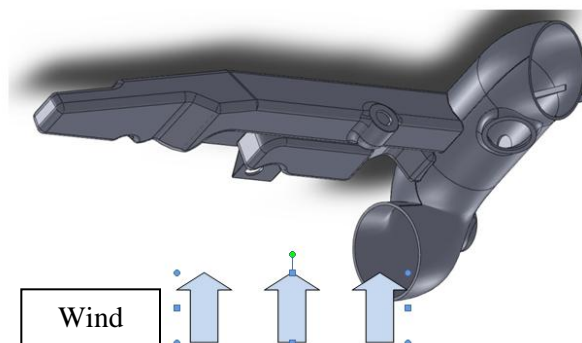


Figure 3.3. Conceptual Schematic of Post-mould Cooling Process

Chapter 4

Numerical Simulation

4.1 Computation Model

A CAD model of the part was generated using Solidworks 2010. Since the electronic drawing or CAD file of the part was not provided by ABC, the CAD model was built by extracting information from the electronic drawing of the moulds and measuring the real product. In order for accurate simulation results, all the details of the part are reflected in the CAD model even though it increase the level of difficulty in meshing and time cost in calculation. Because the shape of the part is extremely complex, the wall thicknesses are modeled with parametric method to facilitate the change in parametric study. Parting line and excessive material which could be found on the inside of the part were also modeled for the realistic results especially in warping.

The electronic model was transferred to ANSYS in the form of Parasolid format maintaining all the surface and volume information.

In order to perform thermal and structural analysis, the project schematic was set up in ANSYS workbench. Transient thermal module is first run using material data with proper boundary and initial conditions to obtain temperature distribution over the body. After that, transient structural module is run using the temperature distribution (the result from transient thermal module) in order to obtain

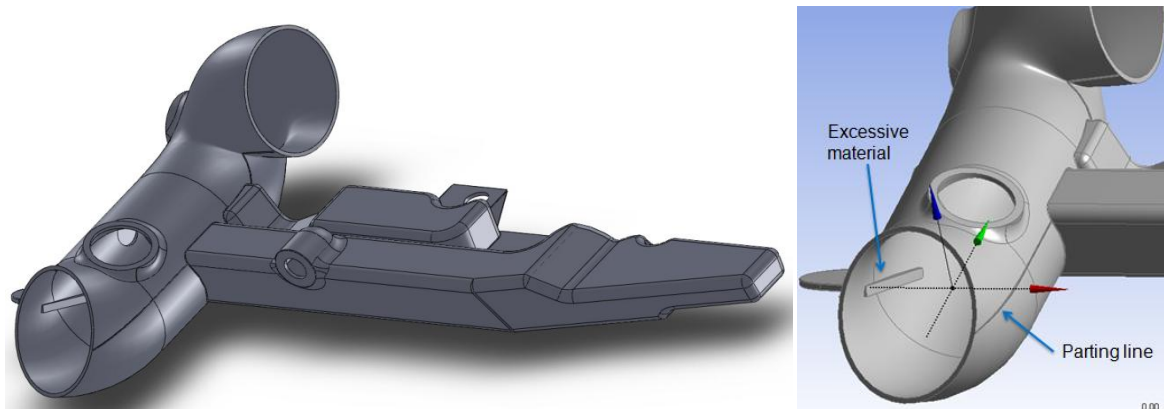


Figure 4.1 CAD model of (a) the whole part and (b) the details

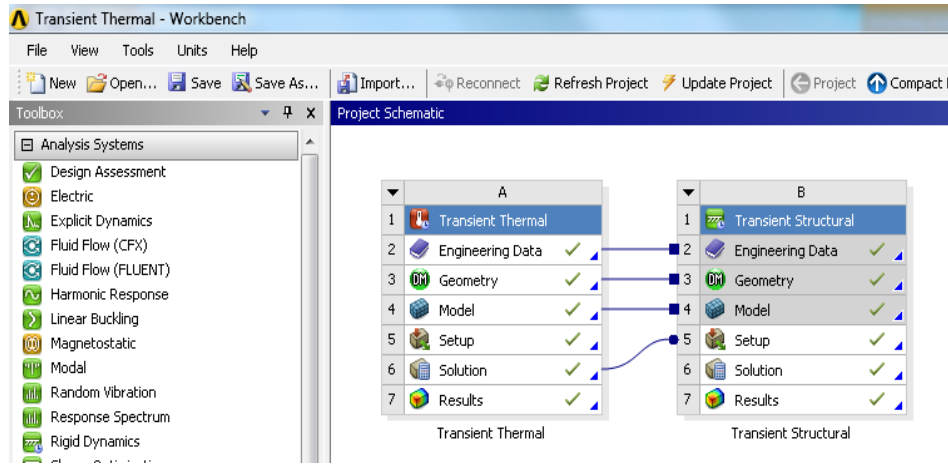


Figure 4.2. Computation schematic design using ANSYS

stresses (Fig. 4.2). The resulting local stress variation will cause deformation which leads to warpage in the longitudinal direction and/or on the welding surfaces (circular holes).

