Engineering Analysis for Plastic Molding Quality Assurance and Productivity

by

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A thesis submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

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Abstract

The injection molding process has been widely used to manufacture various plastic products featuring complex geometry. Product quality and productivity are conflicting requirements which are hard to achieve simultaneously. Some molding simulation packages are available which can accurately simulate the injection molding process based on process parameters, material data and mold configuration, and can help engineers to understand the molding process and evaluate the quality of the parts. However, due to the complexity of the molding process, producing high-quality plastic parts in less cycle time is still difficult, even with the help of advanced simulation technology.

This thesis analyzes the gaps between the real injection molding process and the current available technology, and proposes a finite element analysis method to ensure that high-quality plastic parts are produced in less cycle time. First, a simulation workflow is proposed that aims to analyze the causes of warpage after pilot molding, and four possible methods are suggested to resolve such problems. Next, a molding simulation and structural analysis integrated method is proposed to predict the ejection-induced deformation and the shrinkage resulting from air-cooling. Finally, a new mold design strategy is proposed to facilitate early ejection upon partial solidification. By accurately predicting the molding behavior of plastic parts throughout the molding process, the parts,

the mold and the process itself can be better designed to ensure the quality of plastic parts in less cycle time.

Acknowledgments

I would like to express my sincere thanks to my supervisor, Dr. Yongsheng Ma, for his valuable guidance, encouragement, care and support throughout the course of my doctoral thesis work. Under his guidance, I have gained not only valuable academic knowledge but also useful strategies and methods to deal with real-word problems. It has been my honor to conduct research under his guidance.

I would like to extend my thanks to Dr. Rafiq Ahmad and Dr. Zhigang Tian for their support and valuable advice during my thesis work; and to Mr. Steve Koski from Drader Manufacturing Industries Ltd. for his technical assistance during the experimental work.

I would also like to express my appreciation to the Natural Sciences and Engineering Research Council of Canada (NSERC) for their generous financial support.

Finally, I would like to express my deep gratitude to my parents and friends for their support and encouragement.

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Chapter 1 Introduction

1.1 Background

Plastic material has been widely used in our daily lives for years. Compared to metal, plastic has many advantages: it is lightweight, has high specific strength and a low thermal expansion rate, is easy to fabricate, and is friction-, chemical-, electrical- and, corrosion-resistant. (Felix, et al., 2015; Kitayama and Natsume, 2014; Wong, et al., 2015). Due to its excellent mechanical properties, plastic has been widely used to replace metal in many engineering applications (Boland, et al., 2016; Lyu and Choi, 2015). It is also cheaper and easier to manufacture compared to metal (Goh, et al., 2017).

As can be seen from Figure 1.1, plastic factors heavily in our daily lives in the form of toys, packaging, electronic devices, medical apparatuses, etc. Due to their distinctive properties and applications, both thermoplastics and thermosets have been used to manufacture plastic parts (Azenha, et al., 2016; Bex, et al., 2018; Staab, 2015). The main difference is that thermoplastics are recyclable and can be re-manufactured upon heating as the curing process is completely reversible and no chemical bonding happens (Peres, et al., 2016; Sun, et al., 2015). Thermoset plastics cannot be re-manufactured by heat once they have been shaped because the thermoset curing process contains a chemical reaction which is irreversible (Chinn, et al., 2016; Deringer, et al., 2018; Sridhar and Kumar, 2014).

In order to obtain a desirable combination of properties, some fillers have been added to the plastic material (Sun, et al., 2015; Teixeira, et al., 2015). For example, reinforcing fibers such as those made of glass and carbon are added to enhance the plastic material's mechanical strength; flame retardants are added to prevent fire (Arao, et al., 2015; Cavdar, et al., 2015; Tekinalp, et al., 2014; Versavaud, et al., 2014).

Figure 1.1 Example of injection-molded plastic parts (Google images)

Injection molding is one of the most widely used methods to manufacture plastic parts (Mehat and Kamaruddin, 2011; Xu, et al., 2015; Yin, et al., 2011). It is the second most common process, only slightly less popular than the extrusion, in terms of the total plastic material usage (Kutz, 2011). Injection molding is a cheap and efficient way to manufacture products that have complex geometry, a high surface finish, and dimension accuracy requirements (Kumar, et al., 2016; Su, et al., 2015; Sun, et al., 2015). It is also easily automated, which makes it more suitable for mass production (Achillas, et al., 2015; Antusch, et al., 2015).

Although the injection molding process has been widely used to manufacture all kinds of plastic parts, there are still some challenges. Some injection-molded plastic parts need extra post-processing, such as painting and removing the feeding system (Amran, et al., 2010; Zhao, et al., 2011). Also, plastic part dimensions are becoming larger, which requires larger injection molding machines with a higher clamping force (Kitayama and Natsume, 2014; Sun, et al., 2011). For example, in the automobile industry, an increasing number of large plastic parts, such as the front and rear bumper, need to be injection molded. Moreover, there is an increasing demand for plastic parts with thin thickness and high-quality, which requires more accurate control of the molding process parameters (Chen, et al., 2016; Farshi, et al., 2011; Zhou, et al., 2017).

Injection molding is a complex process involving rheology, heat conduction, material phase transition, etc. (Abbasi, et al., 2010; Hassan, et al., 2010; Khor, et al., 2010; Sidambe, et al., 2012; Sotomayor, et al., 2014). Therefore, engineers designing the plastic parts and molds must know about molding physics. Many tradeoffs must be made during the mold design process in order to produce high-quality plastic parts (Dang and Park, 2011). Traditionally, the plastic part design and mold design are largely based on the engineers' experience and in most cases, the design evolves through trial-and-error. Whether the design is feasible can only be evaluated after the mold has been tested. In many cases, the mold will have to be modified, which is time-consuming and costly (Fu and Ma, 2016).

Usually customers or manufacturers design plastic parts to meet their specific functional requirements such as dimensions. Traditionally, the mold will be detailed designed and manufactured when a product is being developed. Engineers will design the mold by considering the plastic material's theoretical shrinkage rate. After that, the molding test will be done to evaluate whether the mold design is feasible or not and to check whether the mold design will produce a high-quality product. If the part cannot meet the quality requirements, the engineers will identify why and they will redesign and modify the mold accordingly. After that, another round of molding tests will be carried out to verify whether the modification is feasible. The mold redesign process and molding test will be repeated several times until the product meets the quality requirements. However, once the mold has been designed and manufactured, any modification to the existing design is complex as it may interfere with other parts. The traditional mold design process is shown in Figure 1.2.

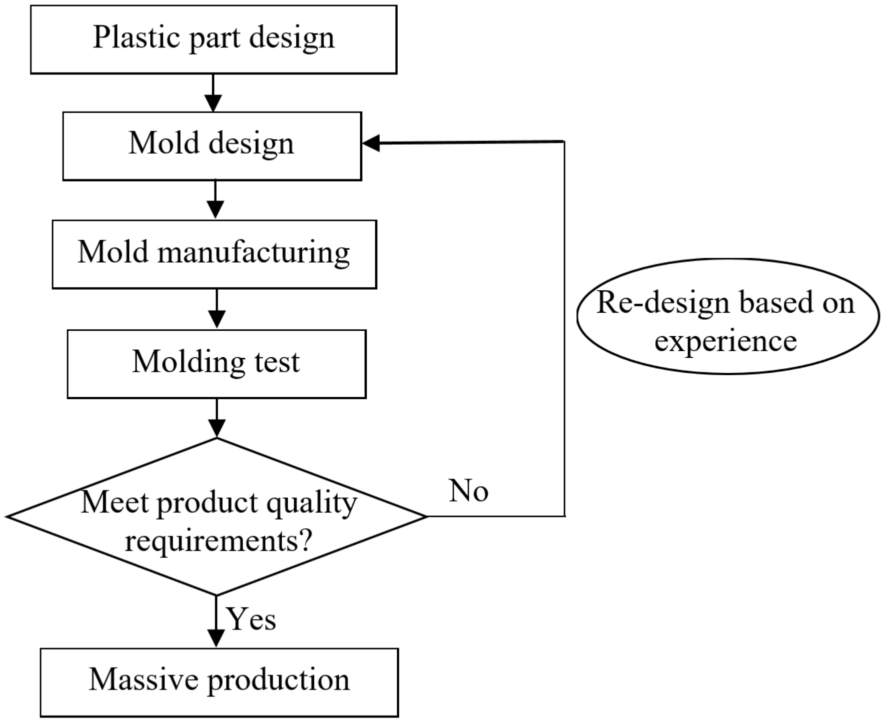


Figure 1.2 Traditional mold design process

The traditional mold design workflow is not viable in the modern market economy. The specifications for plastic products change frequently. Injection molding companies have to be able to produce high-quality plastic products efficiently and economically. A lack of knowledge about plastic molding physics could lead to a lot of time and money wasted in the lengthy molding qualification and mold modification processes. If this happens often enough, eventually, a company will become less competitive.

1.2 CAD and CAE technology

Advances in computer technology make it possible to design a mold and simulate the injection molding behavior on computers (Amran, et al., 2014; Kim, et al., 2017; Kleindel, et al., 2015; Marhöfer, et al., 2016; Peng, et al., 2017; Wang, et al., 2015). Computer Aided Design (CAD) and Computer Aided Engineering (CAE) technology are the most crucial tools in the mold industry and both have been widely used as they can help mold companies to design high-quality molds in a short time. CAD software makes it possible to design the plastic part and mold on computers and to easily modify them as necessary. Some commercial CAE packages can accurately simulate the injection molding process at different molding stages so that engineers can understand how the plastic melt flows into the mold. This will help them to evaluate the product warpage effect.

CAD packages such as Solidworks, Pro-E, NX, and Catia have been widely used to design plastic parts and molds. Most of these packages are knowledge-based and combine engineering rules, analytical results, and engineers' experience into the system, which can help the engineers to reduce design errors and speed up product development cycles by providing easy access to the built-in component database (Krimpenis and Tsakanikas, 2017; Olofsson, et al., 2017). For example, NX has a module, Mold Wizard, which is specially designed for the mold industry.

CAE simulation packages include Moldflow, Moldex3D, and Solidworks Plastics. Of the commercial CAE simulation software, Moldflow is the most successful and has been widely used both in academic research and industrial practice. Moldflow has three simulation approaches: mid-plane, surface and a 3D mesh-based model (Ding, et al., 2012; Longzhi, et al., 2010). The major difference between the approaches is that the 3D mesh-based simulation is more accurate but much more computationally expensive than the mid-plane and surface method. A number of studies have focused on enhancing computational efficiency (Cueto, et al., 2014; Park and Park, 2011; Zhou, et al., 2011). Moldflow has a large material library which includes commonly used materials in the injection molding industry. Moldflow can provide engineers with a clear picture of how the plastic melt flows into the mold and the cooling process afterward. It can also provide some simulation results which can be used to identify the possible quality problems so that the reasons for these problems can be identified by engineers even before the mold has been manufactured. The mold design can be modified accordingly on the computer and the simulation can be run again until the product reaches the quality requirements. Then the real mold can be manufactured, and the production plan can be designed. In this way, Moldflow can help engineers to design the product and the mold more efficiently and make the injection molding company more competitive in the market. A substantial portion of the product's final cost is determined at the early design stage (Chen and Liu, 1999). Therefore, the accuracy of the CAE simulation is vital for the mold design in terms of the product quality and the final cost.

With the help of advanced computer technology, a molding company can check whether the mold design can produce a high-quality product. Figure 1.3 shows the industrial mold design workflow. When a plastic product is being developed, engineers will design the mold first and then carry out the CAE simulation based on the mold configuration to check whether the simulation result meets the pre-defined quality requirements. If the simulation result is acceptable, the real mold will be manufactured, and a molding production trial will be conducted to quality the mold design. If the molding production trial again is able to produce a high-quality product, the mass molding production will be scheduled. If the CAE simulation or the molding production trial cannot meet the quality requirements, potential reasons can be identified, and the mold design can be modified on computers until high-quality plastic parts can be manufactured.

This workflow is also useful if the mold has already been manufactured but the molding production trial goes wrong. Compared to the traditional trial-and-error practice, ideally, using computers to validate the product's quality can greatly shorten the mold development cycle and cost.

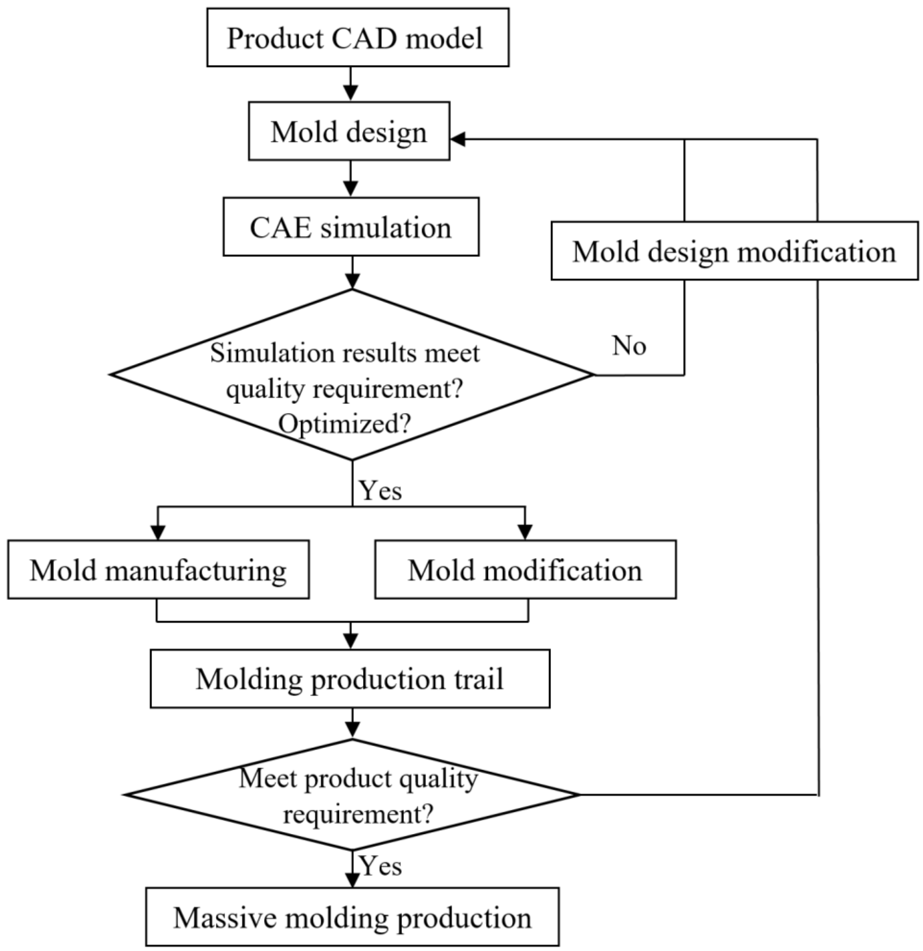


Figure 1.3 Industrial mold design workflow

Ideally, preliminary CAE simulation should be carried out before the mold has been designed. The CAE simulation results can indicate how the product will shrink at different locations and directions, which provides a more clear picture about the localized shrinkage rate. At the same time, the CAE simulation can provide the temperature distribution results, which can be used as a reference to design the cooling channels in order to achieve a uniform cooling effect. Based on the simulation results, it is possible to update the design of the plastic parts by incorporating the molding-induced shrinkage rate into the design of the plastic parts. Based on the updated product design and the product temperature distribution results, the mold can be better designed so that it will have a better opportunity to produce a high-quality product. Compared to industrial practice, the ideal mold design process can save a lot of time. The ideal mold design workflow is shown in Figure 1.4.

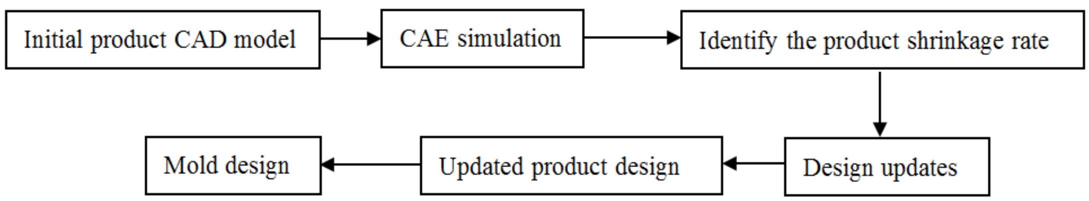


Figure 1.4 Ideal mold design workflow

Despite the wide use of CAD and CAE systems, the CAD mold design process and the molding CAE simulation have not yet been integrated, as they use different models and data structure to describe a design, and they run under their own environments which greatly impeded their interoperability (Gujarathi and Ma, 2011; Park and Dang, 2010; Smit and Bronsvoor, 2009; Su, et al., 2012). To achieve effective CAD/CAE interactions, engineers have to cyclically deal with the mold CAD model which contains only the geometrical information, and further carry out the CAE simulations which require both the geometrical and non-geometrical information. A lot of researchers have proposed different ways to enhance the integration between the design and analysis processes, such as a built-in single CAD/CAE system, or an integrated feature-based representation model, but each approach has some limitations and none of them are mature enough for industrial application (Deng, et al., 2006; Lee, 2009; Ma, et al., 2004; Matin, et al., 2012; Matin, et al., 2014; Yin, 2013). For example, Moldflow also has a modeling module which allows users to modify the mold design in its own environment but compared to the professional CAD software, the efficiency is much lower because some advanced operations are not supported in Moldflow. Currently, the commonly used way to integrate the CAD and CAE systems is through a Neutral Data File (NDF) (Son, et al., 2011; Tang, et al., 2013). In this process, the CAD system is used to design the product, then the designed product can be exported as an NDF which can be read by the CAE system, after which further Finite Element Analysis (FEA) simulation can be carried out. NDF is the bridge for the model transfer between the two different domains. Commonly used NDFs are IGES, STEP, and X-T (Ai, et al., 2010; Cho, et al., 2011; Park and Dang, 2010). Unfortunately, such an NDF approach is a problematic way to exchange data between different domains along the product lifecycle. In the current market, different companies use different CAD or CAE software tools. Even though they use the same brand of software tools, they may not use the same versions. This creates a barrier for data exchanges between different CAD/CAE tools.

Due to the aforementioned problems, the available advanced tools have not been fully utilized in the industry. In industry, a lot of companies still follow the traditional mold design process. Many companies have not been able to utilize CAD and CAE tools effectively to support mold design workflow as they do not have easy access to those tailored functions required from the advanced computer simulation technologies. It is quite common that by the time the quality problems are discovered, the mold has been manufactured and production is running. This situation is partially caused by tight production schedules but more often is due to the shortage of engineering analysis capability in companies. At the same time, CAE technology still has some limitations as the real injection molding production is very complicated and hard to control precisely. This is partially why these advanced tools have not been fully utilized in industry. Therefore, even with the help of these advanced tools, molding quality problems and optimizing the molding process remain complicated, especially when the mold has already been manufactured.

1.3 Injection molding process

The injection molding process is typically divided into four stages: filling, packing, cooling, and ejection (Madan, et al., 2015; Öktem, 2012; Tsai and Luo, 2015; Wu and Huang, 2007). During the filling stage, the plastic melt is injected into the mold at a high temperature to ensure high fluidity so that the melt can fill the mold easily. The pressure at the mold gates increases gradually to overcome the flow resistance and the temperature increases a little bit during the filling stage. When most of the cavity is filled, the molding machine will maintain high pressure for a short period of time to pack additional material into the mold. This is known as the packing stage. During the packing stage, the pressure remains almost the same but the temperature decreases gradually to ensure that the gate is fully solidified at the end of the packing. Then, the coolant removes most of the heat during the cooling stage. It is preferable for the cooling effect to be fast and uniform, but this is hard to achieve. During the cooling stage, the molded part begins to solidify, and both the temperature and pressure decrease. After that, the part is ejected from the mold. During the ejection process, the part will cool down a little bit and the pressure will be released. After being ejected from the mold, the product cools to room temperature.

The molten plastic goes through a complex physical transition in the mold until the plastic product has been manufactured. This makes it difficult to control the quality of the injection-molded plastic part, which is influenced by many factors including the design (of both the part and the mold), the properties of the plastic, and the parameters of the entire molding process (Chen, et al., 2016; Dang, 2014; Zhang, et al., 2015).

The melt temperature will influence the molten plastic viscosity and fluidity, which will ultimately influence the quality of the injection-molded plastic parts (Dobránsky, et al., 2013; Wang, et al., 2013; Xiao and Huang, 2014). Usually, a high melt temperature is preferred as it will minimize the flow resistance and make the polymer melt flow more easily into the mold. Low melt temperature will make it harder for the polymer melt to reach the end of the mold, which will result in a short shot, especially for large plastic parts with thin walls. A hot runner system is commonly used for plastic parts with thick walls, to promote a high melt temperature and good fluidity, which ensure that the mold can be fully filled at the end of the filling stage (Zhen and Gao, 2013). A hot runner system can also shorten the molding cycle time and reduce the material used as the feeding system will remain in a molten state during the molding process (Ferreira, et al., 2010).

The temperature of the mold also influences the polymer melt fluidity during the filling stage, which, in turn, will ultimately influence the quality of the injection-molded plastic part (Jeng, et al., 2010; Nian, et al., 2015; Wang, et al., 2013; Yang, et al., 2011). Polymer melt fluidity improves with an increase in the temperature of the mold. At the same time, a higher mold temperature will give the polymer adequate time to crystallize (Hsiung, et al., 1990; Li and Huneault, 2007). Consequently, the molecular chain will have a longer relaxation time and the flow-induced stress will be lower (Flaman, 1993). Because the temperature of the mold will be high, the product will take longer to cool down so that the non-uniform shrinkage and possible warpage effect are likely to be avoided. Generally speaking, a higher mold temperature will result in a better surface finish.

Packing pressure has a significant influence on the product's final shrinkage rate (Jansen, et al., 1998; Kitayama, et al., 2017; Oliaei, et al., 2016). A high packing pressure will result in low volumetric shrinkage while a low packing pressure will result in high volumetric shrinkage. Low packing pressure will result in a slow melt flow rate, which will cause the frozen layer to grow rapidly. In this case, the cooled frozen layer will prevent the hot polymer melt from filling the cavity fully and easily. Furthermore, inadequate packing pressure will cause the molten plastic to flow backward into the feeding system, which will prevent the mold from being fully filled and possibly lead to a higher volumetric shrinkage along the flow path (Rosato and Rosato, 2012). In other words, the magnitude of the packing pressure has a significant influence on how the shrinkage rate is distributed over the molded part. Unevenly distributed shrinkage will cause warpage after the molded product been ejected. However, warpage is not a monotonic function of the packing pressure. On the one hand, higher packing pressure at the optimum level will compress the product tightly so that the warpage will be reduced. On the other hand, excessively higher packing pressure will result in excess polymer melt being packed into the cavity during the packing stage which will induce higher residual stress, increasing the warpage of the product and even, at times, breaking the mold.