4.2 Material

The mechanical and thermal properties of 10% glass fiber reinforced PP (Table 4.1) were used for the simulation. The material properties were inputted in ANSYS as shown as Fig. 4.3.

Table 4.1. Material properties of 10% glass fiber reinforced PP

Category	Item	Unit	Value	Note
General	Density	kg/m ³	920	
	Poisson's ratio	Non-Dimensional	0.25	
	Modulus of Elasticity	GPa	1.34	
Thermal	Coefficient of Thermal expansion (CTE)	mm/mm/K	6.2*10 ⁽⁻⁵⁾	
	Thermal conductivity	W/(m K)	0.1154	
	Convection Heat Transfer Coefficient	W/(m ² K)	Varies	- Difficult to measure - Needs to be assumed

	Specific Heat Capacity	J/(kg-K)	830~2512
Structure	Yield Strength	MPa	3.3*10 ⁴

	A	B	C	D	E
1	Property	Value	Unit	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
2	Density	900	kg m ⁻³	<input type="checkbox"/>	<input type="checkbox"/>
3	Isotropic Secant Coefficient of Thermal Expansion			<input type="checkbox"/>	<input type="checkbox"/>
4	Coefficient of Thermal Expansion	0.00011	C ⁻¹	<input type="checkbox"/>	<input type="checkbox"/>
5	Reference Temperature	22	C	<input type="checkbox"/>	<input type="checkbox"/>
6	Isotropic Elasticity			<input type="checkbox"/>	<input type="checkbox"/>
7	Derive from	Young's Modulus and...		<input type="checkbox"/>	<input type="checkbox"/>
8	Young's Modulus	7E+08	Pa	<input type="checkbox"/>	<input type="checkbox"/>
9	Poisson's Ratio	0.35		<input type="checkbox"/>	<input type="checkbox"/>
10	Bulk Modulus	7.7778E+08	Pa	<input type="checkbox"/>	<input type="checkbox"/>
11	Shear Modulus	2.5926E+08	Pa	<input type="checkbox"/>	<input type="checkbox"/>
12	Alternating Stress Mean Stress	Tabular		<input type="checkbox"/>	<input type="checkbox"/>
13	Interpolation	Log-Log		<input type="checkbox"/>	<input type="checkbox"/>
14	Scale	1		<input type="checkbox"/>	<input type="checkbox"/>
15	Offset	0	Pa	<input type="checkbox"/>	<input type="checkbox"/>
16	Strain-Life Parameters			<input type="checkbox"/>	<input type="checkbox"/>
17	Display Curve Type	Strain-Life		<input type="checkbox"/>	<input type="checkbox"/>
18	Strength Coefficient	9.2E+08	Pa	<input type="checkbox"/>	<input type="checkbox"/>
19	Strength Exponent	-0.106		<input type="checkbox"/>	<input type="checkbox"/>
20	Ductility Coefficient	0.213		<input type="checkbox"/>	<input type="checkbox"/>
21	Ductility Exponent	-0.47		<input type="checkbox"/>	<input type="checkbox"/>
22	Cyclic Strength Coefficient	1E+09	Pa	<input type="checkbox"/>	<input type="checkbox"/>
23	Cyclic Strain Hardening Exponent	0.2		<input type="checkbox"/>	<input type="checkbox"/>
24	Tensile Yield Strength	2.8263E+07	Pa	<input type="checkbox"/>	<input type="checkbox"/>
25	Compressive Yield Strength	2.3095E+07	Pa	<input type="checkbox"/>	<input type="checkbox"/>
26	Tensile Ultimate Strength	4.8263E+07	Pa	<input type="checkbox"/>	<input type="checkbox"/>
27	Compressive Ultimate Strength	3.3095E+07	Pa	<input type="checkbox"/>	<input type="checkbox"/>
28	Isotropic Thermal Conductivity	0.12	W m ⁻¹ C ⁻¹	<input type="checkbox"/>	<input type="checkbox"/>
29	Specific Heat	460	J kg ⁻¹ C ⁻¹	<input type="checkbox"/>	<input type="checkbox"/>

Figure 4.3. Material data sheet for PP in ANSYS Material setting

4.3 Boundary conditions

In general, there are three modes of heat transfer, which are combined differently depending on the situation. First mode is thermal radiation which is an energy transfer mechanism by emission from bodies in the form of electromagnetic waves depending on their temperature. Radiation is the fastest heat transfer mode because electromagnetic waves travel at the speed of light. However, this heat

transfer mode has been excluded in this study because there is no strong source of radiation around the body of interest.