Packing time also influences product quality and productivity (Chen, et al., 2017; Oliaei, et al., 2016; Ramakrishnan and Mao, 2017; Singh, et al., 2015). If the packing time is too short, the molten plastic cannot be tightly packed and will flow back into the feeding system. In this case, the mold cannot be fully filled, which will result in a short shot and sink marks on the product surface. Generally speaking, a longer packing time is preferred as it can reduce volumetric shrinkage. However, when the gate has been fully solidified, extending the packing time does not provide any further improvement and makes the cycle time longer, which will affect productivity.

The cooling time should be optimized to provide sufficient time for the hot melt to fully solidify and reach the recommended ejection temperature so that the part can be ejected successfully without any damage. A longer cooling time will provide enough time for the oriented polymers and fillers to relax, which will reduce the accumulated residual stress, which can improve the product quality (Dietz, et al., 1978; Jansen, 1995). Generally speaking, increasing the cooling time will reduce warpage.

The cooling system should be carefully designed to make sure that the heat carried in by the hot molten plastic is effectively taken out by coolant and the temperature is evenly distributed across the products in order to minimize the undesired defects such as warpage and sink marks (Everett and Dubay, 2017; Li, et al., 2016; Li, et al., 2018; Lin, et al., 2015;

Venkatesh, et al., 2017). The distribution of the cooling channels is hard to determine and is influenced by many factors such as the geometry of the parts, mold configuration, and the ejection system (Kazmer, 2016; Park and Dang, 2017; Patil, et al., 2016). If the cooling system is well designed, it can dissipate the heat quickly and uniformly so that different parts of the products can solidify at the same time.

Most of the heat is taken out by coolant during the injection-molding cycle. Water and oil are the most widely used coolants as they are cheap and easy to obtain compared to organic coolants (Delaunay, et al., 2000; Zhao, et al., 2011). Water, especially, is easy to obtain and has a relatively high specific heat capacity (Chen, et al., 2009). Generally speaking, it is preferable to have the coolant temperature as low as possible in order to achieve the best cooling effect. However, some plastic material, such as nylon, requires a high coolant temperature (Rosato and Rosato, 2012).

Another significant factor to be consider is the coolant flow status, which will significantly influence the cooling effect. The coolant has two flow statuses: laminar flow and turbulent flow (Dym, 1987; Pötsch and Michaeli, 2008). Laminar flow normally runs slowly and travels in separate layers, so that the heat needs to be conducted through many layers until been removed. As is well known, water is not a good heat conductor, so the cooling effect will be low. Turbulent flow is preferred as it has a relatively high heat transfer coefficient.

The cooling effect improves with the increase of the flow speed when the coolant flow is in the laminar flow state. When the turbulent flow is fully developed, increasing the flow speed will not improve the cooling effect. In this case, increasing the coolant flow speed will only increase the pump burden.

Reynolds number is used to show the coolant flow status (Park and Pham, 2009; Saifullah, et al., 2012; Sun, et al., 2004). It is a dimensionless quantity which is influenced by the speed of the flow, the property of the coolant, and the geometry of the channel (Whelan, et al., 2012). The formula to calculate the Reynolds number is (Himasekhar, et al., 1992; Kenis, et al., 1999; Kim, et al., 2004; Sun, et al., 2002; Zhou and Li, 2005):

$$R_e = \frac{\rho v d}{\eta} \tag{1.1}$$

In which, R_e – Reynolds number;

ρ – density of the fluid;

v – velocity of the fluid;

d – hydraulic diameter of the pipe;

η – dynamic viscosity of the fluid.

The flow is in the laminar state when Re is less than 2000 (Hosseinalipour and Mujumdar, 1997; Mehendale, et al., 2000; Woodfield, et al., 2003). When Re is larger than 4,000, the coolant flow enters the turbulent state and when Re reaches 10,000, the turbulent flow is fully developed (Chien, 1982; Coulter, 2003; Koo and Kleinstreuer, 2003; Parsheh, et al., 2006).

In summary, current research mainly focuses on solving the warpage problem at the initial mold design stage. When the mold has already been made, engineers do not have an effective way to solve the warpage problem, so they rely on the trial-and-error method, which is costly and time consuming.

1.4 Research scope and objective

Traditionally, the plastic part molding is assumed that it should be ejected when the whole part is fully cooled to a temperature lower than the recommended ejection temperature. However, the traditional ejection criterion has been deemed too conservative by molding manufacturers. Especially for a product with walls of thickness above certain amount, it would take long time to effectively cool the center of the product, because plastic is not a good heat conductor; hence productivity of molding operations would be too long to be accommodated fully by manufacturer. They practice trail-and-error approach to determine the "best" cooling time during molding setup period in order to shorten the cycle time. This approach cannot be justified because it occupies molding machines and the valuable production time, and the resulted "best" timing setup only good for "as-is" mold design.

It has little learnt-knowledge impact to new mold design as well as their enhancement for new parts.

It is the candidate's proposal that early ejection upon partial solidification is a possible way to shorten the cycle time, provided that the feasibility of the method and the potential problems involved can be carefully studied. There is a theoretical optimal ejection time when during the ejection process, plastic part deformation happens but the ejection deformation will not be too excessive; even with the longer time air-cooling followed, the total warpage can still be controlled within the allowed tolerance of ejection marks and warpage of the product design, and the product can still maintain its structural integrity. From this angle, a very meaningful research topic is to determine how to predict the final product geometry with non-linear and non-uniform ejection deformation and the shrinkage resulting from air-cooling.

So far, based on the literature review which is to be detailed in Chapter 2, it could be said that there is no plausible method to determine the ejection time so that no excessive plastic deformation will occur during the ejection process and the partially solidified early-ejected product will maintain acceptable quality limits. Researchers still cannot simulate the full molding cycle accurately with early ejection and air-cooling stages, so most molding processes' productivity has not reached to their limits due to the unknown complexity of the proposed approach. The available simulation tools are no longer readily usable when the product is ejected out at a high temperature as they cannot consider the transitional processes during and after the early-ejection process.

Therefore this research work reported is to investigate how to determine when the solidification layer is thick enough to withstand the ejection force by accurately predicting the product transitional mechanical properties, so that no excessive plastic deformation will occur during the ejection process and the quality of the part can be assured with only partial solidification. It is also useful to investigate how to determine which ejection time can most effectively and significantly reduce the molding cycle time and yet be good enough to ensure a quality product.

However, both the ejection-induced deformation and the shrinkage resulting from air-cooing for the partially solidified early-ejected plastic part have not been considered theoretically. To fully understand the possible early ejection upon partial solidification phenomenon, multi-disciplinary research is needed. Within the injection molding cycle, the plastic part goes through complex physical transitions and the mechanical properties of the molded part change continuously. During the in-mold cooling stage, the product transitions from fluid to semi-fluid and then to a partial solidification state. Also, the product temperature distribution is uneven at the end of the in-mold cooling. To optimize the injection molding cycle, it is necessary to predict the partially solidified product transitional mechanical properties, deformation, possible ejection consequences and the impact on qualities such as warpage. To determine how to eject the product earlier, research in this area is necessary.

Therefore, the proposed research scope mainly focuses on the ejection and air-cooling stage and aims to predict the potential early ejection deformation and the corresponding air-cooling shrinkage so that the final product dimensions can be predicted more accurately for the early-ejected partially solidified plastic parts. In this way, we can check whether the product quality is still within acceptable limits for such early-ejected parts. Accurately predicting the non-linear and non-uniform ejection deformation and air-cooling shrinkage makes it possible to consider these factors at the mold design stage, so that the injection-molded plastic parts do not need to be fully solidified before ejection. In this case, only partial solidification is needed to ensure that no excessive plastic deformation will occur during the ejection process and the part can be ejected even earlier with the quality maintaining acceptable limits. Therefore, considering the ejection deformation and air-cooling shrinkage at the mold design stage will make it possible to design a mold that can better support early ejection.

The overall objective of this research project is to ensure injection-molded plastic product quality with less cycle time using advanced CAE technology. Specifically, four main issues have been identified that will be addressed in this thesis:

- Investigate the reasons cause warpage after pilot molding and possible methods to resolve such problems by using advanced CAE technology.
- Theoretically consider the non-linear and non-uniform early ejection deformation and air-cooling shrinkage quantitatively so that we can more accurately predict the product's final dimensions for the partially solidified early-ejected plastic part and check whether the product dimensions are within acceptable limits.
- Predict and consider the potential early ejection deformation and air-cooling shrinkage at the mold design stage, so that the mold can be better designed to support early ejection upon partial solidification and the cycle time can be further reduced by ejecting the product earlier with the product quality still within acceptable limits.
- Investigate how to determine the ejection time which can most effectively and significantly reduce the molding cycle time and yet is good enough to assure the product quality during the highly non-linear and non-uniform molding process.

The remainder of this thesis is divided into six chapters corresponding with the steps in this project.

- Chapter 2 presents the fundamental knowledge and governing equations for the injection molding simulation.
- Chapter 3 focuses on solving the warpage problem when the mold has already been made. Some of the results of this chapter have been published in the journal *Computer-Aided Design and Applications.*
- In order to predict ejection-induced deformation of early-ejected plastic parts, Chapter 4 introduces a Moldflow and Ansys integrated simulation method. The major contributions of this chapter have been submitted to the journal *Robotics and Computer Integrated Manufacturing.*
- Chapter 5 focuses on the evaluation of the shrinkage resulting from air-cooling. The major contributions of this chapter have been submitted to *The International Journal of Advanced Manufacturing Technology.*
- The next chapter (6) presents one more case study to verify the proposed method.
- Finally, Chapter 7 summarizes the main contributions of this work. Possible directions for future work are also given.

Chapter 2 Theoretical background

2.1 Filling and packing analysis

The mold filling and packing stage is a viscous, incompressible Non-Newtonian flow problem with boundaries which follows conservation of mass, conservation of momentum and conservation of energy. The flow governing equations can be expressed as (Foss, et al., 2014; Su, et al., 2012; Yashiro, et al., 2012):

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \vec{V} = 0 \tag{2.1}$$

$$\frac{\partial}{\partial t}\left(\rho \vec{V}\right) = \rho \vec{g} + \left[\nabla \cdot \underline{\sigma}\right] - \left[\nabla \cdot \rho \vec{V}\vec{V}\right] \tag{2.2}$$

$$\rho C_p \left(\frac{\partial T}{\partial t} + \vec{V} \cdot \nabla T\right) = \nabla \cdot (\kappa \nabla T) + \eta \underline{\dot{\gamma}}^2 \tag{2.3}$$

In which, ρ – density;

t – time;

$\vec{V}$ – velocity;

$\vec{g}$ – gravity acceleration;

$\underline{\sigma}$ – Cauchy's stress tensor;

C_p – specific heat;

T – temperature;

κ – thermal conductivity;

η – viscosity;

$\underline{\dot{\gamma}}$ – strain rate tensor.

2.2 Cooling analysis

For the molding behavior thermal analysis, the temperature can be divided into two parts: the fluctuating component and the cycle-average component. The fluctuating component is much smaller than the cycle-average component and can be ignored during the cooling simulation (Shayfull, et al., 2013). During the continuous injection-molding operations, the cycle-averaged temperature reaches a steady state. The heat balance during an injection molding cycle can be expressed as (Shayfull, et al., 2013):

$$\sum Q = Q_P + Q_C + Q_E = 0 \tag{2.4}$$

In which, Q_P – heat carried in by the molten plastic;

Q_C – heat carried out by coolant;

Q_E – heat dissipated to the surrounding environment.

The product will cool down during the cooling stage. The governing equation for the mold cycle-average temperature distribution can be expressed as (Himasekhar, et al., 1992; Matsuoka, et al., 1991; Tutum, et al., 2014):

$$\kappa\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)=0 \tag{2.5}$$

When the hot melt is injected into the relatively cold mold, the part surface will solidify quickly due to the high thermal conductivity of the metal. However, the thermal conductivity of the plastic material is much lower. Therefore, the cooling effect is significantly influenced by the heat transfer rate within the plastic part from the inner region to the outer surface which can be expressed as (Fan, et al., 2010; Himasekhar, et al., 1992):

$$\rho C_p \frac{\partial T}{\partial t}=\frac{\partial}{\partial s}\left(\kappa_p \frac{\partial T}{\partial s}\right) \tag{2.6}$$

In which, κ_p – thermal conductivity for the molten plastic;

s – direction along the part thickness.

The heat carried in by the molten plastic should be removed during the injection molding cycle so that the part can be cooled down to the recommended ejection temperature. The heat can be removed through 3 approaches: 1. Heat transfer between the mold surface and the product; 2. Removed by the coolant; 3. Thermal dissipation through the mold surface.

The heat flux $\bar{q}$ between the mold cavity surface and the molten plastic is given by the following equation (Himasekhar, et al., 1992; Qiao, 2006):

$$\bar{q} = -\kappa_m \frac{\partial T}{\partial \tilde{n}} \tag{2.7}$$

In which, κ_m – thermal conductivity between the mold cavity surface and the molten plastic;

$\tilde{n}$ – direction normal to the surface.

$$\bar{q} = \frac{1}{t_f + t_c + t_o}\left[\int_0^{t_f} q_1(t)dt + \int_{t_f}^{t_f+t_c} q_2(t)dt + \int_{t_f+t_c}^{t_f+t_c+t_o} q_3(t)dt\right] \tag{2.8}$$

In which, t_f, t_c, t_o – filling, cooling, and mold opening time respectively;

q_1, q_2, q_3 – instantaneous heat flux values during filling, cooling, and mold opening time respectively.

The heat removed by the coolant can be expressed as (Himasekhar, et al., 1992):

$$\kappa_m \frac{\partial T}{\partial \tilde{n}} = h_c(T_w - T_c) \tag{2.9}$$

In which, h_c – heat transfer coefficient between the mold and the coolant;

T_w – mold temperature;

T_c – coolant temperature.

The heat dissipation through the mold surface to the ambient air can be expressed as (Qiao, 2006):

$$\kappa_m \frac{\partial T}{\partial \tilde{n}} = h_a(T_w - T_a) \tag{2.10}$$

In which, h_a – heat transfer coefficient between the mold and the ambient air;

T_a – temperature for ambient air.

2.3 Warpage analysis

The plastic part may deform from the designed dimension due to the residual stress accumulated during the molding process. The residual stress can be divided into flow-induced stress and thermal residual stress due to the cooling process. The warpage simulation governing equation follows Hooke's law which can be expressed as (Kamal, et al., 2009):

$$\sigma_{ij} = c_{ijkl}\varepsilon_{kl} \tag{2.11}$$

In which, σ_{ij} – stress tensors;

c_{ijkl} – stiffness tensor;

ε_{kl} – strain tensors

2.4 Material properties

The plastic material properties also change during the injection molding process. Plastic melt is Non-Newtonian fluids whose viscosity changes with shear rates, temperature, and pressure. The viscosity can be expressed with Cross-WLF model shown below (Su, et al., 2009):

$$\eta = \frac{\eta_0}{1 + \left(\frac{\eta_0 \dot{\gamma}}{\tau^*}\right)^{1-n}} \tag{2.12}$$

$$\eta_0 = D_1 exp\left[\frac{-A_1(T - T^*)}{A_2 + (T - T^*)}\right] \tag{2.13}$$

$$T^* = D_2 + D_3 \cdot P \tag{2.14}$$

$$A_2 = \widetilde{A_2} + D_3 \cdot P \tag{2.15}$$

In which, η – viscosity;

η_0 – zero-shear viscosity;

$n, \tau^*, D_1, D_2, D_3, A_1, \widetilde{A_2}$ – material constant

The main reason for plastic product warpage is cooling shrinkage, which is inevitable because the plastic material's specific volume varies with temperature and pressure. The plastic material's specific volume follows a 2-domain Tait equation which is expressed as follows (Osorio and Turng, 2004; Rogelj and Krajnc, 2008; Spina, et al., 2014):

$$v(T, p) = v_0(T)\left[1 - C\ln(1 + \frac{p}{B(T)})\right] + v_t(T, p) \tag{2.16}$$

in which, $v(T, p)$ – specific volume at given temperature (T) and pressure (p);

$v_0(T)$ – specific volume when the pressure is 0;

C – a constant equal to 0.894; and

$B(T)$ – pressure sensitivity for the material related to temperature (T).

2.5 Ejection process

Traditionally, the ejection can be carried out when the whole product completely cools down and the highest temperature of the product (T_{max}) is lower than the ejection temperature (T_E). This criterion can be expressed as (Wang, et al., 2010):

$$T_{max} < T_E \tag{2.17}$$

The ejection temperature is recommended by material suppliers, which is based on American Society for Testing and Materials (ASTM) D3418 standard test method (ASTM Compass; Moldflow help file; Wang, et al., 2010). It can be used as an indicator to determine whether the product has been cooled and solidified enough to withstand the ejection force and whether the product will have remarkable shrinkage after ejection. However, the recommended ejection temperature is purely based on experience. No theoretical evidence can support that the recommended ejection temperature is the proper reference to determine the ejection time. Based on the heat balance equation (5), the in-mold cooling time can be estimated as (Rao and Schumacher, 2014; Singh and Bernard, 1983):

$$t_c = \frac{s^2}{\pi^2 \alpha} \ln[\frac{4}{\pi}(\frac{T_M - T_W}{T_E - T_W})] \tag{2.18}$$

In which, t_c – required cooling time;

s – part thickness;

α – effective thermal diffusivity;

T_M – melt temperature;

T_E – ejection temperature;

T_W – mold temperature.

When the molded part cools down, the amount of solid phase increases and the solicitation layer begins to grow. With the increase of the cooling time, the solidification layer becomes thicker. The amount of solid phase can be determined by indentation test which can be expressed as (La Carrubba, et al., 2003; La Carrubba, et al., 2005):

$$x_s(t) = \frac{\delta(t) - \delta_{max}}{\delta_{min} - \delta_{max}} \tag{2.19}$$

In which, $x_s(t)$ – volumetric solid fraction at time t;

$\delta(t)$ – indentation depth at time t;

δ_{max} – maximum indentation depth;

δ_{min} – minimum indentation depth.

The thickness of the solicitation layer can be expressed as (La Carrubba, et al., 2003; La Carrubba, et al., 2005):

$$x = l * x_s(t) \tag{2.20}$$

In which, x – thickness of the solid layer;

l – half-thickness of the injection-molded part.

As is well known that, the plastic material is highly temperature dependent. The material properties, such as elastic modulus, yield strength, and thermal expansion coefficient, vary dramatically with temperatures. The temperature dependent yield strength can be expressed as (Guo, et al., 2015):

$$\sigma_y = \sigma_0 \exp[-E_a/RT] \tag{2.21}$$

In which, σ_y – yield strength;

σ_0 – a constant;

E_a – energy required to yield;

R – molar gas constant;

T – temperature.

Therefore, when the product temperature is high, the plastic deformation begins very early at a low stress level. The accumulated residual stress and the ejection force may make the product occur plastic deformation which is permanent. The Moldflow material library only has material mechanical properties at room temperature and the warpage simulation only accounts for the elastic deformation involved. The plastic deformation during the ejection process is ignored by Moldflow.

The product should be ejected from the mold at the end of the cooling stage. The ejection force can be estimated in considering the friction between the product and the mold which can be expressed as (Bhagavatula, et al., 2004; Kwak, et al., 2003):

$$F_E = \mu P_A A_E \tag{2.22}$$

In which, μ – friction coefficient;

P_A – contacting pressure between the product and the core;

A_E – contacting area.

Chapter 3 Mold Modification Methods to Fix Warpage Problems for Plastic Molding Products

3.1 Introduction

Warpage is a common quality problem for injection-molded products and it is influenced by all the injection molding stages. Due to its complexity and numerous influencing factors, warpage is extremely difficult to be avoided with only judgment according to engineers' experience; it is not uncommon that warpage problems occur after mold being made. Nowadays, the advancement of the computer technology makes it possible to simulate the injection molding process with confidence. With the reasonable prediction of molding effect at the different stages, engineers could gain useful insight to understand how the plastic melt flows into the mold and why a warpage problem occurs. In reality, on the other hand, companies still face the challenges of fixing warpage problems effectively, and more critically so after the mold has been made. Compared to the traditional way of trial-and-error mold fixing method, Computer Aided Engineering (CAE) technology has the great potential to advise engineers on why the faults occur and how to fix such problems without causing significant production delay and incurring too much mold fixing cost. This chapter proposes a set of useful methods to address the above industrial challenges by leveraging the advanced CAE technology. The materials in this chapter have been documented in paper "Mold modification methods to fix warpage problems for plastic molding products" (Fu and Ma, 2016), and published in the journal *Computer-Aided Design and Applications*.

3.2 Literature review

A lot of researchers have done in-depth research to address warpage problems but most of them focused on the mold design stage with an ideal workflow to minimize the chances of warpage, i.e. starting from plastic part design, followed by molding process analysis to avoid warpage issues, and then finalize the mold design (Agazzi, et al., 2013; Jauregui, et al., 2009). In the recent years, many works also focused on the optimization of the process parameters during the injection molding process to solve the warpage problem. However, as the injection molding process has so many parameters and for each parameter, there are so many levels, the trial-and-error approach takes a lot of molding or simulation time. That is why almost all of them used the Taguchi design of experiment (DOE) method (Deng, et al., 2008; Kusić, et al., 2013; Ozcelik and Erzurumlu, 2006). For example, Oktem et al. (2007) conducted a series of experiments to find the best combination of injection time, packing pressure, packing time and cooling time to manufacture a thin-shell plastic component using Taguchi method. They found that packing pressure is the most significant process parameter influencing the warpage of the thin-shell plastic product. Although DOE has been widely used to find the best possible combination of the process parameters, the so-called “best settings” found may not be the best process settings in the definition domain. It is not uncommon that after the trail of molding processes, there is no satisfactory solution because the processing rectification has a limited effective range for warpage. On the other hand, based on our working experience, it is difficult to precisely control the process parameters as required due to the machine controlling limitation.

Some researchers tried to reduce warpage effect by adding additional ribs to strengthen mechanical performance because using ribs consumes less material than increasing the thickness of the overall product. Yang et al. (2000) compared the warpage effects of an original flat plastic part geometry and three other designs of different ribbed geometries via CAE analysis. They found that the warpage decreased significantly if both the geometry and parameters of the ribs are well selected. However, for some products, the aesthetics consideration is as important as the functional performance. For example, some outer surface could not have ribs because the logo is always placed on the flat surface. Clearly, ribs will also make the mold more sophisticated and the mold machining will be expensive and longer.

Other researchers explored optimizing the cooling system design to reduce warpage.

Cooling stage takes the longest time during the injection molding process which accounts for more than 80% of the whole injection molding cycle, so ineffective cooling system will not only influence the quality of the product, but also result in low productivity (AlKaabneh, et al., 2013; Jauregui, et al., 2009). Poor cooling system design will result in unevenly distributed temperature which in turn will cause warpage. Therefore, Agazzi et al. (2013) used conjugate gradient algorithm and Lagrangian technique to optimize the cooling system design. However, a lot of things should be considered when designing the cooling channels. For example, the cooling channels may interfere with the ejection pins and the cooling channels should be in a reasonable length so that the temperature difference between the inlet and outlet is less than 3℃ (Moldflow help file). Although different optimization procedures can consider some important constraints discussed above, they can be too complicated and may run into non-convergence if many constraints are taken into consideration at a time. For example, so far to the authors' knowledge, there is no optimization program could consider cooling channel machinability.

Nowadays, engineers have more options when designing the cooling channels as the development of advanced manufacturing technology. For example, 3D printing makes conformal cooling channels possible by building the mold insert layer by layer (Wang, et al., 2011). Traditionally, cooling channels are straight channels which are hard to achieve uniform distance from the products' surface, so the temperature distribution is more likely uneven. Conformal cooling channels follow the contour of the mold surface, so the distance between the cooling channels and the mold surface is the same along the cooling lines. Consequently, the evenly distributed temperature is more likely to be achieved. Shayfull et al. (2013) compared the cooling efficiency of conformal cooling channels and the traditional cooling channels over a front panel housing product. It is reported that the temperature distribution uniformity improved as much as 50% and the cooling time shortened more than 8% by using milled groove square shape conformal cooling channels. Therefore, warpage can be reduced with conformal cooling channels. However, in terms of economic efficiency, 3D printing for metals is relatively expensive, and not all the companies have easy access to this high-end technology.

Most of the previous research works follow an ideal CAD/CAE mold design workflow to minimize the warpage, which does the CAE simulation first, finds the possible problem and then solves the warpage problem based on the simulation results before the mold design is finalized. However, in industrial practice, not all the companies follow the ideal CAD/CAE mold design workflow. A lot of them are still following the traditional mold design process as there is a barrier for them to access to the advanced computer technology. It is quite common that the mold has already been manufactured and the production is running when the warpage defects are discovered. This situation is usually caused by tight production schedules or the short of engineering analysis capability in companies. In this situation, the typical design approaches reviewed above are no longer applicable. Therefore, there is a need to investigate effective ways to solve the warpage problem when the mold has already been manufactured. This paper proposes a new workflow and four methods to address warpage problems in such situation.

3.3 Limitations of the traditional methods to address warpage problems when the mold has been made

The traditional way to solve warpage problem after mold made is largely based on the knowledge and experience of the engineers. Typically, when the warpage problem has been discovered, the engineers will modify the mold based on their knowledge and experience. Then the quality of the product could not be guaranteed as the ability of the engineers varies with each other. In most cases, it is a trial-and-error process as the engineers do not have a clear picture about the reasons resulting in warpage. The quality of the molded product could only be evaluated after testing shots which are necessary and time-consuming to evaluate whether the mold modification is effective by checking the quality of the molded product. If the molded products still have warpage problem, another round of mold modification is required, and the testing has to continue until satisfactory products are constantly produced.

The trail-and-error warpage fixing approach after mold made is no longer acceptable to the modern manufacturing. The plastic products upgrade rapidly which requires the mold companies be able to manufacture mold of high-quality quickly and economically. Therefore, making any change after the mold has already been manufactured has to have the predictable effect. Unfortunately, it is hard to be said than done. Usually, without an effective methodology, the mold modification process is a guessing game in the first place and it repeats several times until the qualified product is produced. It is also possible that if the mold modification process is not effective, the mold has to be reworked substantially or totally abandoned because the mold can become more and more complicated and yet molding production gets delayed. Therefore, a lot of time and money can be wasted in the mold modification process, which makes the company less competitive in the market.

3.4 The proposed workflow to address warpage problems after the mold made

The mold modification process can be greatly shortened with the help of advanced molding simulation software, which makes it possible to confidently evaluate the molding quality and process behavior on computers. Compared to the traditional trail-and-error methods, using computers to validate the quality of molding can save a lot of cost and time.

The molding simulation software offers analysis results that indicate the possible quality defects and hence the reasons resulting in these problems can be judged by engineers after a series of simulations has been done. After the possible quality problems are identified, the mold CAD model can be modified virtually on the computer to address the possible reasons causing the defects and do the simulation again, until the simulation result is fully satisfactory. After that, the real mold can be modified. In this research work, Moldflow has been used to evaluate four different mold modification methods so that the quality of the molded product can be well predicted before the physical mold modification process.

The proposed process to address warpage problem after mold made has the following steps: (1) Utilize the CAD model of the plastic product and develop the detailed mold design model with the feeding system, cooling channels; and then export the geometrical entities to the molding simulation CAE software (Moldflow) via a NDF format (X-T was used in this work). This step realizes the transfer of geometrical information from CAD to CAE. (2) Setup CAE analysis conditions. Apply the non-geometrical information, such as material properties and process parameters. Then the simulation is ready to go. (3) Conduct molding process simulation with cooling effect analysis. Based on the simulation results, such as temperature distribution, the causes resulting in warpage can be analyzed and identified. (4) Modify the mold design or the process parameters to address the warpage causes accordingly. (5) Go through the steps from (1) to (4) again in order to verify whether the mold modifications and the new process parameters can produce qualified products. (6) If the result is not satisfactory, iterate the mold design and process modification cycle until the high-quality product is produced. (7) When the simulated product result meets the design requirement, apply the design modifications to the existing mold. The proposed workflow is shown in Figure 3.1.

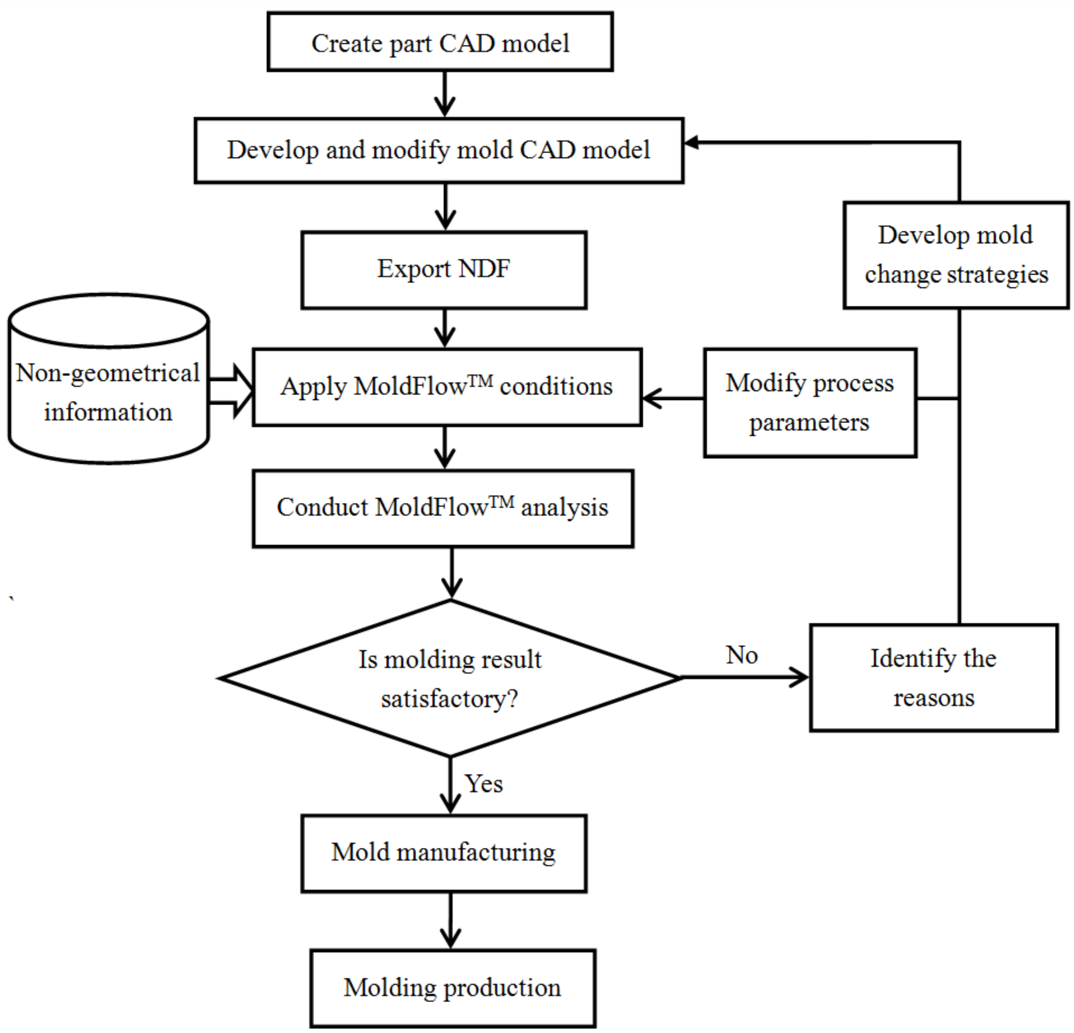


Figure 3.1 Proposed workflow addressing warpage after the mold made

3.5 Analysis of warpage influenced factors

Generally speaking, the plastic material's specific volume goes up when the temperature increases and goes down when the pressure increases. This characteristic is usually illustrated with PVT (Pressure – Volume - Temperature) curves. Figure 3.2 gives the PVT curves of HDPE while the solid black curve highlights the molding part's generic shrinkage characteristics. The curve shown in Figure 3.2 is developed with reference to the Moldflow material library (Moldflow material library). Figure 3.3 shows the HDPE molding shrinkage characteristic curve with one more dimension, i.e. molding time. HDPE is a commonly used material in the plastic industry because of its excellent mechanical performance and chemical resistance (Kanagaraj, et al., 2007).

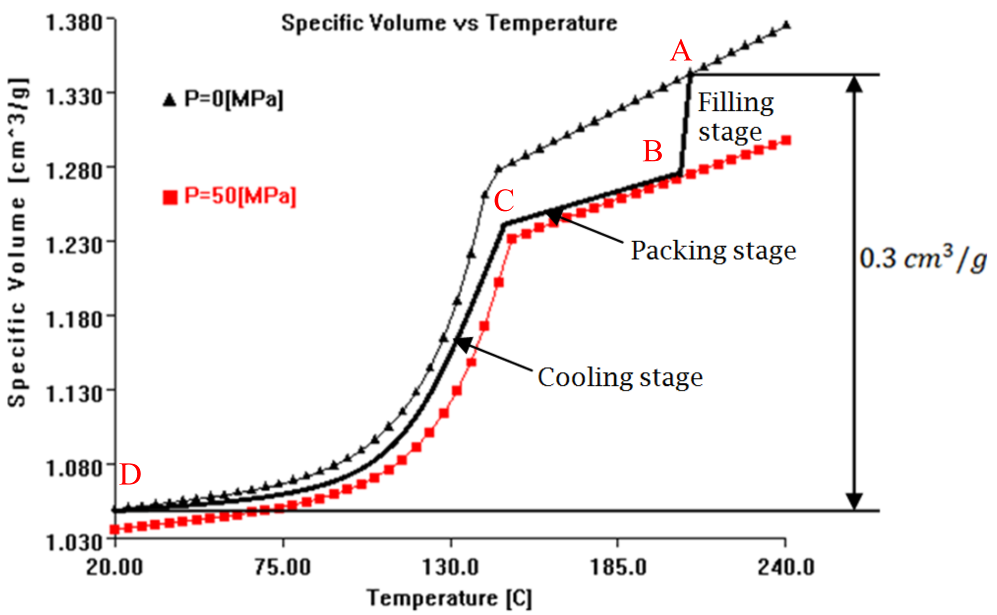


Figure 3.2 PVT curve of HDPE under different pressures (Moldflow material library)

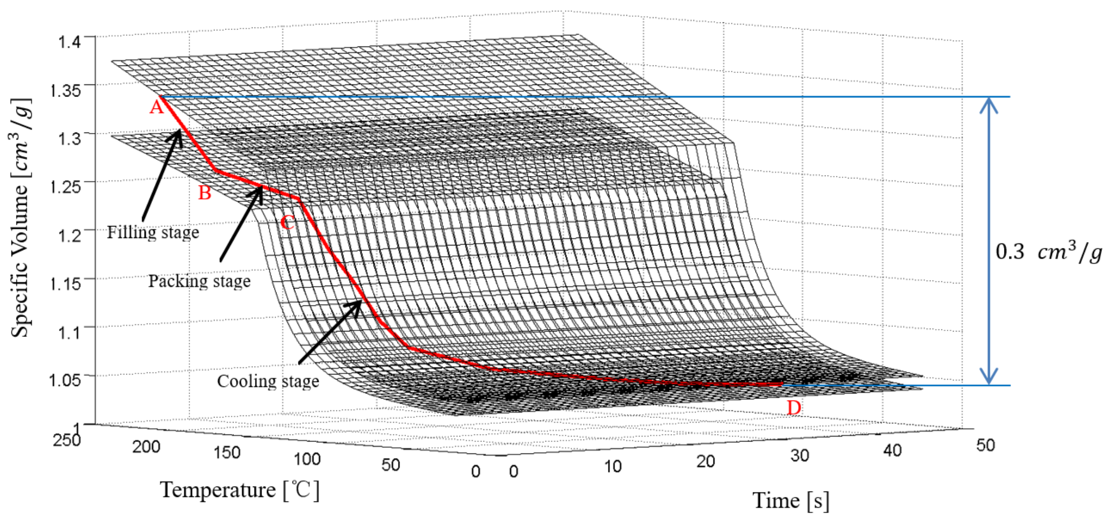


Figure 3.3 3D specific volume curve of typical HDPE

The molded part's thermal-mechanical process history and the mold constraints determine the product's warpage behavior. Assume the melt temperature is set to 210℃ and the packing pressure 50MPa which are the same as the recommended process settings for generic HDPE (Moldflow material library). The solid black curve in Figures 3.2 and 3.3 highlight the molding part's generic shrinkage characteristics, A-B shows the filling stage, B-C segment shows the packing stage and C-D shows the cooling stage.

The theoretical specific volume change of an HDPE during the injection molding process is shown in Figs. 3.2 and 3.3, i.e. approximately 0.3 cm3/g. However, the plastic product could not shrink freely because of the mold constraints. The mold also shrinks during this process to cancel the thermal expansion that happened during the injection molding process, which is less than the plastic part. Therefore, strain is created within the plastic part and the residual stress accumulates in the molded part. After being ejected from the mold, there are no more mold constraints and hence the unevenly distributed residual stress will be released, and this release makes the product deviate from the cavity shape and produces the final shape of the plastic product and so is the unwanted warpage.

Clearly, minimizing the warpage of the product should be considered during both the product design and mold design stages. The structure of the product has a significant influence on the warpage of the molded products. Products with the thicker wall will have the higher mechanical strength to resist warpage but unevenly distributed wall thickness will worsen the situation. The large flat face has a higher risk of warpage which should be avoided and changed into the ribbed structure as the ribs have higher rigidity. However, for some products, it is unrealistic to add ribs to flat faces because of the aesthetics consideration. Therefore, both functionally and aesthetically consideration should be taken into account when designing the product. Corners tend to have a higher risk of warpage because it is hard for the cooling channels to remove heat effectively in the corners, so the heat tends to be gathered. Therefore, the cooling effect might be poor and asymmetric. Also, corners have a lot of mold constraints which will have a higher chance of un-uniform shrinkage. We should give special consideration to the sharp corners when designing the product.

In the mold design stage, both the location and size of the gates will influence the final shrinkage of the product. Inappropriate selection of gate types and sizes will result in product warpage. Compared to the filling end of the product, areas near the gates tend to have smaller shrinkage rate as better packing effect can be achieved. The gates will solidify too early if the size of the gates is too small. In such circumstances, the packing pressure could not reach the end of filling, therefore, the product could not be fully packed and warpage will be resulted.

The cooling system design is extremely important as it affects warpage phenomena dominantly. The cooling system should remove the heat quickly and make the temperature evenly distributed over the product. The efficiency of the cooling system can be measured by heat flux distribution. It not only indicates how much heat can be removed during a unit time through a unit area, but also the cooling effect differences among regions. Although a cooling system with high heat flux is preferred as it can shorten the cycle time, poorly designed cooling system will result in unevenly distributed temperature which will result in warpage of the product after ejection.

The ejection system will also influence the warpage of the product. The molded product needs to be ejected at the end of the cooling stage. Usually, the product is still at a high temperature and not fully solidified inside when it is ejected in order to shorten the cycle time. Therefore, the product will deform too much if the ejection force is too high and unbalanced, which will result in unacceptable warpage of the product.

3.6 Proposed methods to fix warpage problems after mold made

The author believes that there are four promising methods to minimize warpage after the mold has been made: (1) modifying cooling channels; (2) changing the plastic material used; (3) optimizing molding process setting parameters; and (4) using a different material for mold inserts. In this paper, the author investigated the mechanisms and effectiveness of these four options and developed a simulation-guided interactive method to fix warpage problems with quantitative and predictive measures by using these methods comprehensively.

3.6.1 Modifying cooling channels

Changing the layout or increasing cooling channels is a promising option because it can effectively influence the heat removal flux and temperature distribution of the product. The heat exchange flux $\bar{q}$ is the heat transferred per unit area in unit time and it is expressed as (Ãzisik and Özışık, 1993):

$$\bar{q} = \frac{q}{A} \tag{3.1}$$

in which q – total heat transferred in unit time;

A – surface area.

Each cooling circuit should have a reasonable length and remove more heat with less temperature rise. In many cases, enhancing cooling circuit layout helps to address warpage issues. The common limitations of this method are the constraint of complex mold structure and the available spaces. For example, sometimes it is impossible to modify the cooling channel layout as the mold is so much compacted with sub-systems that no more space for new cooling channels. Further, changing the cooling channel layout may be difficult after the mold has been made because the cooling channels are distributed in many different inserts and modules, and they may need to be redesigned too. For example, additional cooling channels could spatially collide with ejectors. Last but not least, it is not a good option to design as many cooling channels as possible, because more cooling channels will make the molding system more complicated, the manufacturing cost will be higher, and the process control will be more difficult.

3.6.2 Changing plastic material

Warpage problem can also be addressed by using different plastic materials because that there exist many choices with large variations of mechanical properties and shrinkage characteristics. Some materials tend to have better fluidity so that the plastic melt can fill the mold easily and can be compressed tightly at the packing stage. Some materials have a higher strength so that they demonstrate better resistance to deformation. All these favorable plastic properties can result in a low extent of warpage. Note that the molding process parameters vary for different materials, their optimization needs good effort too.

Commonly used plastic materials are HDPE, PP, ABS, POM, PMMA, PC and PVC and their recommend process parameters and mechanical properties are shown in Table 3.1 (Moldflow material library). When choosing a material, its application properties and cost need to be evaluated in addition to the moldability. For example, PVC has excellent mechanical behavior and a PVC product tends to have less warpage compared to HDPE; this is because that PVC has much less specific volume difference during the injection molding process. For PVC (see Figures 3.4 and 3.5), under the recommended process settings, the specific volume difference is only 0.05 cm3/g while HDPE has 0.3 cm3/g as mentioned previously. Therefore, the strain and residual stress in an identical PVC part are much less comparing to a HDPE counterpart. However, PVC is not suitable for food contacting products. When the temperature goes up, PVC molecules may decompose and then release chloride ions which are poisonous and harmful to human health.

Table 3.1 Common plastic materials used in injection molding process (Moldflow material library)

Material	Mold temperature range(℃)	Melt temperature range(℃)	Ejection temperature (℃)	Elastic modulus 1st principal direction(MPa)	Shear modulus (MPa)
HDPE (T50-4400)	20-95	180-280	100	911	319.4
PP (A-333)	20-80	200-280	93	1634.35	591.477
ABS (6003)	25-80	200-280	88	2000	694.444
POM (Tenac3010)	40-90	190-210	142	2987.13	1008
PMMA (KT-80)	40-90	220-280	95	2700	980
PC (PC X-1)	70-120	260-293	127	2280	804.5
PVC (HTX6220)	21-37	180-210	70	3280	1155
PVC (FPVCFN01)	20-70	160-220	75	3280	1155

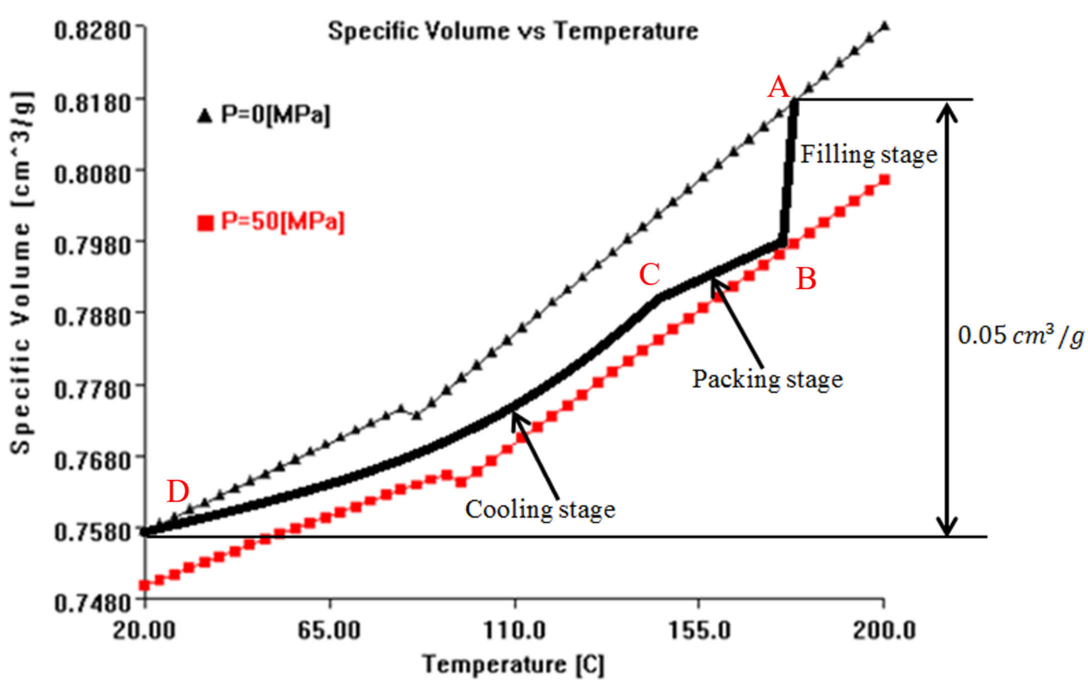


Figure 3.4 PVT curve of generic shrinkage characterized PVC (Moldflow material library)

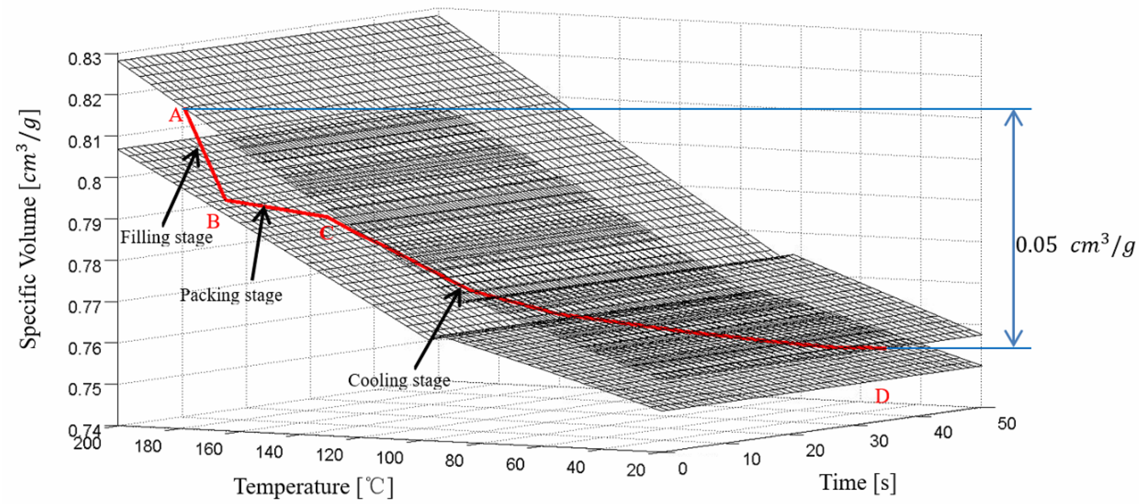


Figure 3.5 3D specific volume curve of typical PVC

3.6.3 Optimizing molding process setting parameters

Warpage issue can also be reduced by optimizing the molding process settings. The injection molding process can be controlled by a set of parameters either manually or automatically with the molding machine controller; some of them have a direct influence on the extent of warpage on the product. Modifying the process parameters could be a good option when modifying mold is more costly and time consuming, especially when the mold has already been manufactured.