The second mode of heat transfer is conduction. Conduction occurs in solids, liquids, and gases, but is dominant in solids. Therefore, conduction should be taken into consideration for the current thermal analysis. Rate of heat conduction depends on the temperature gradient and the thermal conductivity, K . The values of K for widely used materials are widely available, so conduction heat transfer can be easily simulated.

The third mode is convection. Convection is the heat transfer mechanism between a solid face and adjacent moving fluid (the air in this study). Convection involves the combined effects of conduction and the moving fluid. The rate of heat exchange can be expressed as:

$$\frac{dQ}{dt} = hA\Delta T(x) \quad (8)$$

where h is the convection heat transfer coefficient.

The forced convection and natural convection have different values of convection heat transfer coefficients (h in Eq. (8)). In general, natural convection heat transfer coefficient is known to have the order of $1 \sim 10$ while the coefficient for forced convection heat transfer has the order of $10^2 \sim 10^4$ depending on the air flow rate generated by the cooling device. This should be reflected in computational analysis.

In this study, the values, $h_n = 9W/m^2\text{°C}$ and $h_f = 1000W/m^2\text{°C}$ were used for natural and forced convection, respectively.

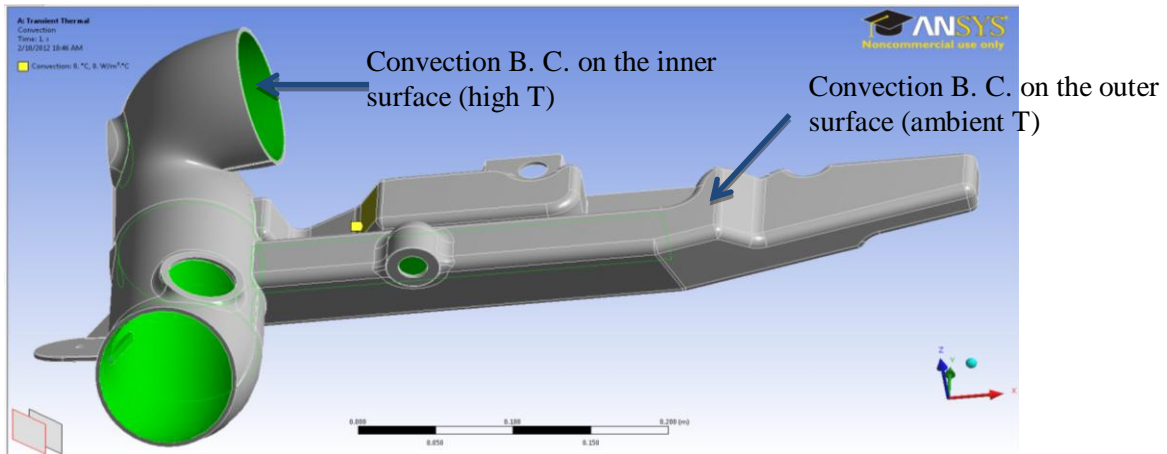


Figure. 4.4 Thermal Boundary Conditions

Another important factor is the temperature of the air captured in the cavity of the part. Note that the part is ejected from the mould machine without having any holes in the attached burr, so that the air trapped in the cavity cools down very slowly while the ambient air (outside) can be considered to be constant. Based on temperature measurement on various positions on the outer surface of the part, the temperature profile of the inside of the part was generated with the assumption that the cooling rates of the inside and outside PP were identical. The assumed temperature profile was employed for the simulation as the boundary condition on the inner surface.