As discussed in chapter 1, high mold and melt temperatures will make the plastic melt has a high fluidity during the filling stage, so that the mold can be filled easily. High packing pressure at the optimized level will ensure sufficient plastic melt flows into the mold so that the mold can be fully filled and the product can be tightly compressed. However, if the packing pressure is too high, severe residual stress will be accumulated in the product which will result in a higher risk of warpage. The packing time also needs to be optimized so that both the quality and productivity of the product can be ensured. If the packing time is too short, the product could not be fully compressed, sometimes the plastic melt will even flow backward into the nozzle.

In industrial practice, it is also feasible to adjust the temperature of each cooling circuits to influence the cooling performance. It can lead to some parts of the product solidifies first so that they have higher rigidity. However, this option is only a remedy option because it makes molding process very complicated to control and time consuming to stabilize. Another promising approach is optimizing the packing profile to make the shrinkage rate evenly distributed along the flow path (Kitayama, et al., 2014). As mentioned previously, the packing pressure distribution is uneven along the flow path which will result in different shrinkage rate over different areas. The optimized packing profile could result in the pressure distribution more even along the flow path so that the warpage can be reduced. This method is very useful for products with thick walls.

3.6.4 Using a different material for mold inserts

Using a different material for mold inserts is another promising approach. A mold has many parts and the materials for some parts can be different. As mentioned previously, the thermal performance varies with different metals. There are some metals whose thermal conductivities are much higher than typical mold steels. The heat flux $\bar{q}$ in this situation is expressed as (Qiao, 2006):

$$\bar{q} = -\kappa_m \frac{\partial T}{\partial \tilde{n}} \tag{3.2}$$

in which, κ_m – thermal conductivity;

T – temperature of the product; and

$\frac{\partial T}{\partial \tilde{n}}$ – temperature gradient.

Therefore, high thermal conductivity enables them to remove heat more effectively because of the heat flux increases linearly with thermal conductivity. Usually, due to the cost reason, high heat-conducting materials are only used for individual mold inserts in a cooling system to enhance heat removal in some specific areas. Table 3.2 compares the thermal performance of some typical metals (Moldflow material library). Based on the observation, changing the material of the parts is proposed to influence the temperature distribution of the mold and finally minimize the warpage of the product.

Table 3.2 Thermal performance of some typical metals (Moldflow material library)

Material	Specific heat (J/kgC°)	Thermal conductivity (W/mC°)	Coefficient of thermal expansion (1/C°)
P-20	460	29	1.2e-005
H-13	462	29.8	1.04e-005
Copper (pure)	380	388	1.76e-005
Al	880	190	2.39e-005
Be-Cu	360	130	1.7e-005

3.7 Case study 1

A thorough industrial case study sponsored by a Canadian plastic molding company is carried out with a container to carry milk bottles. This product, named as Milkcrate, encountered serious warpage problem which has already influenced its functionality. As shown in Figure 3.6, the side walls warp towards the core and make the inside space not enough to hold 4 bottles of milk. When we got this project, the mold has already been designed and manufactured. Therefore, it was required to minimize the changes on either the Milkcrate model or the mold design because such changes would be extremely expensive and time consuming to do so.

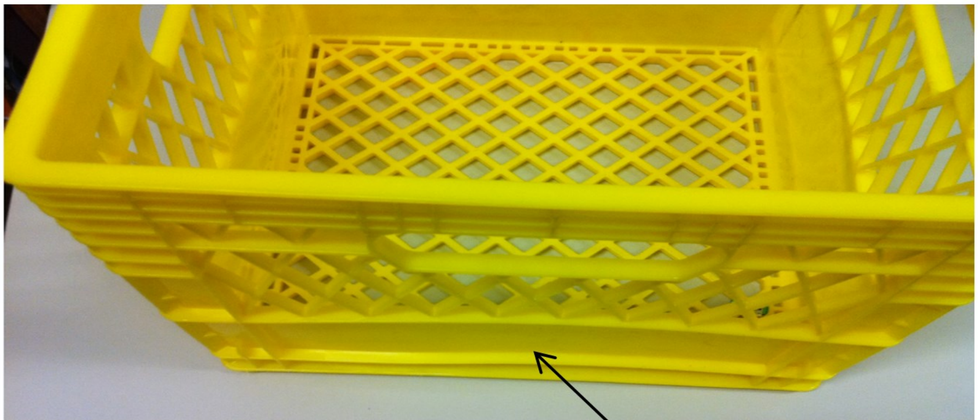


Figure 3.6 Warpage of Milkcrate, a real product

As the real production scenario is so complicated, to build up the basis of confidence for Moldflow simulation results, the initial simulations using the real mold design and initial process settings were carried out. Table 3.3 shows the real process parameters collected from the industry partner. The material used for the simulation is Marlex 9708 PE from Chevron Phillips and the material properties are shown in Table 3.4. The mold configuration is shown in Figure 3.7 and the results are shown in Figs. 3.8 and 3.9.

Table 3.3 Moldflow process settings for Milkcrate

Melt temperature	227 ℃	Cooling time	26 s
Injection time	3.8 s	Coolant	Cold water
Packing time	2 s	Packing pressure	55 MPa

Table 3.4 Mechanical properties of Marlex 9708 PE

Elastic modulus (E1)	1429 MPa	Poisson's ratio	0.433
Elastic modulus (E2)	1580 MPa	Shear modulus	498 MPa
Coefficient of thermal expansion (α1)	0.0001871/℃	Coefficient of thermal expansion (α2)	0.0001941/℃

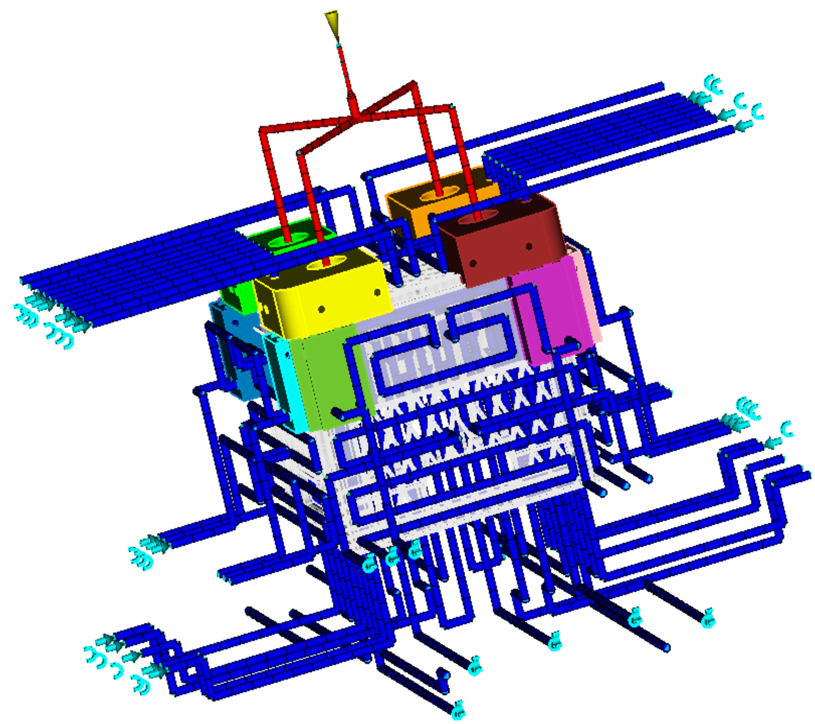


Figure 3.7 Mold configuration of Milkcrate

Comparing Figures. 3.6 and 3.8, it can be observed that the warpage pattern is tally to the real product and the deformation amount simulated is approximately reflecting the actual value within a tolerance of +/- 20%; hence it can be concluded that Moldflow is an effective tool to predict warpage. Figure 3.9 shows that the temperature distribution of the Milkcrate was uneven. Some areas near the bottom section of the side walls get cold quicker while the middle section cools much slower. This was because 12 Be-Cu inserts were used in the bottom areas of the mold. As can be seen in Table 3.2 that Be-Cu has a very high thermal conductivity compared to the mold steel, which makes the areas contacting with Be-Cu inserts solidified quickly and this is an important contributing factor for the warpage.

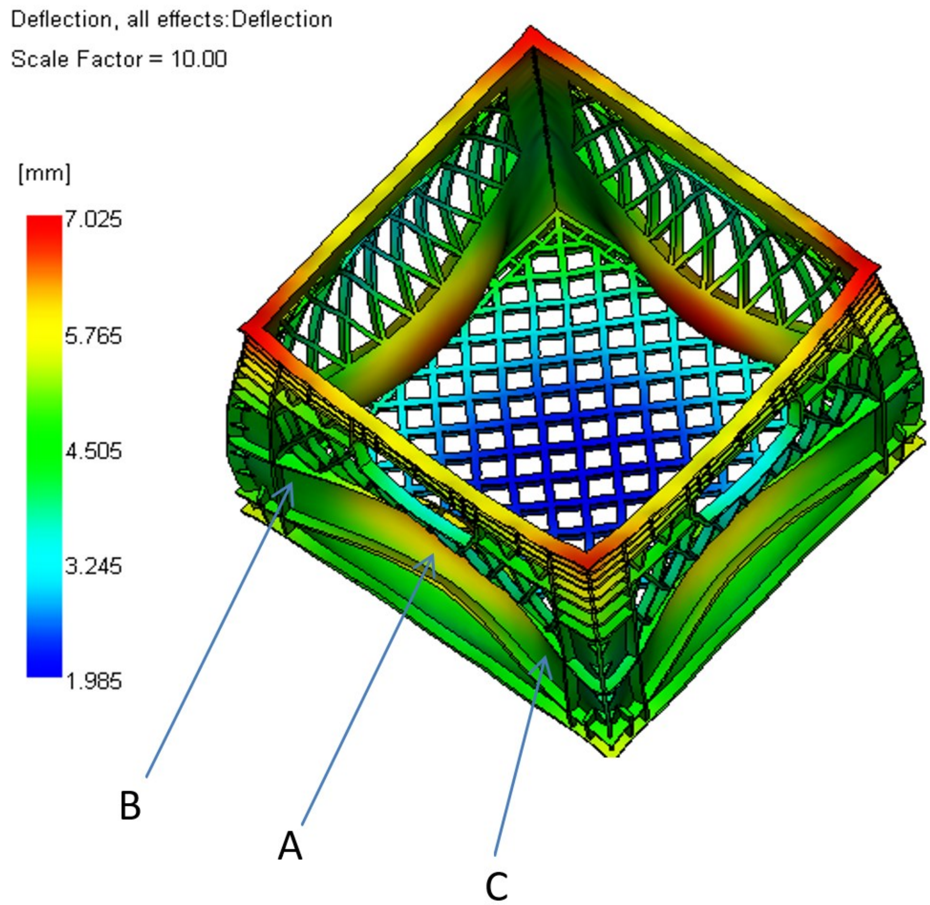


Figure 3.8 Warpage of Milkcrate (initial simulation)

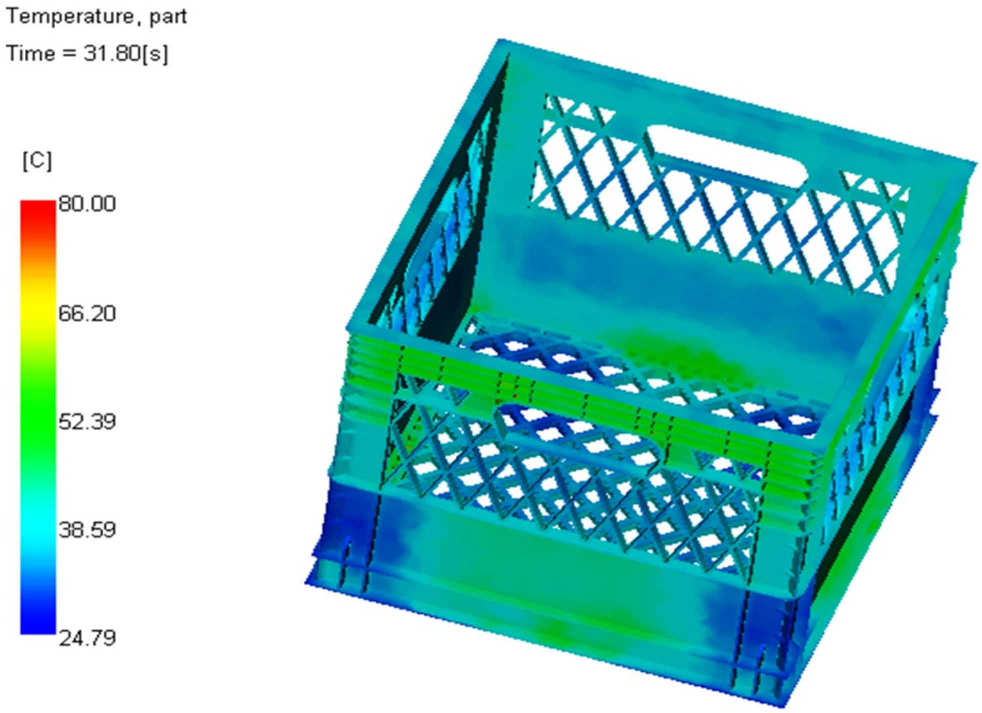
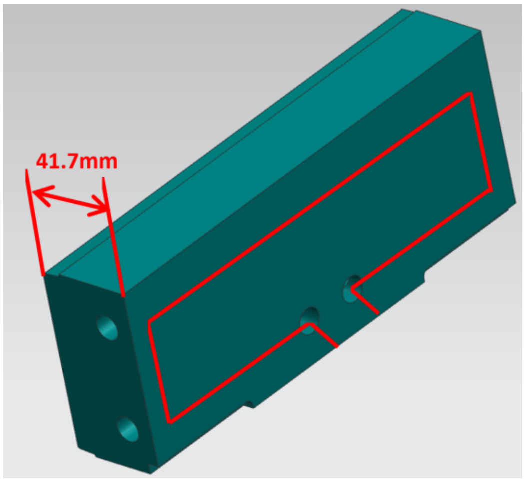
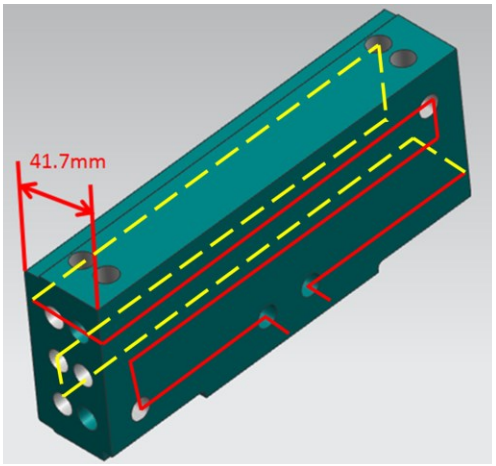


Figure 3.9 Temperature distribution of Milkcrate (initial simulation)

With the support of molding CAE simulation capability, some potential ways to minimize the warpage of Milkcrate were explored. One possible way suggested was to add more cooling channels to the side walls so that the temperature would be more evenly distributed over the middle section. After simulating the original and the enhanced designs of cooling channels as shown in Figure 3.10, the result was shown in Figure 3.11. It can be seen that the warpage quality improved a lot. The simulated deflections of three representative points for the original and the new design of the cooling channels are shown in Table 3.5.





(a) Original cooling circuit design (b) New cooling circuit design

Figure 3.10 Original and new design of the cooling circuit for side insert

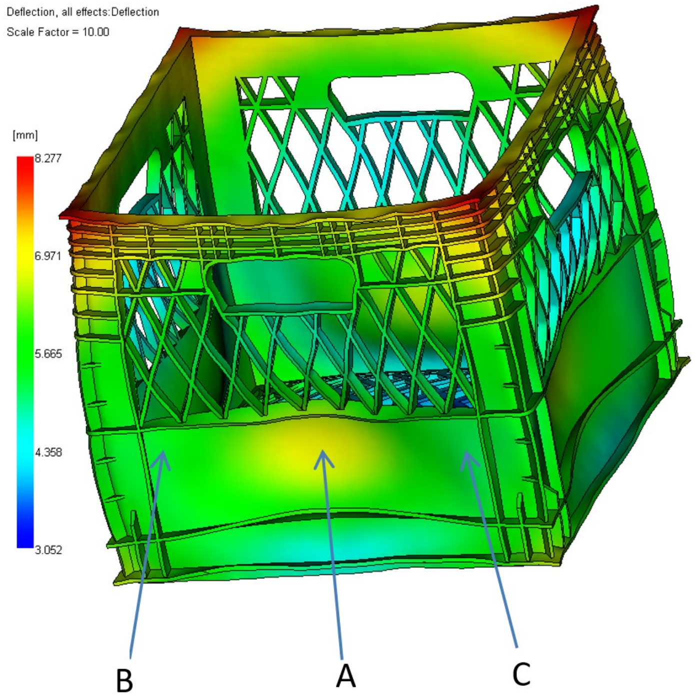


Figure 3.11 Warpage of Milkcrate with the enhanced cooling channels (simulation)

We define warpage as the maximum relative deflection of the three points A, B, and C on the interested face of the product: Points B and C are two furthest points with minimum deviation which form a reference baseline; Point A is the maximum deviation point from the reference baseline measured in the direction normal or perpendicular to the selected face. In a mathematic formula, after discounting the material shrinkage, the warpage is measured as the following:

$$\vec{\Delta} = \left(\left|\overrightarrow{X_A} - \overrightarrow{X_B}\right| + \left|\overrightarrow{X_A} - \overrightarrow{X_C}\right|\right)/2 \tag{3.3}$$

Where $\overrightarrow{X_P}$ is the coordinates of the specific point, p represents the characteristic points, i.e. A, B, or C. $\left|\overrightarrow{X_A} - \overrightarrow{X_B}\right|$ stands for the resulted vector component along the face normal direction.

In this definition of warpage, only the deviation along the normal direction of the face is considered because other orthogonal components are relatively small. As shown in Figure 3.8 and Table 3.5, the warpage can be worked out as 2.405 mm for the initial simulation. After adding more cooling channels, the warpage of Milkcrate improved, i.e. it has been reduced to 1.468 mm, or 38.96%. However, the mold has already been designed and manufactured at that time. It can be seen from Figure 3.10 that the insert parts contacting with the side walls are only 41.7 mm and the diameter of the cooling channels is 11 mm which is too constrained to accommodate new cooling channels. In terms of manufacturing, re-machining is also very difficult and expensive to implement more cooling channels in these parts.

Table 3.5 Deflection of three representative points for Milkcrate (more cooling channels)

Deflection Points	N515704(XA)	N515120(XB)	N515232(XC)	Warpage
Simulated deflection from the original model (mm)	7.00	4.53	4.66	2.405
Simulated deflection with enhanced cooling channels (mm)	6.818	5.373	5.328	1.468

Changing the plastic material approach was explored as well. As mentioned previously, PVC has excellent mechanical performance and it tends to shrink less during the injection molding process. Hence, the warpage of Milkcrate with PVC was simulated as shown in Figure 3.12. The warpage shown was reduced significantly as expected. The deflections of three representative points are presented in Table 3.6, the warpage of the product made of PVC can be improved up to 0.140 mm, or 94.18% less than the original HDPE material. However, this product is supposed to hold milk and as mentioned previously, PVC is poisonous if the temperature is high. Therefore, changing the plastic material to PVC was not a good option in this case.

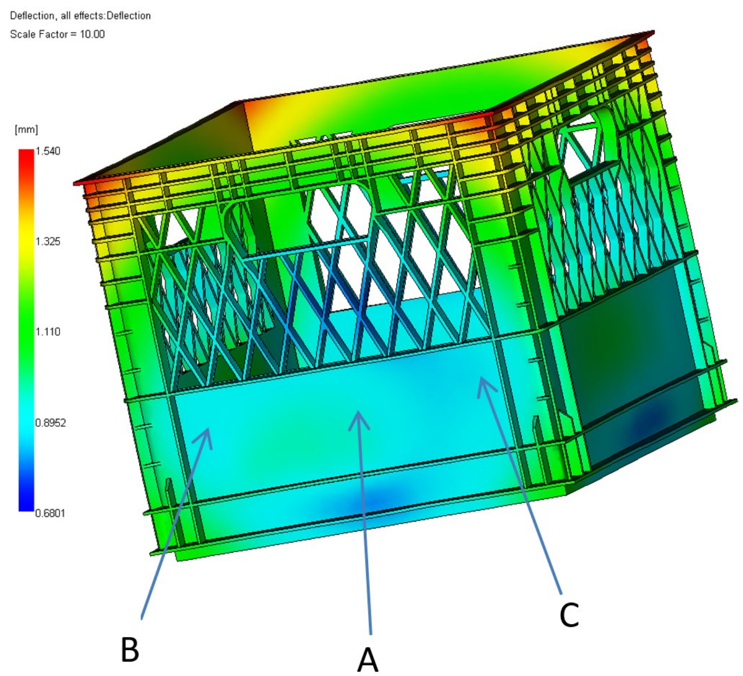


Figure 3.12 Warpage of Milkcrate with PVC (simulation)

Table 3.6 Deflection of three representative points for Milkcrate (changing material)

Deflection Points	N515704(XA)	N515120(XB)	N515232(XC)	Warpage
Simulated deflection with PVC material (mm)	1.10	0.956	0.965	0.140

Another approach of enhancement attempted was to optimize the process settings such as the packing profile. However, for Milkcrate, the packing stage only lasts 2 seconds and the gates solidified quickly, so there is no time window to modify the packing profile. In addition, the idea of changing the sidewall design with more ribbed geometry was considered, because the structure's mechanical strength can be increased; but it was ruled out simply due to the fact that the client logos are supposed to be placed on the four side walls. Moreover, the module to form the side walls is large and the mold insert modification will be complicated and expensive. Increasing the thickness of the side walls might be also useful, but the more effective cooling circuit is needed if the wall thickness increases. This resulted in a longer cooling time and will influence the productivity. Further, increase the thickness will increase the plastic material cost at the same time.

The most cost-effective way found for this case study was using different mold insert material with high thermal conductivity for the side modules. Most parts of the mold are made of H-13 (mold steel) whose thermal conductivity is 29.8 W/m℃. For Be-Cu its conductivity is 130 W/m℃ which is much higher than H-13. Based on Equation 3, by using Be-Cu, the cooling efficiency can be improved 3.36 times. So the simulation with Be-Cu side parts was carried out. Warpage deflections with changed side inserts are shown in this Figure 3.13. We can see the warpage can be reduced a lot. As also seen from Table 3.7, the warpage of the product, after changing the side insert material, has been reduced to 0.710 mm, or 70.48% less than the original design.

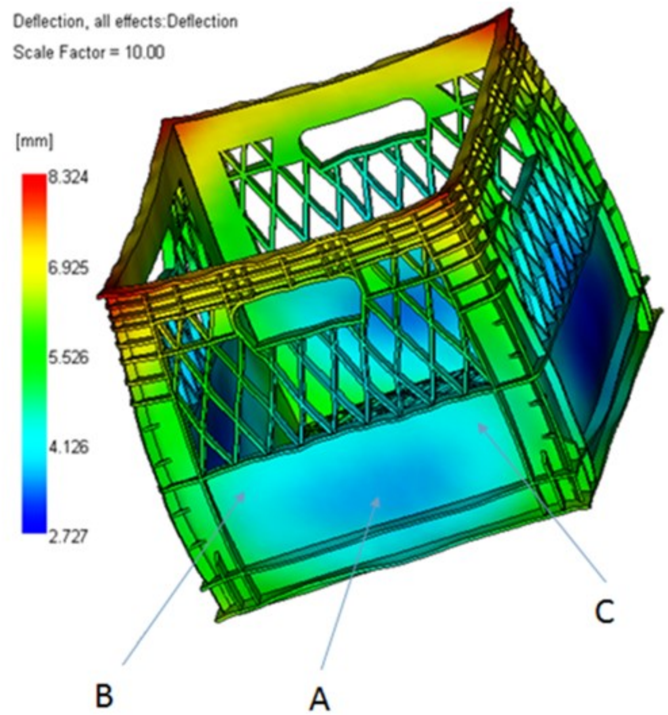


Figure 3.13 Warpage of Milkcrate with changed side inserts (simulation)

Table 3.7 Deflection of three representative points for Milkcrate (side inserts)

Deflection Points	N349820(XA)	N349870(XB)	N349767(XC)	Warpage
Simulated deflection with changed side inserts (mm)	3.75	4.51	4.41	0.710

3.8 Case study 2

Here is another case study with Canada Post tray manufactured by the same manufacturer. The tray is a thin wall plastic product used to carry mails. As can be seen in Figure 3.14, this product has a lot of edge blends and holes, which makes it extremely complicated. When we got this project, the mold has already been designed.

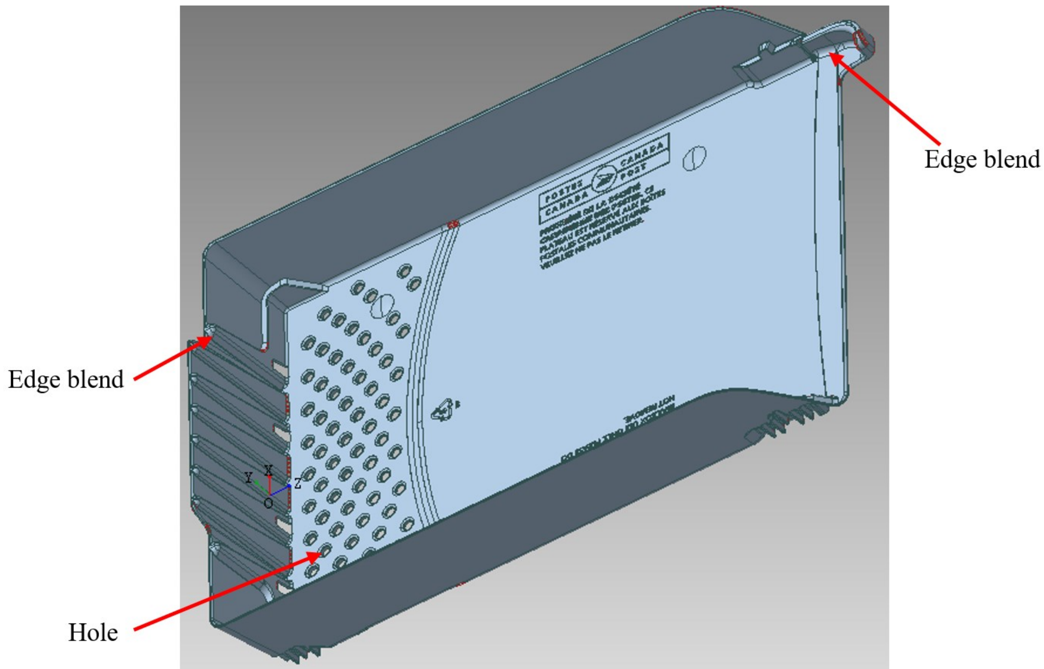


Figure 3.14 CAD model of Canada Post tray

The initial simulation was conducted using the real mold design and initial process settings. Table 3.8 shows the real process parameters collected from the industry partner. The material used for the simulation is Marlex AGN-200 PP and the material properties are shown in Table 3.9. The mold configuration is shown in Figure 3.15 and the Moldflow simulation results are shown in Figs. 3.16 and 3.17. Figure 3.16 shows that this product has a large chance of warpage. The side walls bowing towards the center of the product. From Figure 3.17 we can see that the temperature distribution of the product is highly uneven. The inner wall has a higher temperature compared to the outer wall. This is because the inner wall is formed by the core which is in the middle of the mold and that region is difficult to remove the heat although the cooling channels at the core side have

5 baffles which are designed to remove heat quickly. The temperature distribution in Figure 3.17 indicates that the cooling efficiency at core side is inadequate. At the same time, due to the semi-open structure, there is no support when the product shrinks. Poor mechanical strength together with the uneven temperature distribution results in the warpage after ejection.

Table 3.8 Moldflow process settings for Tray product

Melt temperature	277 ℃	Cooling time	18 s
Injection time	2.41 s	Coolant	Cold water
Packing time	3 s	Packing pressure	32.5 MPa

Table 3.9 Mechanical properties of Marlex AGN-200 PP

Elastic modulus (E1)	1100 MPa	Poisson's ratio	0.44
Elastic modulus (E2)	1100 MPa	Shear modulus	429 MPa
Coefficient of thermal expansion (α1)	0.000091/℃	Coefficient of thermal expansion (α2)	0.000171/℃

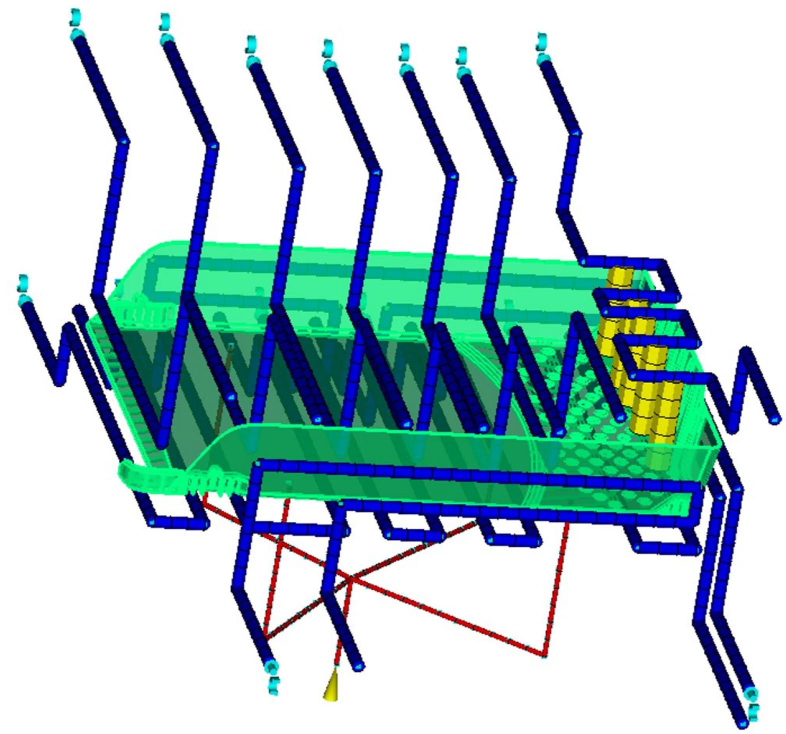


Figure 3.15 Mold configuration of Tray

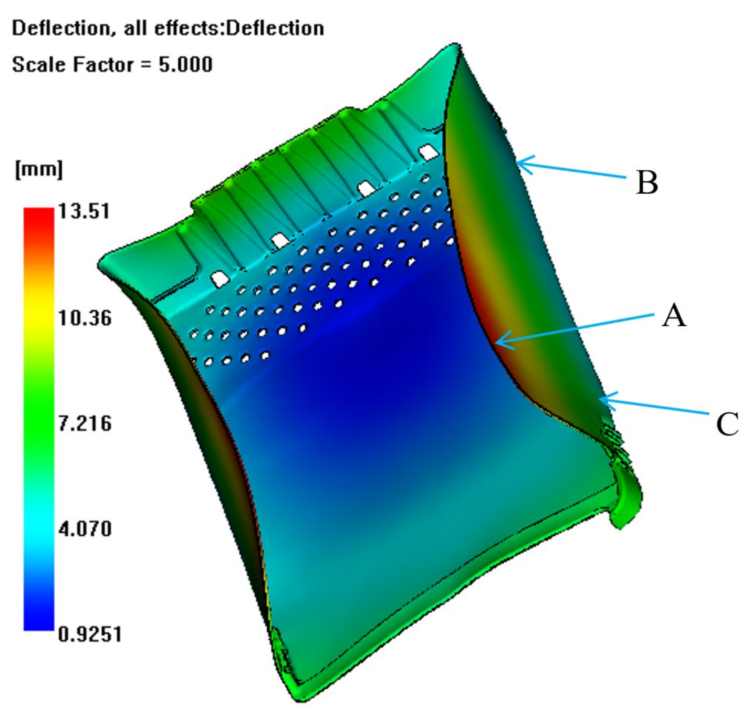


Figure 3.16 Warpage of Tray (initial simulation)

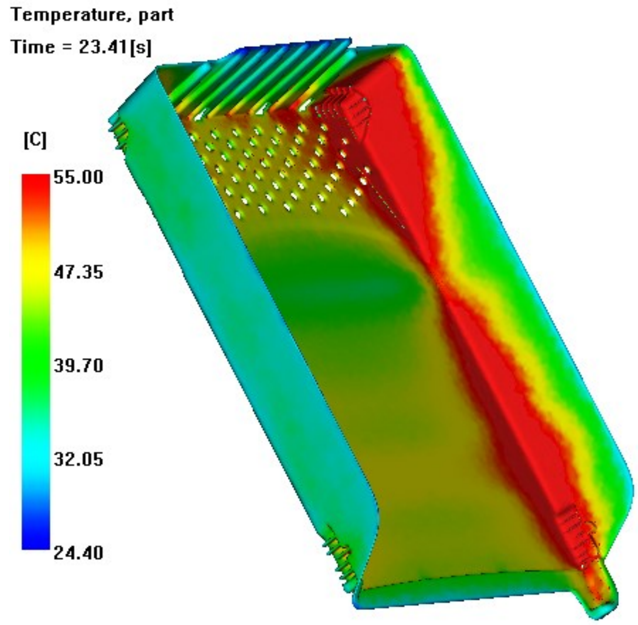


Figure 3.17 Temperature distribution of Tray (initial simulation)

Again, with the support of molding CAE simulation capability, more cooling channels were added to the mold design to minimize the warpage of Tray so that the temperature difference between the inner and outer side walls can be reduced. After checking the availability of space and spatial collide with other modules, two more cooling channels at the core side were added as shown in Figure 3.18. Then the molding simulation showed that the warpage has been reduced by 40%, but still could not be accepted. Then, decreasing the coolant temperature of the core side (marked in pink in Figure 3.18) is tried. The simulation result is shown in Figure 3.19. It can be seen that the warpage quality improved a lot. The deflections of three representative points for initial and more cooling channels simulation are shown in Table 3.10. Following the warpage definition mentioned above, the warpage for the initial simulation is 8.91 mm. After adding more cooling channels, the warpage of the Tray has been reduced to 0.96 mm, or 89.23%.

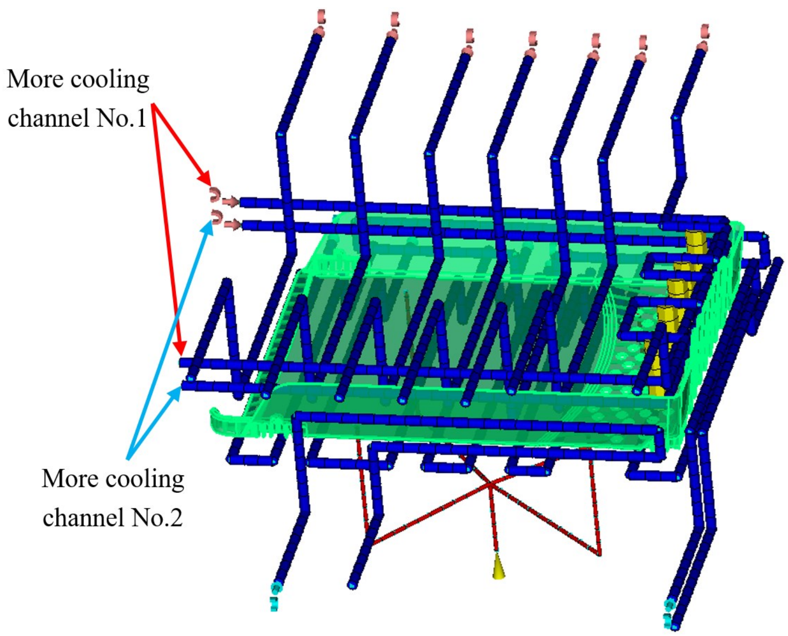


Figure 3.18 Mold configuration of Tray (more cooling channels)

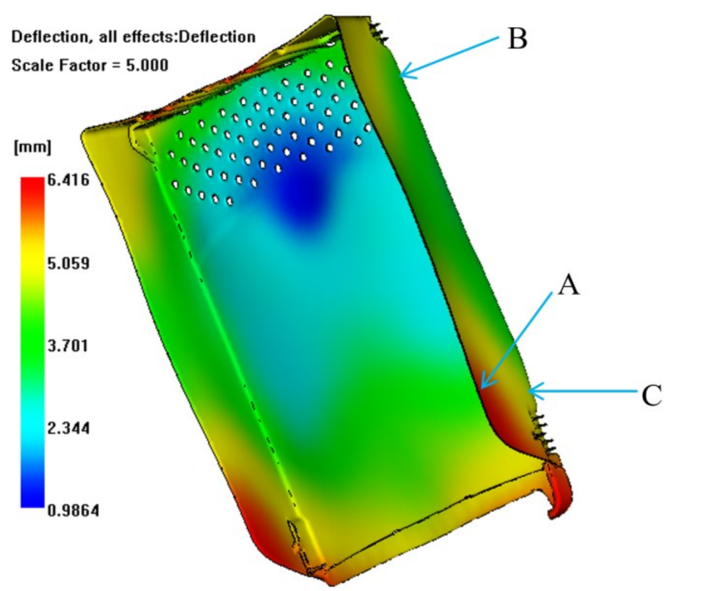


Figure 3.19 Warpage of Tray after adding more cooling (simulation)

Table 3.10 Deflection of three representative points for Tray (more cooling channels)

Deflection Points	N191578 (XA)	N212055 (XB)	N211030 (XC)	Warpage
Simulated deflection from the original model (mm)	13.44	4.36	4.70	8.91
Simulated deflection with more cooling channels (mm)	5.01	4.12	3.98	0.96

Changing the plastic material is another possible way. We changed the plastic material to PVC and did the simulation again. The warpage of the product with PVC is shown in Figure 3.20. As can be seen that the warpage reduced as expected. The deflections of three representative points are shown in Table 3.11. After changing the plastic material, the warpage of the product improved, i.e. it has been reduced to 7.17 mm, or 19.53%.

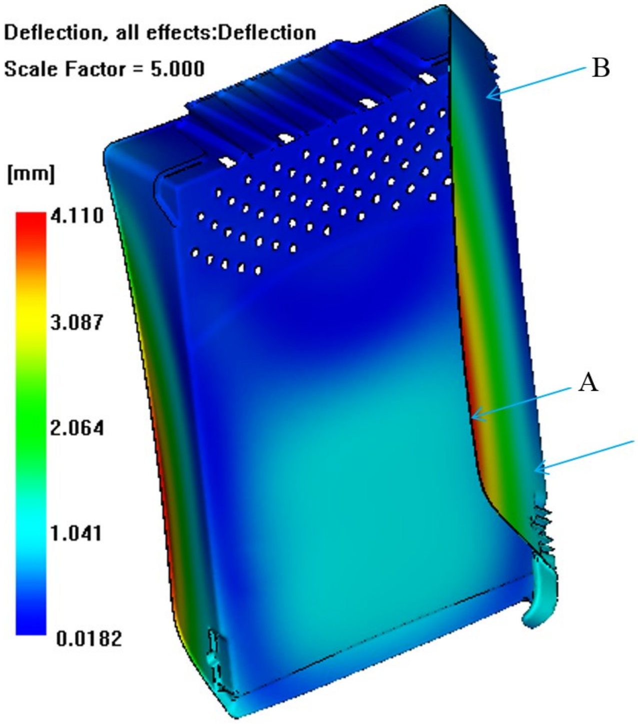


Figure 3.20 Warpage of Tray with PVC (simulation)

Table 3.11 Deflection of three representative points for Tray (changing material)

Deflection Points	N191578 (XA)	N212055 (XB)	N211030 (XC)	Warpage
Simulated deflection from the original model (mm)	13.44	4.36	4.70	8.91
Simulated deflection with PVC material (mm)	4.05	0.37	0.56	7.17

Another possible way is optimizing the process settings such as packing profile. However, same as case study 1, the packing stage is too short and the gates solidified quickly, so there is no time window to modify the packing profile. Or, we can change the side walls into ribbed geometry whose mechanical strength can be increased; but it will make the mold complicated and the machining cost will increase. Increasing the thickness of the side walls might be also useful, but the more effective cooling circuit is needed if the wall thickness increases. This resulted in a longer cooling time and will influence the productivity. Further, increase the thickness will increase the plastic material cost at the same time. The author believed that using mold inserts with high thermal conductivity could also reduce the warpage. But after checking the mold design, the core, as well as the cavity, is a whole part. Therefore, it would be difficult and expansive to use the inserts.

3.9 Conclusion

In this chapter, we proposed four warpage-fixing methods aiming to solve the common problem more effectively and quickly after the molds have been made with integrated

CAD and molding CAE simulation cycles. The design change effectiveness has been virtually simulated on the computer with different options. This CAD/CAE coupling analysis capability greatly shortens the warpage fixing engineering cycle compared to the traditional trial and error method. Two industrial case studies are presented. The findings of this cyclic CAD/CAE simulation research offer insightful engineering scenarios of different mold-fixing options. A recent update we heard from the company was that the solution proposed by us to address the Milkcrate case has been proven effective by a new mold set for the same product with new mold insert design of more thermally conductive material, and the warpage problem has been solved. In conclusion, the proposed methods can guide optimization directions and shorten the warpage fixing engineering time in industrial applications.

Chapter 4 Computer Aided Engineering Analysis for Early-ejected Plastic Part Dimension Prediction and Quality Assurance

4.1 Introduction

The plastic part should be ejected out from the mold at the end of cooling stage. Usually, the plastic part is only partially solidified and still at a high temperature at the moment of ejection in order to shorten the cycle time and improve productivity. In this case, the mechanical strength of the early-ejected plastic part is poor, and the ejection process may cause high localized stress and so as the unfavored ejection marks or even part failure. After being ejected from the mold, the plastic part will continue to shrink and cool down to the room temperature in the open air.

Increasing demands for high-quality injection-molded plastic part with a good surface finish and high tolerance require that the ejection system should be carefully designed so that the plastic part will not induce excessive deformation during the ejection process. Commonly used ejection system consists of ejection pins, ejection sleeves, stripper plates or their combination (Bhagavatula, et al., 2004). The ejection system design is a complex task because it is influenced by many factors such as part geometry, surface finish and the available space. In some cases, the ejection system design may also interfere with the cooling channels which makes such design even more complicated (Pouzada, et al., 2004). In the industrial practice, engineers can only rely on their experience and some general design guidelines to design the ejection system. The feasibility of the ejection system can only be evaluated until the mold testing. Improper ejection system design may make the molding system very complicated, increasing the mold cost or even lead to unqualified parts.

Commercial simulation packages can only account for the complex physical transition processes that happen in the mold. The calculation terminates at the end of the cooling stage. However, injection-molded plastic parts may continue to go through complex physical transitions during the ejection process. The ejection process will influence the final quality of the molded parts, and the prediction of the ejection-induced deformations are still not well supported. It is crucial to accurately evaluate the ejection-induced deformation to make sure that no excessive deformation will happen during the ejection process and the product quality is still within the acceptable limit after the product cools down to the room temperature.

This chapter will focus on the ejection process simulation and the possible deformations involved. By accurately predict the possible ejection-induced deformations, it can facilitate the prediction of the best ejection time which can effectively reduce the cycle time significantly and yet good enough to ensure the product quality for the highly non-linear and non-uniform molding process. Ideally, based on the ejection simulation result, the ejection process can be optimized, and the mold can be better designed to support early ejection upon partial solidification. The materials in this chapter have been documented in paper "A Method to Predict Early-ejected Plastic Part Air-cooling Behavior towards Quality Mold Design and Less Molding Cycle Time", and have been submitted to the journal *Robotics and Computer Integrated Manufacturing*. Remaining questions such as how to predict the shrinkage induced during the product cools in the open air will be discussed in next chapter.

4.2 Literature review

Despite massive research works have been done for the injection molding process, the ejection stage has not been well investigated. There is very limited research work concerning the ejection process, especially the deformations occurred during the ejection stage. Kwak et al. (2003) proposed a wavelet transform method to optimize the layout and size of ejector pins to minimize strain energy so that the ejecting forces of every ejector pin are well balanced to push off the molded part evenly. They claimed that this method can minimize the number of ejector pins and part deformation. Bhagavatula et al. (2004) proposed an analytical model to estimate the ejection force and compared the result to

Ansys simulation and the experimental data. They also investigated the influence of melt temperature, packing pressure and packing time on the magnitude of the ejection force. Wang et al. (2000) proposed a numerical way to predict the ejection force and its distribution over the ejector pins. Further, they treated the injection-molded product as an elastic part and optimized the ejection system design (ejector number, location, size etc.) to make sure that plastic deformation will not happen during the ejection process. Yang and Kwon (2007) developed a numerical system based on the hybrid finite element-difference method to predict the residual stress and the final shrinkage rate for the injection-molded optical product. They treated the product as an elastic part at the ejection process and the simulation results are in good agreement with the experimental data. Zafosnik et al. (2015) came up with an analytical model to predict the maximum ejection-induced stress by using DOE and FEA simulation to make sure that no plastic deformation will happen during the ejection process. Instead of using FEA simulation for every possible combination of the geometric parameters, the analytical formula is a more efficient way to get the ejection-induced stress. In this way, they investigated the influence of four geometric parameters on the maximum ejection-induced stress. Su and Gilchrist (2016) conducted a series of experiments to investigate the influence of four process parameters on the demolding force using DOE and ANOVA. They found that mold temperature had a significant impact on the magnitude of the ejection force. Song et al.