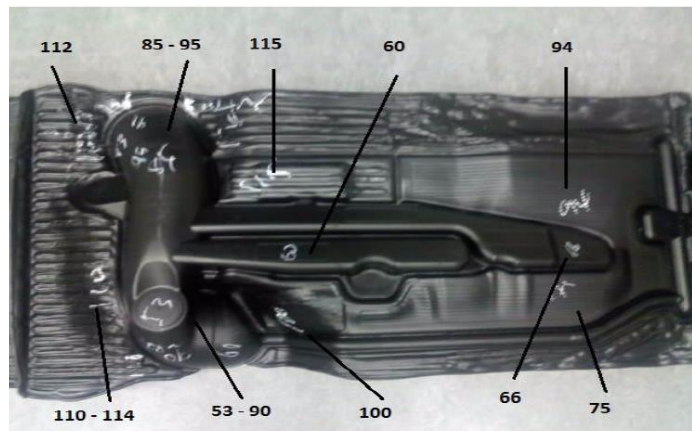
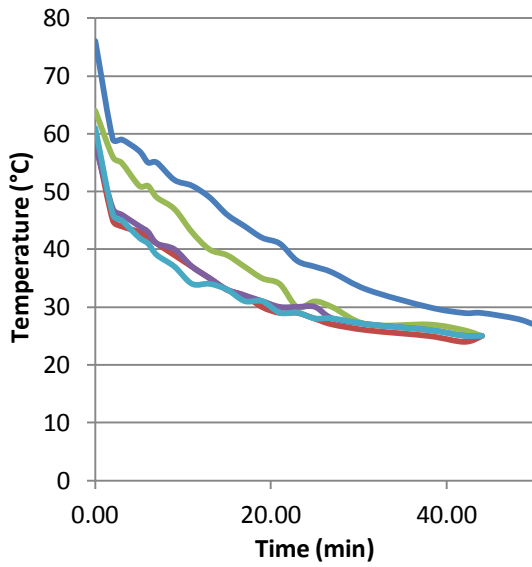
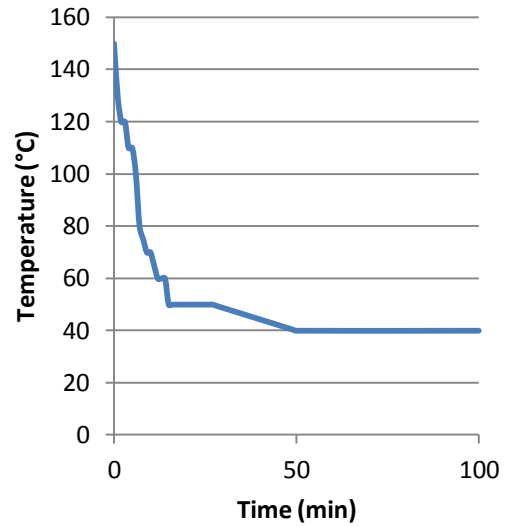


Figure 4.5 The shape of the ejected part. The numbers are temperatures measured using an IR thermometer



(a)



(b)

Figure 4.6. (a) Temperature measurements on various positions on the outer surface of the part, (b) Modeled temperature profile of the inside of the part

4.4 Analysis results

The temperature variation of the part in natural convection condition after it was extracted from the mould has been simulated, assuming the initial temperature of all surfaces of the part is at 150 °C and the ambient air temperature is at 25 °C. It was observed that it took approximately 100 seconds for the part to reach ambient temperature (Fig. 4.7), and the cooling profile of the simulation was in good agreement with the actual measurements. It is important to note that the surfaces with no hollow region underneath (Points A, B, C) cooled significantly faster than the rest of the part, and hence contracted faster, which caused warping of the part about the z-axis.

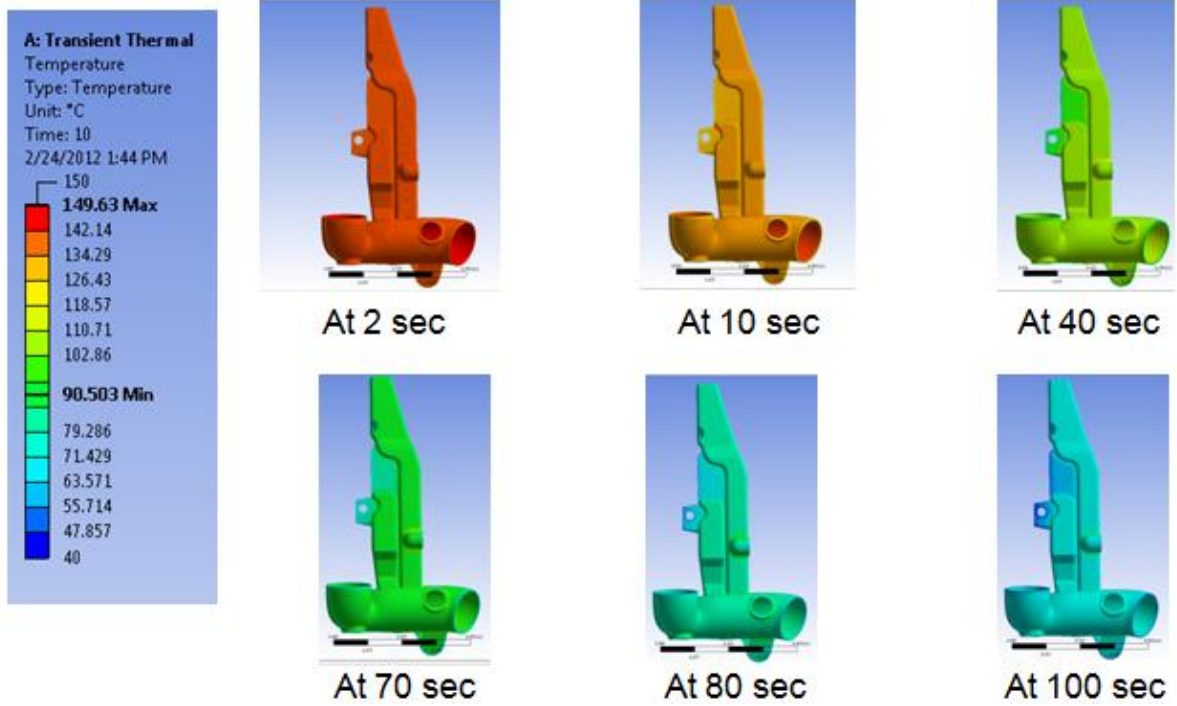


Figure 4.7. Simulation of the overall temperature of the extracted part at different time intervals