(2008) proposed a finite element method to study the ejection-induced stress and deformation by using Ansys simulation. They also investigated how does the demolding rate, demolding angle, and stamp aspect ratio will influence the molded part mechanical response during the ejection process. They claimed that the plastic part is a failure if the ejection-induced stress exceeds the yields stress and plastic deformation happens during the ejection process.

The above research works only account for the elastic deformation happens during the ejection process. To the author's knowledge, the possible ejection-induced plastic deformation has not been studied because of the lack of plastic material comprehensive mechanical properties at different temperatures and the molded part mechanical properties are kept changing. La Carrubba et al. (2003; 2005) proposed an indentation method to monitor the injection-molded plastic part solidification process during the cooling stage. By evaluating the indentation depth at different in-mold cooling time, the solidification front and the thickness of the solidification layer can be determined. Guo et al. (2015) investigated the mechanical properties of Nylon 6 at different temperature using tensile test. They found that the yield strength and Young's modulus decreased with the increase of temperature. They also reported the stress-strain curves from 30℃-90℃ covering elastic deformation, yield, and plastic deformation.

Some researchers are trying to integrate Moldflow and Ansys in order to get a more accurate picture of the injection-molded plastic product mechanical performance, especially for product manufactured with fiber reinforced plastic material (Kulkarni, et al., 2012; Kumar, et al., 2010; Seo, et al., 2014). Kulkarni et al. (2012) proposed a Moldflow-Ansys integration way to facilitate the design of a fiber reinforced plastic injection-molded product by using Autodesk Moldflow Structural Alliance (AMSA). The fiber orientation of the product is predicted using Moldflow and then the anisotropy material properties are passed to Ansys using AMSA. Product structural analysis is carried out with Ansys. They found that, compared to isotropy material model, the orthotropic material model is more suitable for product manufactured with fiber reinforced plastic material and the accuracy is more than 92%.

4.3 Research innovation

Most of the existing research works (Bédoui, et al., 2006; Bhagavatula, et al., 2004; Kwak, et al., 2003; Song, et al., 2008; Wang, et al., 2000) about ejection deformation only consider elastic deformation at room temperature. They all treated the injection-molded product as homogeneous linear elastic part. Traditionally, only elastic deformation is acceptable during the ejection process. When the maximum localized stress is greater than the yield stress, they treat the product as a failure (Wang, et al., 2000). However, this is not always the case. It is possible that although plastic deformation happens during ejection process, the plastic parts can still keep its structural integrity and satisfy the quality requirement.

The temperature distribution of the injection-molded plastic part is uneven at the moment of ejection. The mechanical properties of plastic material are highly temperature dependent. Guo et al. (Guo, et al., 2015) reported the stress-strain curves for PA from 30℃ -90℃ covering elastic deformation, yield, and plastic deformation as shown in Figure 4.1. It can be seen that the plastic mechanical strength decreased significantly with the increase of the temperature. Therefore, for the plastic parts ejected at high temperature, the mechanical properties of the part surface and center are not the same. Especially, for plastic parts with thick walls, it is possible that the part outer surface has already solidified and rigid enough to withstand the ejection force, but the product interior part may still soft and in a transition state from molten to solidification with a temperature gradient. If the plastic parts with thick walls were to be cooled down to the temperature that only elastic deformation happens during the ejection process, the productivity will be too low. The mechanical properties of the plastic part are kept changing with the increase of the solidification lawyer. When the solidification lawyer is thick enough, the partially solidified product can be ejected out successfully with the product quality still within acceptable limits even though the center of the part is still soft or even in a molten state.

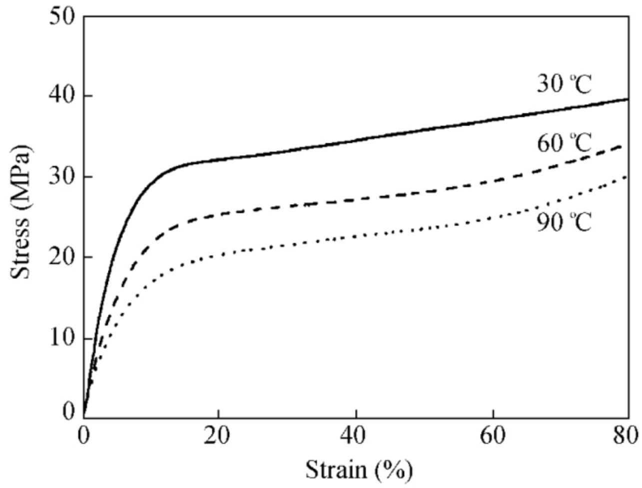


Figure 4.1 Temperature dependent stress-strain curves for PA (Guo, et al., 2015)

However, it is hard to predict whether the partially solidified part has been cooled down rigid enough to sustain the ejection force as the mechanical properties of the product keep changing. If the partially solidified part is ejected at too high temperature, the mechanical strength of the product is poor. The ejection force may leave unfavorable marks on the part and the product will deform too much, which will result in unacceptable warpage. Sometimes, the ejection process may even break the part, and in that case, the quality and stability of the production cannot be guaranteed.

The ejection time will significantly influence the product final shrinkage rates. The shrinkage rates for the product ejected at a high temperature with partial solidification differ a lot compared to the product ejected at the recommended ejection temperature. The industry so far does not have a plausible scientific method to determine the ejection time which can guarantee both the product quality and productivity simultaneously. In most cases, engineers can only rely on experience and use the trial-and-error method to determine the ejection time for the existing mold system, and the product quality and possible defects can only be evaluated after the molding test. However, they do not know whether the ejection time determined by the trial-and-error method is the best solution or not. At the same time, the injection molding process is for mass production and every second count. Therefore, shortening every second of the cycle time means a lot. Also, the trial-and-error method costs money and may not have a satisfying solution at the end.

When the mold has not been manufactured, engineers cannot estimate the ejection time by the trial-and-error method anymore. In this case, engineers have no feasible way to estimate when the part will be fully solidified and whether the product will satisfy the quality requirements after been ejected from the mold. Therefore, it is hard to determine whether early ejection upon partial solidification is feasible. It is even harder to estimate the potential ejection deformation involved as the product temperature distribution and mechanical properties are uneven and keep changing during the in-mold cooling process. The ejection deformation is influenced by many factors such as the ejection speed, contact area, the size of the product, wall thickness, friction coefficient, surface finish, mold steel material, plastic material, draft angle, release agent, ejection temperature and so on (Dearnley, 1999; Harris, et al., 2002; Pouzada, et al., 2006; Shen, et al., 1999; Su and Gilchrist, 2016). The partially solidified early-ejected plastic parts may have unevenly distributed wall thickness and mechanical properties so that the ejection stages might cause complex uneven deformations which will account for a large portion of the whole product deformation.

The available CAE simulations are no longer trustable if plastic deformation happens during the ejection process. It has been the claim of Moldflow that plastic part molding deformation can be simulated. However, the detailed review can tell that the possible ejection-induced deformations were basically ignored. The calculation terminates at the end of the in-mold cooling. Therefore, the evaluation of the partially solidified product transitional mechanical properties, deformation, possible ejection consequences and the impact on qualities such as warpage and so on, has to be predicted in order to optimize the injection molding cycle.

So far, the author has not found any effective tool which can readily predict the final product geometry with the non-linear and non-uniform ejection deformation. By accurately predict the potential early ejection induced deflection at the design stage, the mold can be better designed with the non-linear and non-uniform ejection deformation accounted for, so that only partial solidification is required, and the product can be ejected earlier with product quality still within acceptable limits. By considering the transitional solidification physics into the intelligent mold design stage, the cycle time can be further shortened compared to the case only in-mold shrinkage is considered.

4.4 Proposed methodology

4.4.1 A new ejection criterion

During the in-mold cooling process, the coolant removes most of the heat and the product begins to solidify. The mechanical properties of the plastic part are kept changing with the increase of the cooling time. When the solidification layer is thick enough which can stand the ejection force and only elastic deformation will happen during the ejection process, the partially solidified plastic part can be ejected at a relatively high temperature to shorten the production cycle time while maintaining product quality within acceptable limits even though the center of the product is still soft or in molten state. The ejection-induced stress-strain follows the simple linear relationship and the criterion can be expressed as:

$$\sigma_E = E\varepsilon_E = \frac{F_E}{A_E} < \sigma_y \qquad (4.1)$$

In which, σ_E – ejection-induced stress;

E – Young's modulus;

ε_E – ejection-induced strain;

F_E – ejection force;

A_E – area of the ejection pin;

σ_y – yield strength.

However, from the industrial point of view, this criterion is still too conservative. In most cases, it still takes a lot of time to cool the product to the state which only elastic deformation will happen during the ejection process. Actually, the product quality is still acceptable if no excessive plastic deformation happens during the ejection process. Localized plastic deformation such as the ejection marks is acceptable in most case. However, how much plastic deformation is acceptable need to be investigated.

Therefore, it is also possible for the partially solidified product to be ejected even though plastic deformation may happen during the ejection process. If the ejection-induced stress is not too large, the partially solidified plastic part can still keep its structural integrity and not break. When plastic deformation happens, the ejection-induced stress-strain no longer follows the simple linear relationship, nonlinearity exists during the ejection process. In this case, the ejection-induced stress-strain relationship follows the power law (DeGarmo, et al., 1997):

$$\sigma_E = K\varepsilon_E^n \tag{4.2}$$

In which, K – strength index;

n – strain hardening exponent.

The compromised ejection criterion can be expressed in two ways:

- If the cumulative deformation (warpage/deflection across the 3D shape) at a targeted location is less than the allowed limited, the product quality can still within acceptable limits.

$$D_c = \left(\int_0^{t_a} \dot{\gamma}_s \, dt + \int_0^{t_E} \dot{\gamma}_P dt\right) L < S_A \tag{4.3}$$

In which, D_c – cumulative deformation;

$\dot{\gamma}_s$ – shrinkage induced strain rate;

$\dot{\gamma}_P$ – ejection-induced plastic strain rate;

S_A – allowed cumulative deformation;

L – measured length;

t_a – total cooling time from T2—T6;

t_E – ejecting time.

- If the plastic deformation (local ejection deformation or damage caused by ejection) generated during the ejection process is less than allowed limits as scientifically allocated according to the full molding stages, the product quality can still within acceptable limits.

$$D_p = \left(\int_0^{t_E} \dot{\gamma}_P dt\right) L < \theta \cdot S_A \tag{4.4}$$

In which, D_p – ejection-induced plastic deformations;

θ – percentage of the allowed plastic ejection deformation.

4.4.2 Computer-aided method to predict product final dimensional and spatial deformations after ejection

Usually, the ejection process is quick and the temperature change during the ejection process can be ignored. As mentioned in chapter 2, the product temperature distribution can be expressed as:

$$\kappa\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) = 0 \tag{4.5}$$

The temperature dependent yield strength can be expressed as:

$$\sigma_y = \sigma_0 \exp[-E_a/RT] \tag{4.6}$$

The ejection force can be expressed as:

$$F_E = \mu P_A A_E \tag{4.7}$$

Based on our understanding, the ejection deformation can be expressed as:

$$D_\mathrm{E} = f(F_E, A_E, T_E, E_M) \tag{4.8}$$

In which, D_{E} – ejection-induced deformation;

F_E – ejection force;

T_E – ejection temperature;

E_M – transitional material properties.

By solving equations (4.2) (4.5) (4.6) (4.7) (4.8), the non-uniform and non-linear ejection deformation can be evaluated quantitively. In this way, we can predict the final product geometry of the partially solidified early-ejected product more accurately and check whether the product satisfies the quality requirements after been ejected at a pre-determined ejection time. Also, it paves the way for the optimization of the best ejection time which can effectively reduce the cycle time significantly and yet good enough to ensure the product quality.

$$\begin{cases} \text{Plastic deformation stress-strain relationship: } \sigma_E = K\varepsilon_E^n & (4.2) \\ \text{Temperature distribution result: } \kappa\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)=0 & (4.5) \\ \text{Temperature dependent material mechanical property: } \sigma_y = \sigma_0 \exp\left[-E_a/RT\right] & (4.6) \\ \text{Ejection force: } F_E = \mu P_A A_E & (4.7) \\ \text{Ejection deformation: } D_{\mathrm{E}} = f(F_E, A_E, T_E, E_M) & (4.8) \end{cases}$$

As mentioned previously, Moldflow does not support the ejection deformation simulation. Ansys has both the thermal and structural analysis modules which can conduct the thermal-mechanical couple field analysis. Ideally, the integration of Moldflow and Ansys combines the advantages of both software and has the ability to predict the final product dimensions more accurately for partially solidified early-ejected plastic product with ejection deformation accounted for. In this way, we can check whether the product satisfies the quality requirements when ejected at a given ejection time.

The integration between Moldflow and Ansys is not an easy task as Moldflow is not an open sourced software. Further, both Moldflow and Ansys run in their own environment. In order to integrate Moldflow and Ansys, both geometrical information, non-geometrical information and the simulation result should flow from Moldflow into Ansys. The integration between Moldflow and Ansys can be achieved in many ways: Neutral Data File (NDF), Moldflow Structure Alliance and Moldflow-Ansys Application Programming Interface (API) (Fu and Ma, 2016; Kulkarni, et al., 2012; Kumar, et al., 2010; Moldflow help file). IGES and STEP are NDFs widely used to transfer data from one domain to another. Moldflow has an API (mpi2ans.vbs) that enables the transfer of both geometrical and non-geometrical data into Ansys. Moldflow Structure Alliance is developed by Moldflow to enables the interoperability between Moldflow and Ansys.

In this paper, Moldflow-Ansys API has been used to achieve the integration. The integration schematic model is shown in Figure 4.2. First, the injection molding simulation is carried out with the real mold configuration and process settings and the simulation result is obtained. Then, Moldflow-Ansys API is executed and generates Moldflow-Ansys integration file which contains both the geometrical information and non-geometrical information. Together with the temperature distribution result at the end of the in-mold cooling from Moldflow and the corresponding comprehensive material mechanical properties (Young's modulus, Poisson's ratio, yield strength etc.) at different temperature, we should program in Ansys to consider the customized material properties for each element at different temperature and different depth of the parts and use finite element method to calculate the potential ejection deformation in Ansys. After that, design updates are carried out by incorporating the manufacturing induced shrinkage to the initial product design, so that the ejection deformation can be accounted for at the early design stage. In this way, the mold can be better designed to support early ejection upon partial solidification and the quality of the part can still be ensured with even less cycle time.

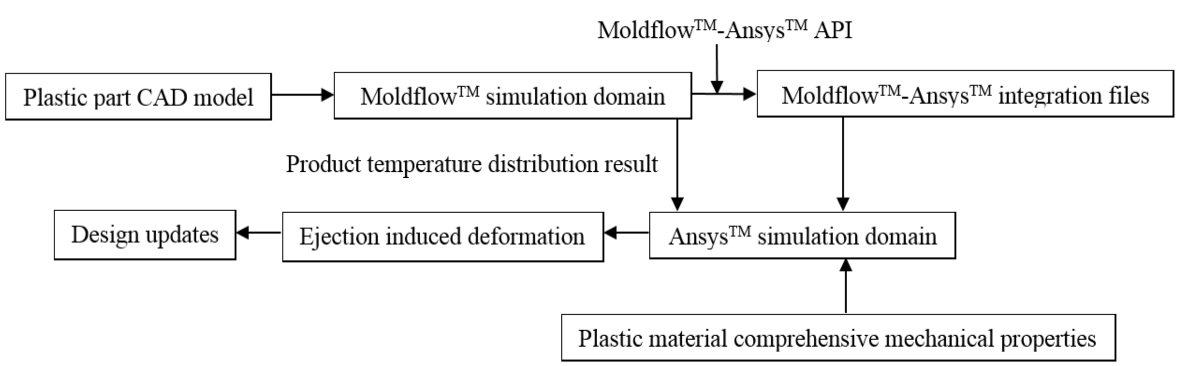


Figure 4.2 Schematic of the proposed approach for ejection simulation

Moldflow simulation result is based on node. Moldflow calculates the temperature result at each node and then form the result for the whole product. In order to transfer the simulation result from Moldflow to Ansys, the node number should be kept constant in both software.

Moldflow-Ansys Application Programming Interface (mpi2ans.vbs) can generate the Moldflow-Ansys intermediate file (.cdb). It contains the mesh information, node number, node location, coordinate system and etc. The product temperature distribution result at the end of the in-mold cooling process is also needed as the initial condition to predict the ejection defamation. The temperature distribution result at the end of the in-mold cooling process together with the corresponding node number can be exported as Patran format with extension .nod.007. At this time point, all the information needed to do the ejection simulation is available. Ansys *vread* command is used to read in the node number and temperature for each node as two arrays, and then apply the temperature result to the corresponding node. Together with the comprehensive material mechanical properties (Young's modulus, Poisson's ratio, yield strength etc.) at different temperatures, we should code in Ansys to make sure that Ansys can understand the customized mechanical properties for each element at different temperature so that the simulation can predict the ejection-induced deformations for the partially solidified plastic part. The information integration model is shown in Figure 4.3.

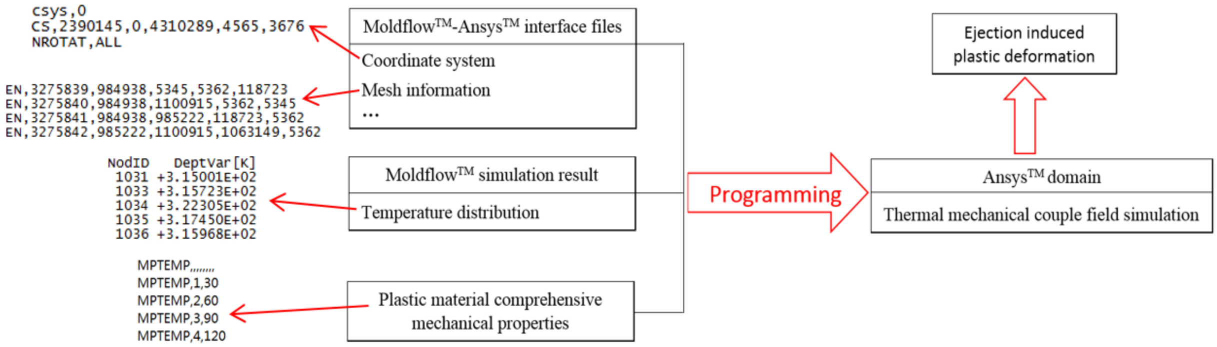


Figure 4.3 Information integration model for ejection simulation

Although Moldflow-Ansys interface files can transfer the mesh elements from Moldflow to Ansys, these two software use different element type during the simulation. Moldflow uses 4 nodes element, but Ansys uses *SOLID187* element which is a *3D 10* node tetrahedral structural solid. Ansys *EMID* command is used to add the mid-point to the 4 nodes element in order to make sure that the new element can be recognized by Ansys and can generate a reliable simulation result.

4.4.3 Ejection optimization by considering the part localized and transitional mechanical properties

As mentioned previously, the mechanical properties of the cooled part are transitional and ununiform. By solving equations (4.5) (4.6), we can predict the localized and transitional product mechanical properties which paves the way for the optimization of the ejection system. For example, we can predict whether the product has been cooled down rigid enough to be ejected, where does the product solidify first so that it is more reasonable to place the ejection pins and whether the localized deformation is within the acceptable limits. Also, we can advise the designer to better design the product and mold such as enhancing the mechanical strength of the ejection sensitive areas by adding ribs so that no excessive deformation will occur during the ejection process and place more cooling channels to cool down the ejection position first so that it can solidify quickly to support early ejection. In this way, the product and mold can be better designed to support early ejection and even less cycle time can be expected.

Together with the proposed ejection criterion, the ejection time can be optimized. By accurately predict the product deflections at several given ejection times (t_e), the formula reveals the relationship between the ejection time and product deflections can be obtained. Then, the best ejection time can be calculated using this formula so that the product can satisfy the given quality requirements. In this way, the ejection time can be optimized. The optimization problem can be expressed as:

$$\begin{cases} \text{Minimize: Ejection time } (t_e) \\ \text{Subject to constraint: } D_c = f_1(t_e) < S_A \end{cases} \tag{4.9}$$

$$\begin{cases} \text{Minimize: Ejection time } (t_e) \\ \text{Subject to constraint: } D_p = f_2(t_e) < \theta \cdot S_A \end{cases} \tag{4.10}$$

4.5 Case study

Tough grip is a product used in the oil industry to guide rods (Liu, et al., 2015). It requires very precise dimensions so that it can fit a hole and a rod simultaneously. The product, produced by Drader Manufacturing Industries Ltd., has some quality problem. As shown in Figure 4.4, the shrinkage rates for different sections are not the same and the final dimensions are hard to control. The shrinkage rate is defined as the relative dimension change caused by the injection molding process, as shown in Equation 4.11. For the real products, the shrinkage rates change from 5% — 12% at various points around the product.

$$\text{shrinkage rate} = 1 - \frac{\text{real product dimensions}}{\text{product designed dimensions}} \tag{4.11}$$

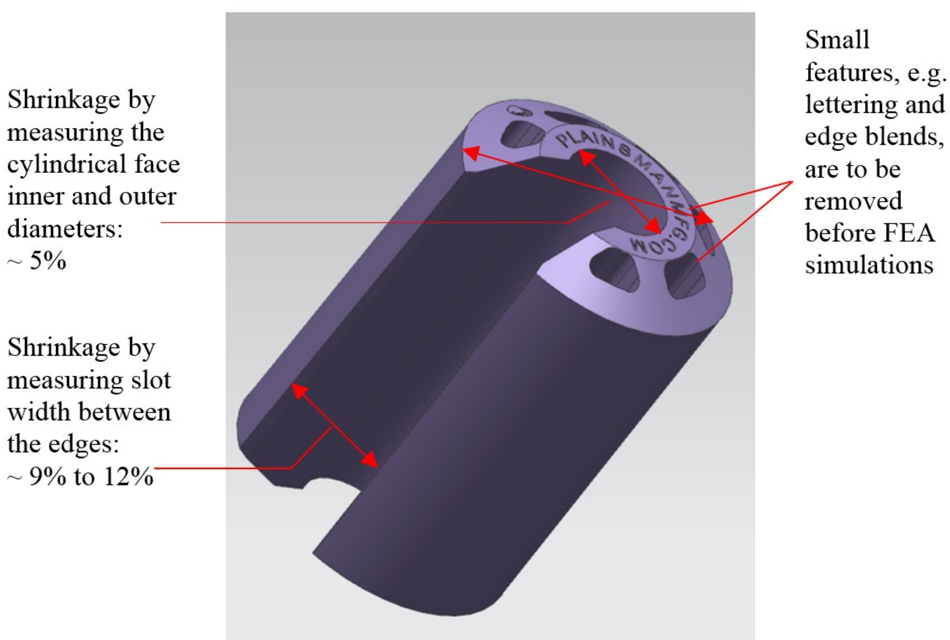


Figure 4.4 Original 3D CAD model of tough grip

We carried out the Moldflow simulation first with the real process parameters and mold configuration. All the small features are removed such as the characters on the surface and the edge blends at the holes. The feeding system and the cooling systems are created according to the real mold design. Figure 4.5 shows the meshed product with cooling channels and feeding system.

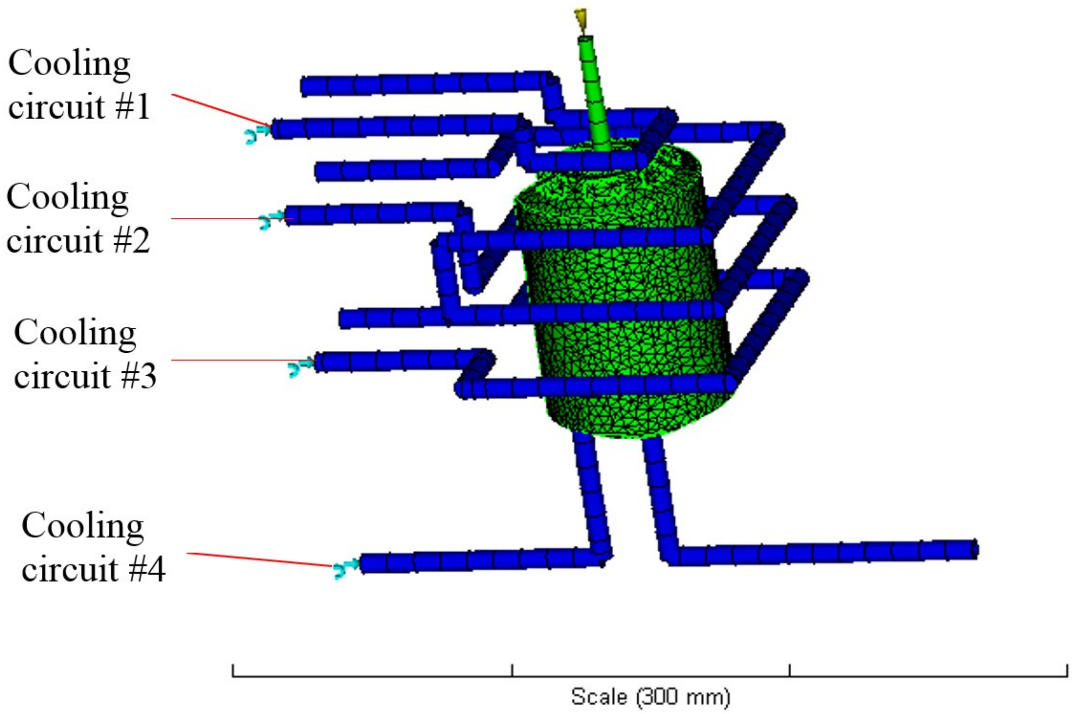


Figure 4.5 Mold configuration for tough grip

Real process parameters collected from our industry partner shown in Table 4.1 are fed into Moldflow. There are four set of cooling channels in the mold, and hot water (150℉) is used as the coolant. The flow rates for the four sets of cooling channels are different and more details are shown in Table 4.2.

Table 4.1 Moldflow process settings for tough grip

Melt temperature	274 ℃	Cooling time	45.4 s
Injection time	1.6 s	Coolant	Warm water
Packing time	8 s	Packing pressure	27.6 MPa

Table 4.2 Cooling channel flow rates provided by the industrial partner for tough grip

Flow rate \ Cooling channel	Cooling channel #1	Cooling channel #2	Cooling channel #3	Cooling channel #4
Gallon per minute (gal/min)	1.7	2.3	2.0	2.8
Liter per minute (lit/min)	6.44	8.71	7.57	10.6

The material used in Drader to produce the tough grip is PA66 from ADELL PLASTICS, which is not in the Moldflow material library. Although the material supplier provides a test report about the material (Adell Plastics), it only has some basic material properties such as tensile strength, and elongation, which are insufficient for the simulation. Hence, a material type that behaves similarly, BASF Ultramid A3Z HP, is employed in this research to replace the original material (Adell Plastics; BASF Corporation). The material properties for BASF Ultramid A3Z HP are shown in Table 4.3.

Table 4.3 Mechanical properties of BASF Ultramid A3Z HP

Elastic modulus (E1)	1920 MPa	Poisson's ratio	0.37
Elastic modulus (E2)	1880 MPa	Shear modulus	890 MPa
Coefficient of thermal expansion (α1)	0.00011811/℃	Coefficient of thermal expansion (α2)	0.0001211/℃

The deflection result is shown in Figure 4.6. Based on Equation 4.11, the shrinkage rates for both the top and the bottom sections are around 2.9%, the shrinkage rate for the upper slot is 4.54% and the shrinkage rate for the bottom slot is 4.2%. The exact shrinkage rate obtained from Moldflow simulation is shown in Table 4.4. It can be seen that the shrinkage rate obtained from Moldflow simulation differs significantly from the real product.

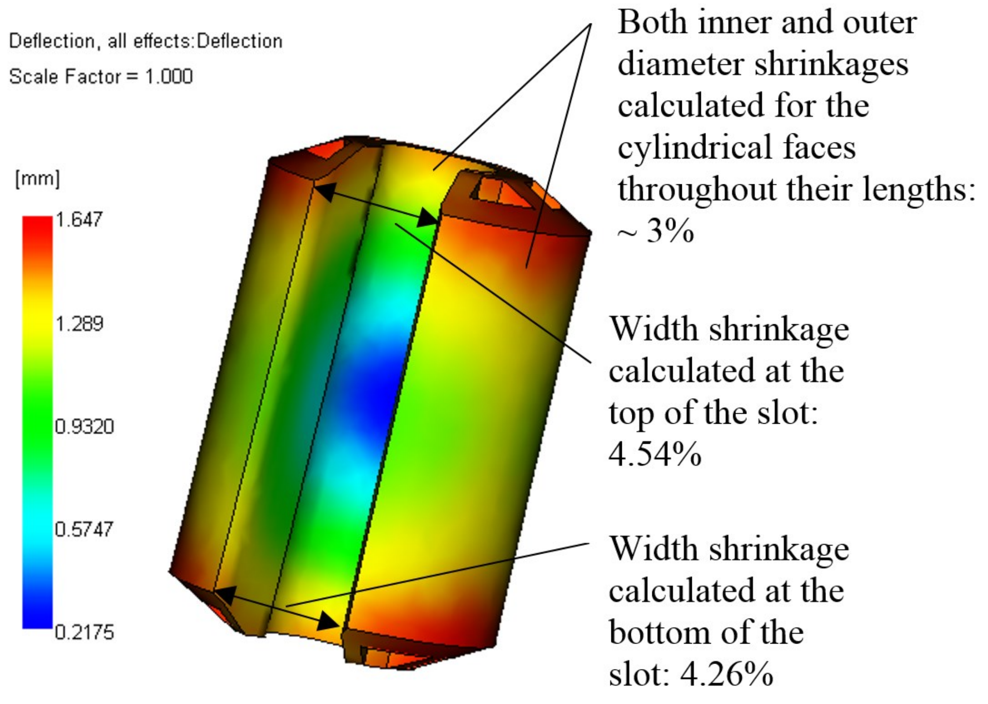


Figure 4.6 Moldflow deflection simulation result for tough grip

Table 4.4 Tough grip shrinkage rate from Moldflow simulation

	Upside Width			Downside Width			Length	
	Outer Diameter	Inner Diameter	Edge Distance	Outer Diameter	Inner Diameter	Edge Distances	Outer Length	Inner Length
Before Deformation(mm)	67.69	24.35	18.95	68.49	25.23	19.97	88.16	104.7
After Deformation(mm)	65.8	23.62	18.09	66.55	24.55	19.12	85.56	101.8
Shrinkage (%)	2.79	3	4.54	2.83	2.7	4.26	2.95	2.73

Figure 4.7 shows the product temperature result. It can be seen that the product is very hot at the end of the in-mold cooling process. It is also interesting to notice that the holes are extremely hot as they are so narrow and no cooling lines can go into them.

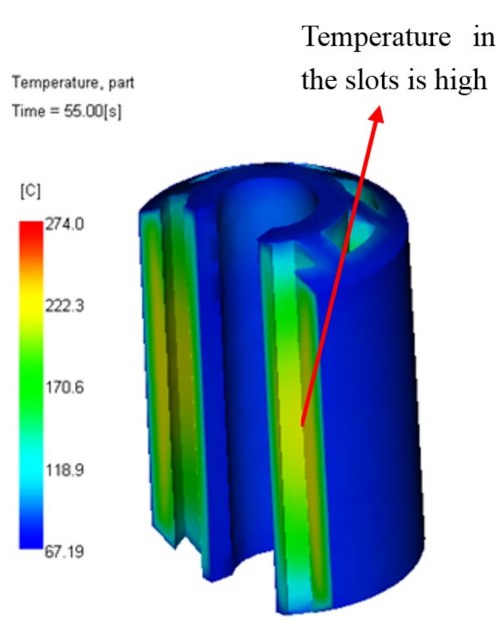


Figure 4.7 Tough grip temperature result

As can be seen from Figure 4.8, the product interior temperature is very high and uneven at the end of the in-mold cooling process, even higher than the Moldflow recommended ejection temperature which is 213 ℃ (Moldflow material library). After a further scale down of the temperature result, it is worth noticing that more than 20% of the material is hotter than 213 ℃ at the end of the in-mold cooling process. As can be seen from Figure 4.8, in the thickness direction, around half of the plastic material is hotter than the recommended ejection temperature, even after the in-mold cooling process. Therefore, ejection-induced plastic deformation might happen during the ejection process.

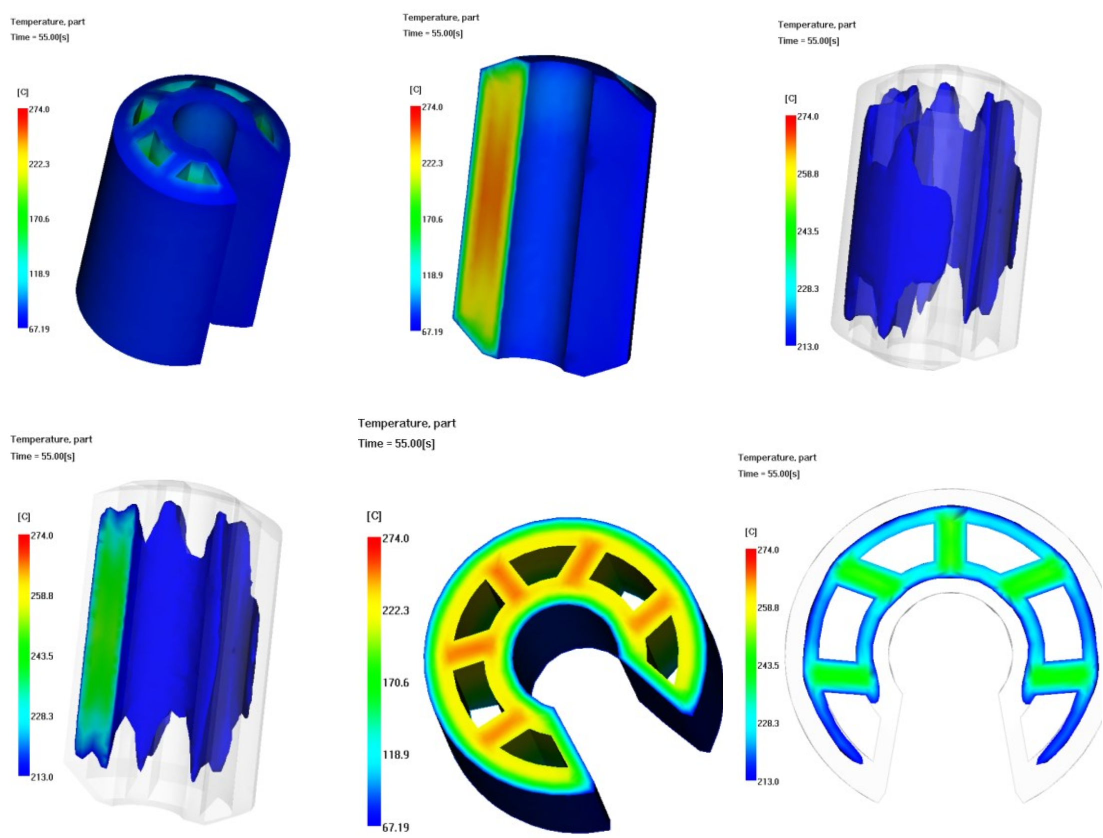


Figure 4.8 Tough grip interior temperature result

Using the method mentioned above, Moldflow-Ansys Application Programming Interface (mpi2ans.vbs) is executed and generates the Moldflow-Ansys intermediate files (.cdb). The ejection force induced pressure is around 30MPa as estimated by our industrial partner. The PA66 comprehensive mechanical properties at different temperatures are estimated based on the literature (Guo, et al., 2015) and Moldflow material library. Together with the temperature distribution result provided by Moldflow, the Ansys simulation is carried out and the ejection-induced plastic difermion is shown in Figure 4.9.

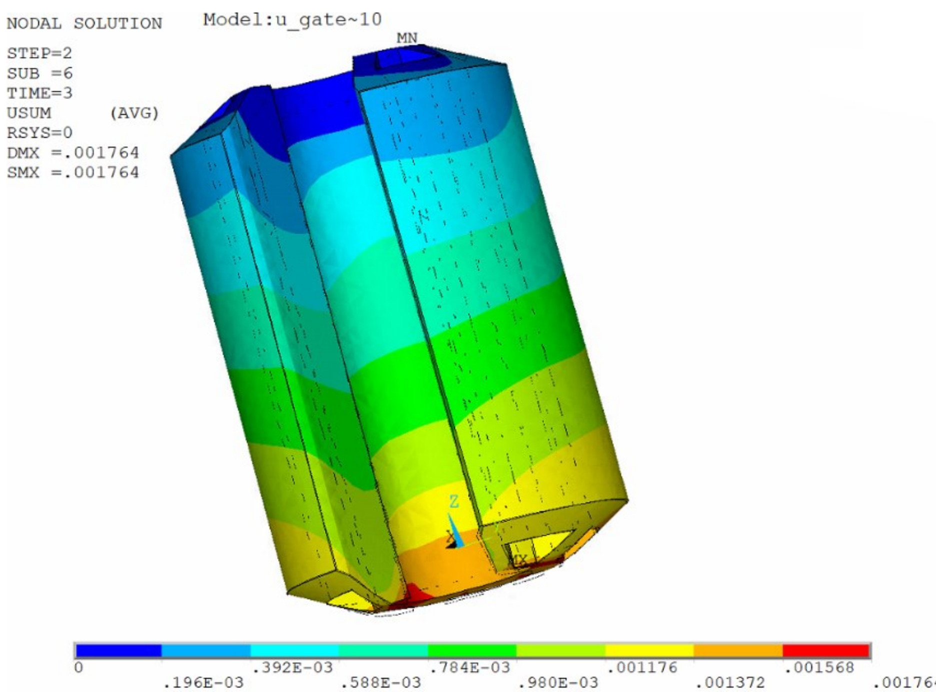


Figure 4.9 Ejection-induced deformation for tough grip

We can see that plastic deformation does happen during the ejection process. However, the product can still maintain its structural integrity and it may still satisfy the quality requirements. Based on the node distance before and after simulation, we can get the ejection-induced plastic deformation for the inner length is around 1.12mm, which account for 1.07% of the product final shrinkage rate.

After being ejected, the product is still at a high temperature and will continue to be cooled down to the room temperature in the open air with no mold constraints. The shrinkage induced during the air-cooling process might be significant and will be discussed in detail in chapter 5.

4.6 Conclusion

The traditional ejection criterion is too conservative, especially for thick wall product. It is possible that the plastic parts can still maintain its structural integrity and satisfy the quality requirement although plastic deformation happens during the ejection process. The existing research works only consider the elastic deformation involved during the ejection process. No commercial software can predict the early-ejected partially solidified product final dimensions accurately as the temperature distribution is uneven, the mechanical properties of the plastic material are transitional and the ejection process involves complex non-linear plastic deformation.

In this paper, we propose a new ejection criterion and a Moldflow-Ansys integrated way to predict the non-uniform and non-linear ejection deformation under the transitional cooling conditions with highly non-uniform and time-dependent plastic material mechanical properties. It paves the way for the optimization of the best ejection time which can effectively reduce the cycle time significantly and yet good enough to ensure the product quality.

A real industrial case study has been presented using the proposed approach. The results showed that plastic deformations happened during the ejection process and account for 1.07% of the product final shrinkage rate. The shrinkage rate got from the Moldflow-Ansys integrated simulation is more close to the real production results than using Moldflow alone for the simulation.

Chapter 5 A Method to Predict Early-ejected Plastic Part Air-cooling Behavior towards Quality Mold Design and Less Molding Cycle Time

5.1 Introduction

The ejection process and the transition after ejection will influence the quality of the injection-molded plastic parts. The last chapter discussed the ejection-induced plastic deformation for a partially solidified part that was ejected early. However, ejection-induced plastic deformation may not occur for all such parts. It is also possible that the ejection process will not seriously deform the partially solidified plastic part and that only elastic deformation will happen, even though the part is at a very high temperature at the moment of ejection. For such parts, shrinkage during the air-cooling process might be significant and cannot be ignored, especially for plastic parts that have thick walls and are ejected at high temperatures. However, the transition after ejection is not accounted for by commercial software. Therefore, even with the help of these advanced tools, solving molding quality problems and optimizing the molding process remain challenging.

Among the injection molding process, the cooling stage takes the longest time and accounts for more than 80% of the injection molding cycle (Chen, et al., 2008; Hassan, et al., 2009). At the same time, the majority of the shrinkage happens in the cooling stage, which will influence the product quality eventually. Poor cooling system design will result in longer cooling times, and will undermined productivity and increase production cost. What is more, in many cases product quality and the productivity are in conflict and cannot be optimized simultaneously (Agazzi, et al., 2013).

The most widely used methods to improve cooling efficiency and shorten the injection molding cycle are to use cold water and increase the cooling water velocity. However, this may aggravate the pump burden and make the molding system more complicated. Ejecting the plastic parts earlier is another possible way to shorten the cycle time. When the plastic part is ejected from the mold, it does not factor into the cycle time anymore. A shorter cycle time means lower production costs, increasing the company's competitiveness in the market. However, to the author's knowledge, so far, there have been no published, scientific reports on the study of early ejection and the possible problems involved. This chapter aims to investigate the complexity of predicting the air-cooling shrinkage so that the injection-molded plastic parts can be ejected earlier, while maintaining product quality with a shorter cycle time. In this way, the cost factor can be considered at the mold design stage and a cost-effective injection mold design can be achieved. The materials in this chapter have been documented in paper "Computer Aided Engineering Analysis for Early-Ejected Plastic Part Dimension Prediction and Quality Assurance", and have been submitted to *The International Journal of Advanced Manufacturing Technology*.

5.2 Literature review

Because the cooling stage takes the longest time during the injection molding process, many researchers have attempted to shorten the injection molding cycle time and improve molding productivity by optimizing the cooling system design and improving cooling efficiency (Sun, et al., 2004). Poor cooling system design results in longer cooling times and unevenly distributed temperatures, undermining product quality and productivity. Further, in many situations, product quality and productivity cannot be optimized simultaneously. Wang et al. (2010) proposed a Rapid Heat Cycle Molding process (RHCM) to produce a thin-walled plastic part. The mold is rapidly heated by steam to a temperature higher than the material glass transition temperature (Tg) and kept at the high temperature during the filling stage to ensure good plastic melt fluidity. Once the cavity is completely filled, cooling water will flow into the mold to cool the product quickly. In this way, high productivity and product quality can be produced. The author claimed that the total cooling time can be reduced by 15% with the RHCM process.

Nowadays, advanced manufacturing technologies provide engineers more options when designing the cooling channels. For example, 3D printing technology makes it possible to build conformal cooling channels which follow the shape of the mold surface and keep a uniform distance between the cooling channels and the mold surface around the product (Au, et al., 2011; Dimla, et al., 2005; Wang, et al., 2011). In this way, a more evenly distributed temperature and more uniform cooling effect can be achieved. Park et al. (2011) introduced local conformal cooling channels and compared the cooling efficiency over an injection-molded automotive part. They found that, by using the localized conformal cooling channels, a 23% cooling time reduction can be expected.

5.3 Identification of current limitation and research innovation

Current research, such as the RHCM technology (Wang, et al., 2010) and the conformal cooling channels (Shayfull, et al., 2013) mentioned in the literature review, focuses on improving the cooling efficiency to shorten the cycle time. These available technologies are all very useful in terms of shortening the cooling time. However, special devices or advanced manufacturing technologies are needed, which will make the molding system complex and costly. Early ejection is another possible way to shorten the cycle time. The author suggests that the cycle time can be even can be further reduced by early ejection.

Ideally, the plastic parts should be fully cooled before ejection. However, because plastic is such a poor conductor of heat, waiting to eject the product, negatively influences productivity. As mentioned in chapter 1, the commonly used ejection criterion is that the whole part should be cooled down to the ejection temperature. However, this does not always happen, especially for products with thick walls. If parts with thick walls were to be cooled down to the ejection temperature, productivity would be too low. At the same time, it is not necessary for the product to be fully cooled to the ejection temperature before ejection. As mentioned in chapter 4, for plastic parts with thick walls, if the solidification layer is thick enough to stand the ejection force, and no plastic deformation will happen during the ejection process, the product can be ejected out at a relatively high temperature, in order to shorten the cycle time and improve productivity.

In fact, it has been a common industrial practice to eject plastic parts before they have fully cooled down to the ejection temperature to shorten the cycle time and save cost. This is a more favorable option than improving the cooling efficiency because no other device or subsystem is needed and it costs nothing. At the end of the in-mold cooling stage, the molded part is usually still very warm. After ejection, the part will continue to cool to room temperature in air, with inevitable shrinkage. The shrinkage during in the mold with mold constraints and out of the mold in the open air are entirely different processes. During the in-mold cooling stage, the mold configuration will constrain the part from shrinking freely and the part tends to copy the mold geometry. After being ejected from the mold, there is no more mold constraint and the part will continue to shrink freely in the open air. For injection-molded parts with thick walls, the deformation during the air-cooling phase accounts for a large portion of the whole product deformation.