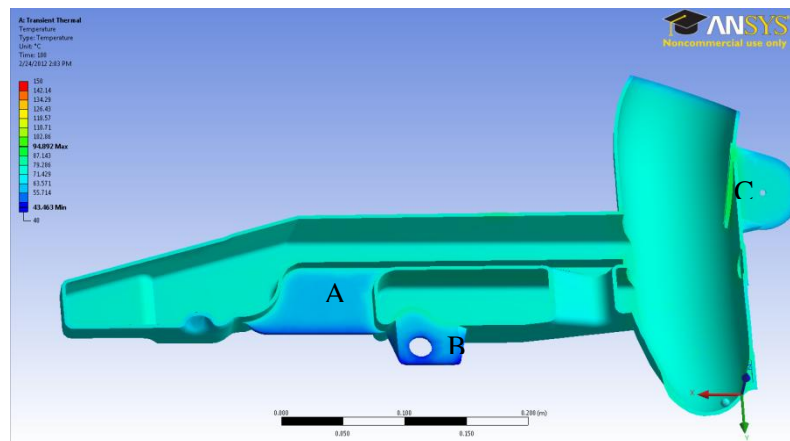


Figure 4.8. Section view of the model showing the inner surface of the part. Note that the temperature of all hollow surfaces cool uniformly

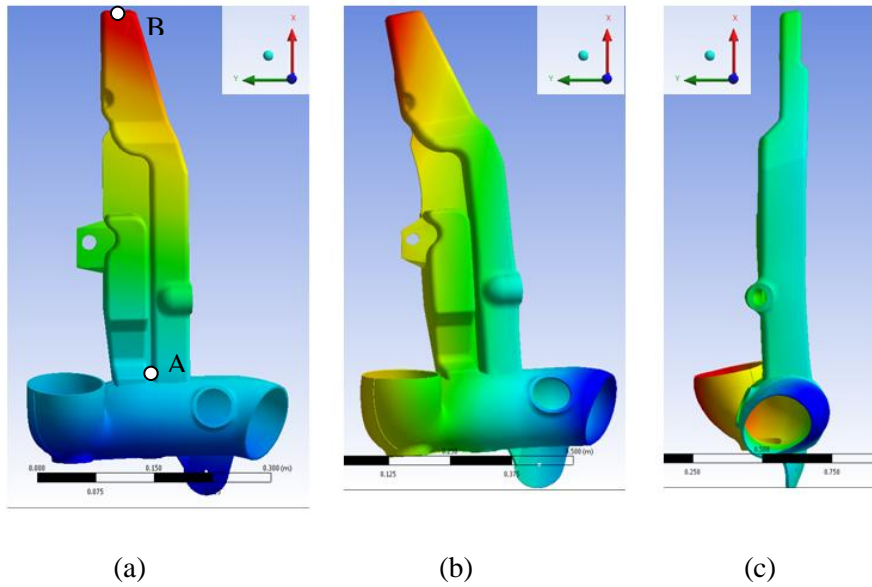


Figure 4.9 Contours of deformation in (a) x, (b) y, and (c) z directions

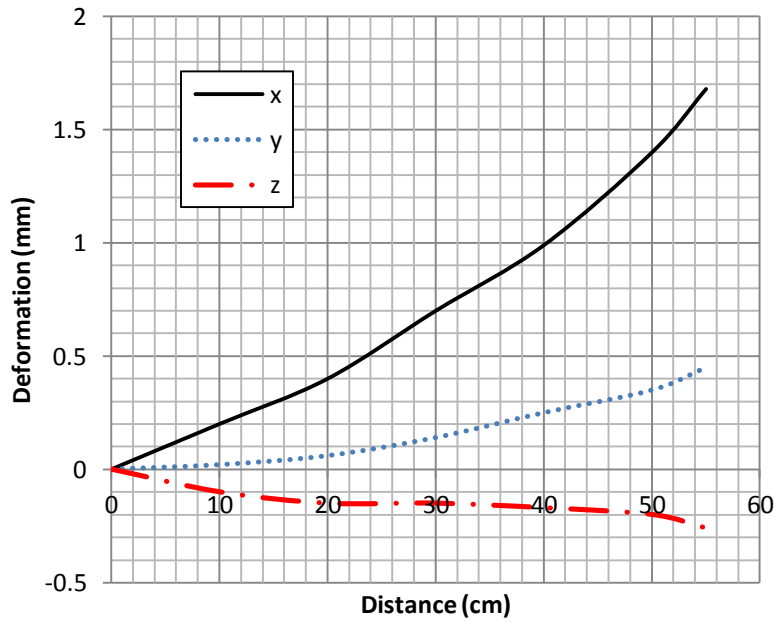
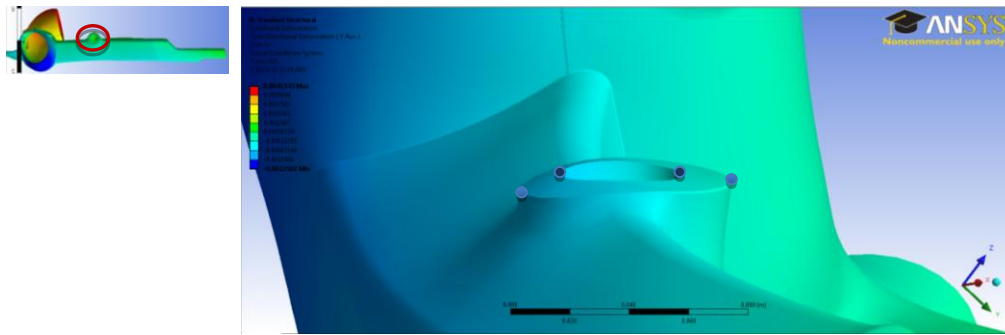


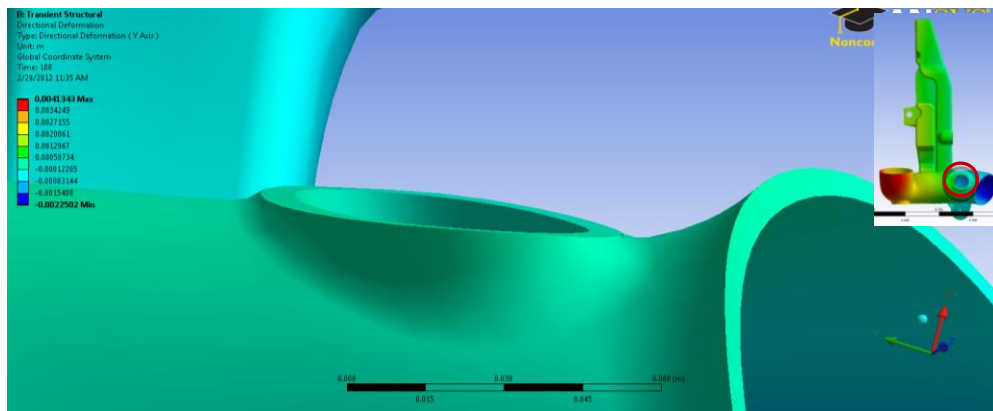
Figure 4.10 Deformation in each direction: x, y, and z

The amount of warping during the cooling process was investigated. It was observed that the maximum warping of point B with respect to point A were 1.68 mm, 0.45 mm, and -0.26mm, in x, y, and z directions, respectively (Fig. 4.9 and Fig. 4.10).

It was also observed at the welding hole A that significant warping occurred in the neighboring region of the hole. The height difference between two diametrically opposed points along the z-axis of the inner and outer diameters of the hole were -0.61mm and -0.97mm, respectively, which suggests that the surface of the hole warps significantly as the radius increases, as shown in Figure 4.11. This is due to the shape of the part, i.e. there is less supporting material underneath the outside of the hole, which consequently allows for higher degree of deformation. Warpage in the hole surface can cause problems in the subsequent welding process, since the uneven surface of the hole can cause incomplete joining with another part. Similar behaviors were observed in another welding hole B, as illustrated in Figure 4.11. However, hole B is located on relatively flat area, and surrounded by relatively even material, which leads to less deformation compared to that of hole A. The difference between the highest and the lowest point of the outer diameter of hole B is approximately is 0.48mm, and the inner diameter height difference is approximately 0.2mm.



(a)



(b)

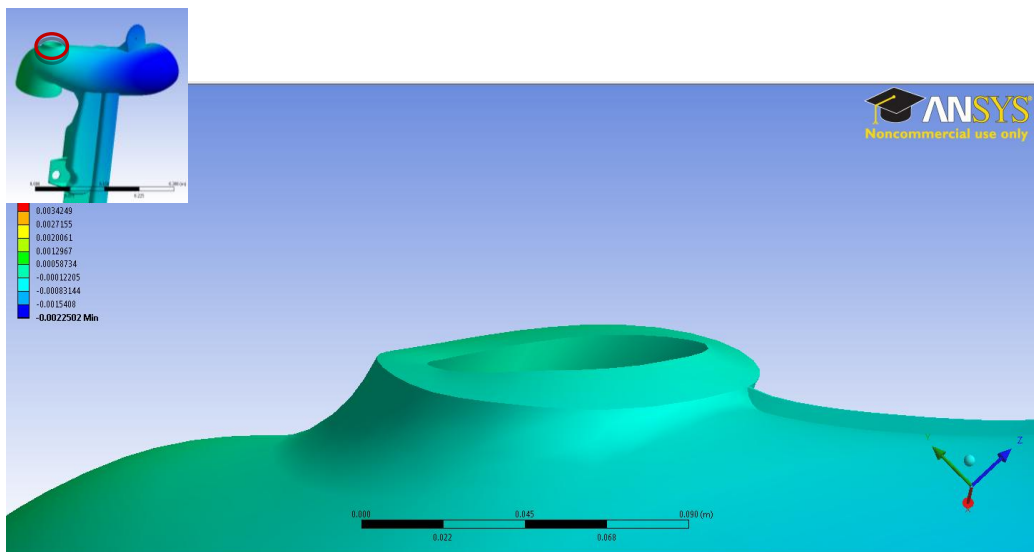
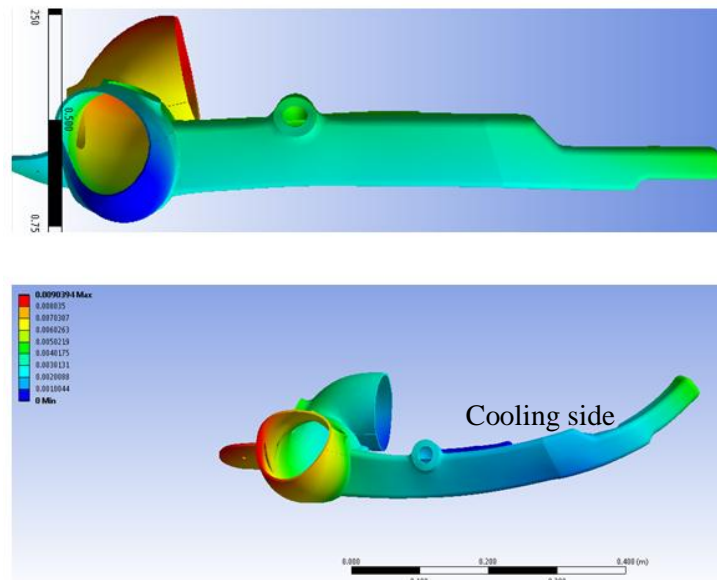


Figure 4.11 (a), (b), (c). Warping of welding holes A, B and C, respectively

As mentioned above, warping by natural convection (no additional cooling) and forced convection (cooling by fan) can result in significant different deformation behaviors. Currently, the part is cooled by a fan on a metal framed rack in production line, so it is necessary to verify the effect of cooling fan. To account for this, the cooling fan is modeled, and the degree of warping by natural convection and forced convection were compared. When the part was cooled through natural convection, it was noticed that the overall warping of the part along its y-axis was -0.266mm, as shown in Figure 4.12. However, when the current cooling method was simulated by introducing forced convection on one side along the x-y plane, the degree of warping was significantly higher at 2.44mm, which is approximately nine time times great than that in natural convection case, as shown in Figure 4.12.

Therefore, it can be stated that rapid cooling using a fan is not desired. Especially, if only one side is cooled by a fan, much rapid cooling occurs on that side, which causes asymmetric contraction and warpage. To eliminate the dimensional inconsistency, the currently used cooling method has to be reviewed and optimized. Generally, annealing (a stress releasing process) under controlled conditions (at least enough high near the material's glass transition temperature) is needed, so that residual stress within the moulded part should be relieved. However, it is very challenging to set up a new machine and a procedure for improvement because of continuous production.



4.4.1 Geometric factors

The shape of the part is very complicated with many holes in different orientations; thus the distortion and warping are highly complex in an arbitrary manner. In order to review how much overall thickness of the part affect warpage, the overall thickness is changed from 3 mm to 5 mm and the simulation was conducted again. The results showed that although overall warping decreased with the increase of the thickness, the effect is relatively ignorable in the thickness range considered in the simulation (3 mm ~ 5 mm). The inner diameter is also changed by maximum 2 mm in height assuming that these inner diameters can vary within a limited range. The result also showed that the inner diameters do not affect overall warping. However it is notable that the bellow hole and cuff hole have different tendency in distortion (or warping). In all cases, bellow hole is less deformed than cuff hole (Fig. 4.13), which is caused by their orientation. This tendency also agrees well with the actual measurement.

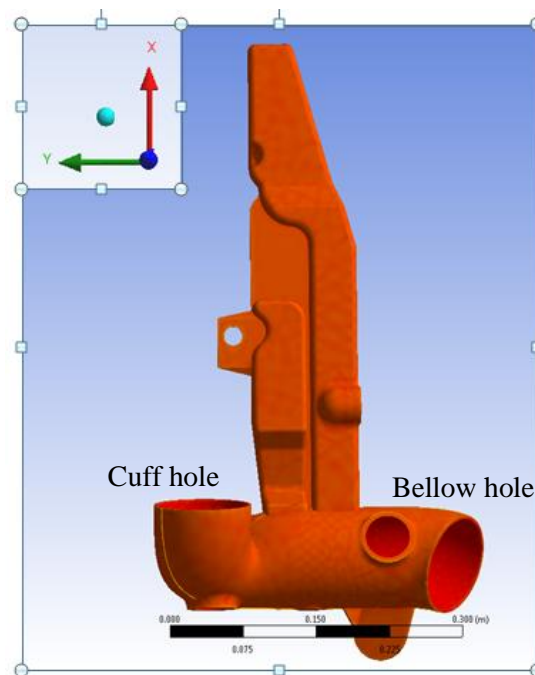


Figure 4.13 Cuff hole and bellow hole

4.4.2 Cooling system

The part is cooled in the mould by cooling system comprising many pipes through which coolant flows. The pipes have to be close to the part surface and the gap between pipes and the surface should be uniform to ensure uniform cooling. However, the current cooling system of the mould machine needs to be improved in design (Fig. 4.14). The pipes are not perfectly optimized for the cooling uniformity, which needs further study on it.

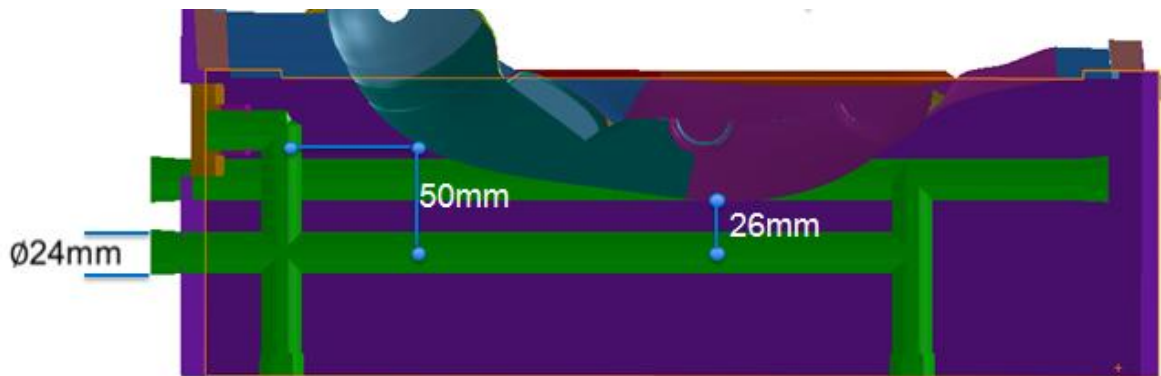


Figure 4.14 The current cooling system

Chapter 5

Conclusion

5.1 Conclusion

In this project, the moulding and related process were reviewed to find the cause of dimensional errors in the moulded part, and structural simulation is performed taking account of the thermal deformation to find the tendency and degree of warping. Through the study, several conclusions have been made:

- The current cooling method, forced convection cooling, causes warping approximately nine times larger than natural convection cooling.
- The overall warping decreases as the overall wall thickness increases in the simulated thickness range between 3 mm and 5 mm, but the effect is not significant.
- The distortions of the welding holes are very different, which is due to the shape of the part - whether there is supporting material around the holes and whether the holes are located on flat area are an important factor predicting the surface warping. However, it is almost impossible to change the design of holes such as diameter or location because the part is assembled to other parts and it has its design requirements.
- Welding holes' inner diameters do not influence warping significantly. Note that the sizes of cuff hole and bellow hole are dependent on the overall thickness, so that they cannot be individually changed.
- Bellow hole deforms more than cuff hole because of its orientation, and the tendency fairly agrees with the measurement.

5.2 Suggestions

Based on the study results, a few improvement suggestions have been made.

- According to the computation results, natural cooling is better than forced cooling for this case. Therefore, currently cooling method shall be replaced by natural cooling as long as there is no problem in the time management of the process
- The cooling system needs to be redesigned for more uniform cooling, which can reduce the number of bad parts. In-mould cooling is the most important phase, so it should be improved for the quality of the product and economy of manufacturing. A conformal cooling system should be designed considering the manufacturing easiness and its cooling capability simultaneously.
- If possible, it is recommended to anneal the part at about 85 °C and/or to increase in-mould cooling time. Normally, annealing is done at a temperature slight higher than glass transition temperature, but it is also gives quite good results to anneal the moulded part at a temperature a little lower than glass transition temperature if the annealing time is long enough (2 hours).

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