The available FEA technology cannot be relied upon if the part is ejected at a high temperature. It has been the claim of Moldflow that product deformation due to the injection molding process can be simulated. However, the detailed review can tell that the effective deformation after ejection was basically ignored. Therefore, the final shrinkage rates and product dimensions are inaccurate for injection-molded parts ejected at a high temperature.

So far, the authors have not found any effective tool that can readily predict the final product dimensions accounting for air-cooling shrinkage. Product quality and possible defects can only be evaluated after the molding test. Therefore, there are problems for controlling the quality of parts ejected at a high temperature. Because early ejection is a problematic practice, companies tend to use more than the required time to ensure full solidification of the part before ejection.

Therefore, there are still some barriers between real industrial production and the FEA simulation, and a lot of problems are yet to be solved both industrially and theoretically if the product is ejected at a high temperature. To the author's knowledge, very little research has been carried out concerning the early ejection and there is no commercial plastic molding simulation software can simulate both the in-mold cooling and air-cooling process precisely and produce decent shrinkage and deformation distribution results when the product is ejected at a high temperature.

This research work focuses on the natural plastic part shrinkage deformation during the air-cooling process. More specifically, the proposed research theoretically considers the air-cooling effect quantitively by accurately predicting the shrinkage that occurs during the air-cooling process so that it can be accounted for at the early design stage and the quality of the part can be ensured in less cycle time. In this way, the cost factor can be considered at the mold design stage and a cost-effective injection mold design can be achieved.

5.4 Methodology

Figure 5.1 shows the injection-molded part's temperature history. The temperature increased from melt temperature T1 to T2 during the filling process due to the friction between the plastic melt and the feeding system. During the packing stage, the temperature decreases gradually to T3 to ensure the gate is fully solidified at the end of the packing.

Then the coolant removes most of the heat and the temperature decreases gradually to T4 during the in-mold cooling stage. After that, the part will be ejected from the mold and the temperature will cool down a little bit to T5 during the ejection process. Immediately after the part is ejected from the mold, there are no more mold constraints and the part will shrink freely until it reaches room temperature, T6. Note that the period from T5 to T6 is the so-called *air-cooling* period.

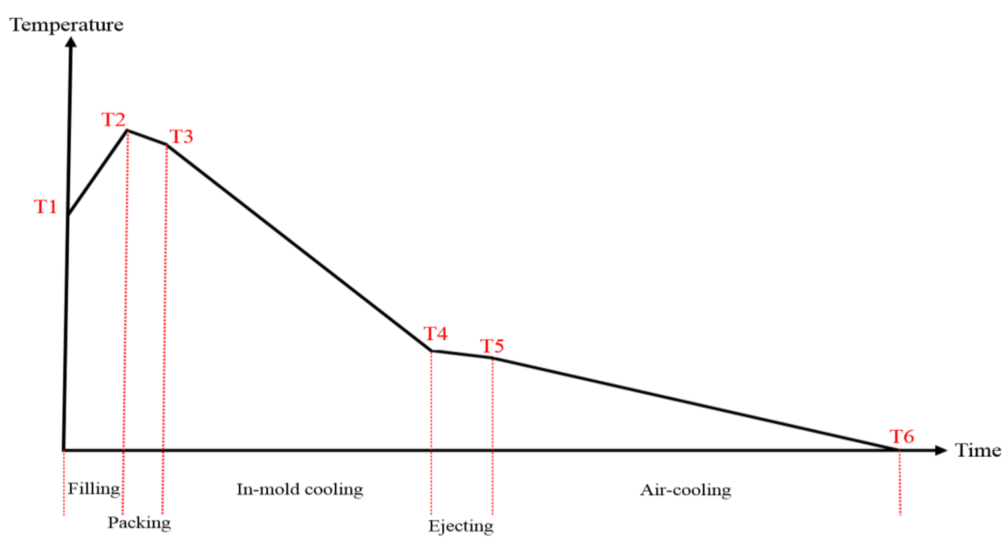


Figure 5.1 Temperature history of the injection molding product

When the plastic part's surface has been cooled to a relatively low temperature during the in-mold cooling process, the temperature gradient between the mold and the plastic part will be low. In this case, not too much heat can be carried out by coolant effectively. Therefore, the center of the plastic part is extremely hard to be cooled down and elongate the cooling time is not a favorable option at this time.

The proposed early-ejected plastic part temperature history is shown in Figure 5.2. By ejecting out the product earlier, the in-mold cooling time can be reduced. After being ejected from the mold, the product can be cooled down in the open air until achieving the room temperate. In this way, the molding cycle time, as well as the molding cost, can be reduced.

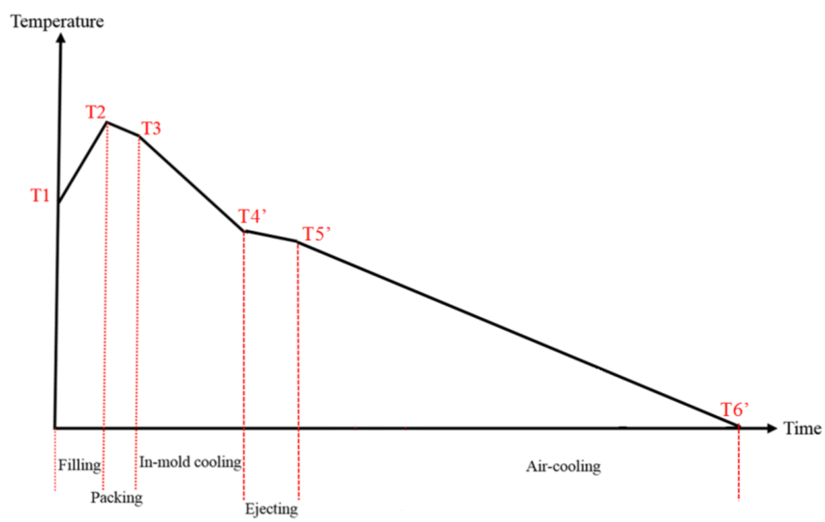
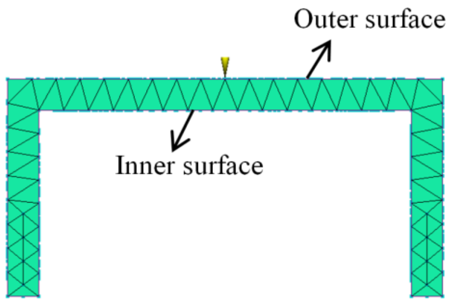
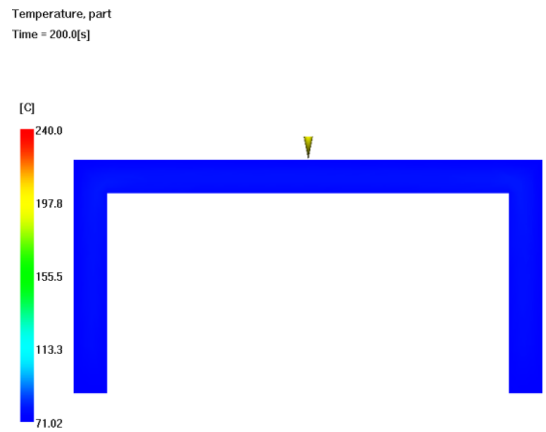


Figure 5.2 Temperature history of the proposed early-ejected injection molding product

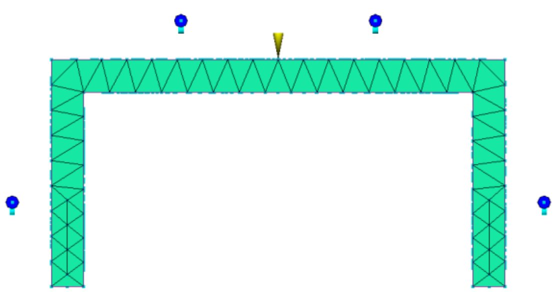
With the in-mold cooling process is going on, the solidification process keeps happening, the temperature distribution and the transitional plastic part mechanical properties keep changing. Both the product design, mold design and the material properties will influence the ejection time. For ideal even cooling effect which the product cools down in the mold with no cooling channels as shown in Figure 5.3 (a), the part temperature distribution is more likely to be even. As shown in Figure 5.3 (b), the whole part is around 70℃. As can be estimated from Figure 4.1 from last chapter, the mechanical strength of the evenly cooled part surface at 70℃ is around 80% of the mechanical strength at 30℃. However, the ideal even cooling effect takes too much time and is not practicable for industrial production. For the identical part with 4 cooling channels distributed in the cavity side as shown in Figure 5.3 (c), the temperature distribution for the part varies dramatically as shown in Figure 5.3 (d). For the outer surface, the temperature can be cooled to 32℃ while the inner surface can be as high as 120℃ due to the lack of cooling effect on the core side. For the inner surface which is around 120℃, the plastic material is even softer and more vulnerable and the mechanical strength is only 50% of the mechanical strength at room temperature as estimated from Figure 4.1. The center of the part is also hard to be cooled down and the temperature can be as high as 200℃. In order to cool down the inner surface more effectively, 3 more cooling channels are added to the core side as shown in Figure 5.3 (e) and the temperature distribution result is shown in Figure 5.3 (f). Compared to Figure 5.3 (d), both the inner and outer surface can be cooled down to around 30℃ and the temperature distribution is more even. Therefore, the ejection time is influenced by the mold design, cooling channel distributions, ejection system and etc. It is hard to determine the best ejection time only based on human knowledge and imagination. CAE simulation is needed to facilitate the mold design and the possible early ejection.



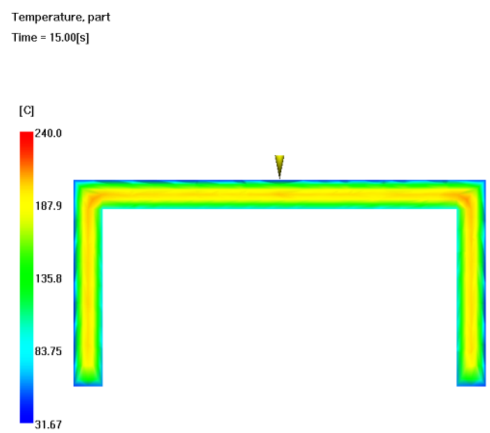
(a) Ideal even cooling effect mold design



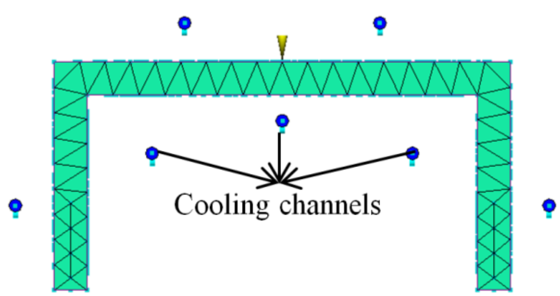
(b) Temperature distribution simulation result for case a



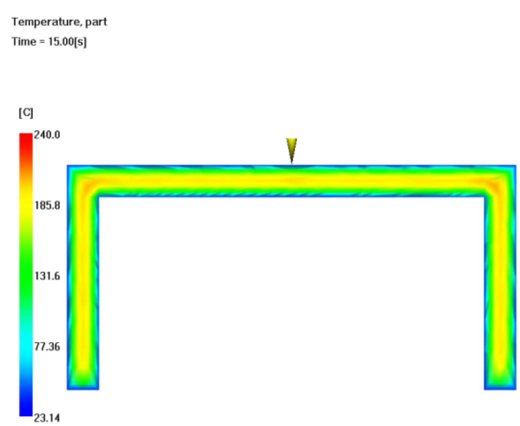
(c) 4 cavity side cooling channels mold design



(d) Temperature distribution simulation result for case c



(e) Practical mold design with cooling channels in both cavity and core side



(f) Temperature distribution simulation result for case e

Figure 5.3 Conceptual illustration of the temperature and mechanical properties distribution of the cooled parts

For the plastic parts with thick walls, the quantity of molten plastic remains significant after the part has been ejected. During the air-cooling process, these materials will continue to cool down to room temperature and the shrinkage cannot be ignored. For those kinds of plastic parts, the air-cooling process might cause complex, uneven deformations, which will account for a large portion of the whole product deformation.

It is better for those kinds of plastic parts ejected at high temperatures to be cooled down with some constraints during the air-cooling process. Some jig features may be required so that the air-cooling shrinkage will not develop freely. If the plastic part is constrained for a little bit of time right after ejection, the air-cooling shrinkage might be reduced significantly. However, the jig features need to be designed and the feasibility of this method needs to be investigated. By controlling the air-cooling shrinkage with additional devices such as facilitating devices and jig features, the in-mold cooling time can be reduced and productivity improved.

Ideally, the integration of Moldflow and Ansys can predict the final product dimensions more accurately with both the in-mold cooling and the air-cooling shrinkage accounted for. Then, the initial product CAD model and the mold design can be updated, based on the trustworthy simulation result, so that the air-cooling shrinkage can be considered at the early design stage and the quality of the part can be ensured in less cycle time. In this way, the cost factor can be considered at the mold design stage and a cost-effective injection mold design can be achieved.

The integration semantic model is shown in Figure 5.4. First, the initial product 3D model is simplified in CAD system and then imported into Moldflow. In Moldflow, cooling channels and feeding system are created and process parameters and material data are specified. Then, the injection molding simulation is carried out and the simulation result is obtained. After that, Moldflow-Ansys API is executed and generates the integration files which contain both the geometrical information and non-geometrical information. Together with the temperature distribution result from Moldflow, the thermal load is applied to each node of the model, then Ansys simulation is carried out and the final product shrinkage rates after the part cools down to the room temperature are obtained. Then, design updates are carried out by incorporating the manufacturing induced shrinkage to the initial product design, so that the updated design will satisfy the dimension requirements after going through the whole injection molding process. Finally, the mold can be designed accordingly.

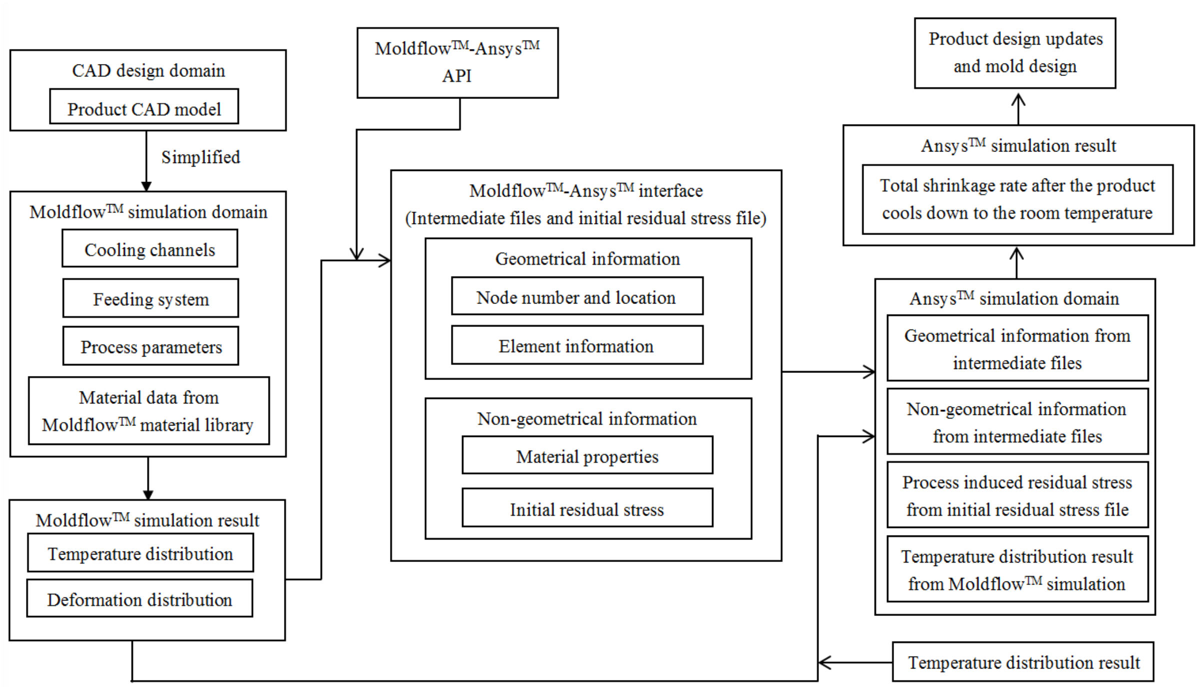


Figure 5.4 Schematic of the proposed approach for air-cooling simulation

Moldflow-Ansys API generates two interface files: the Moldflow-Ansys intermediate file (.cdb) and the initial residual stress file (.ist). The Moldflow-Ansys intermediate file contains the mesh information, material properties, node number, node location, constraint, coordinate system and etc. The initial residual stress file contains the Moldflow simulated residual stress accumulated during the injection molding process from T1 — T4 for all the element, but does not include the thermal residual stress generated during the air-cooling process (T4 — T6). Therefore, the product temperature distribution result at the end of the in-mold cooling process (T4) is also needed as the thermal load to do the air-cooling simulation. Together with the initial residual stress result and the material properties provided by the Moldflow material library, the Ansys simulation is ready to go. Finally, we can get a more accurate simulation result which considers the whole injection molding process. In this way, the air-cooling shrinkage can be accounted for at the early design stage and the quality of the part can be ensured in less cycle time by ejecting out the part earlier.

5.5 Case study

The ejection-induced deformations have been considered in the last chapter. Here we will focus on the air-cooling shrinkage prediction which has not been accounted for by the Moldflow simulation. In this way, we can simulate the whole cooling process which includes both the in-mold cooling process considered by Moldflow and the ejection-induced deformation and air-cooling process that never been considered so far.

Using the method mentioned above, Moldflow-Ansys Application Programming Interface (mpi2ans.vbs) is executed and generates two interface files: the Moldflow-Ansys intermediate files (.cdb) and the initial residual stress file (.ist). Together with the temperature distribution result provided by Moldflow, the Ansys simulation is ready to go and the simulation result is shown in Figure 5.5.

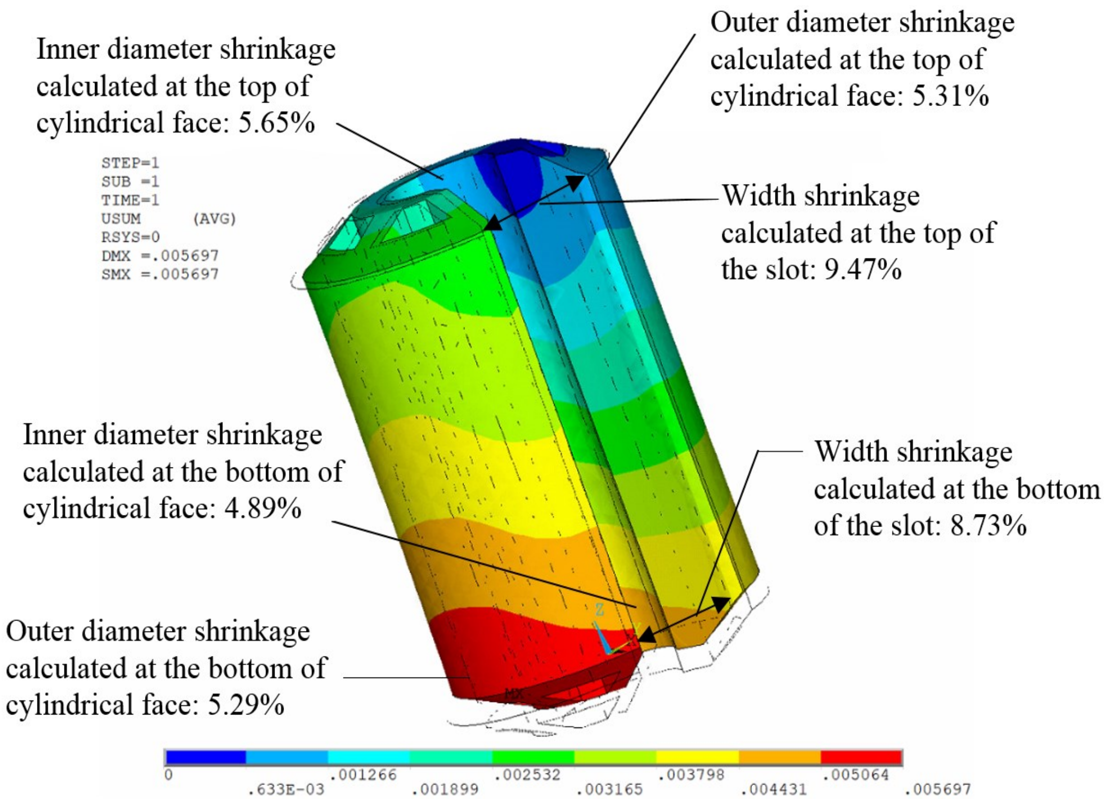


Figure 5.5 Deformation of tough grip with in-mold cooling and air-cooling

Based on the node distance before and after the injection molding process, the shrinkage rates can be obtained using Equation 4.11. The total shrinkage rates after the products cool down to the room temperature are shown in Table 5.1. Compared to the shrinkage rates obtained from Moldflow, the Moldflow-Ansys integrated simulation result is more close to the real product.

Table 5.1 Tough grip shrinkage rate (in-mold cooling and air-cooling)

	Upside Width			Downside Width			Length	
	Outer Diameter	Inner Diameter	Edge Distance	Outer Diameter	Inner Diameter	Edge Distances	Outer Length	Inner Length
Before Deformation(mm)	67.69	24.35	18.95	68.49	25.23	19.97	88.16	104.7
After Deformation(mm)	64.097	22.975	17.156	64.867	23.997	18.227	83.45	99.65
Shrinkage (%)	5.308	5.645	9.469	5.290	4.886	8.730	5.34	4.82

The air-cooling induced shrinkage rate is shown in Table 5.2. It can be seen that the air-cooling induced shrinkage rates are comparable to the shrinkage rate we got from the Moldflow simulation which includes flow and in-mold cooling induced shrinkage rate. Therefore, we can conclude that the air-cooling shrinkage is significant and cannot be ignored for the early-ejected partial solidified parts.

Table 5.2 Air-cooling induced shrinkage rate for tough grip

	Upside Width			Downside Width			Length	
	Outer Diameter	Inner Diameter	Edge Distance	Outer Diameter	Inner Diameter	Edge Distances	Outer Length	Inner Length
Shrinkage (%)	2.518	2.645	4.929	2.46	2.186	4.47	2.39	2.09

Together with the ejection-induced deformation we got from last chapter, the product final shrinkage rate when cooled down to the room temperature including flow and in-mold cooling induced shrinkage, ejection-induced deformation and the air-cooling shrinkage is shown in Table 5.3.

Table 5.3 Tough grip final shrinkage rate when cooled down to the room temperature

	Upside Width			Downside Width			Length	
	Outer Diameter	Inner Diameter	Edge Distance	Outer Diameter	Inner Diameter	Edge Distances	Outer Length	Inner Length
Before Deformation(mm)	67.69	24.35	18.95	68.49	25.23	19.97	88.16	104.7
After Deformation(mm)	64.23	22.975	17.156	65.07	23.87	17.44	83.39	98.57
Shrinkage (%)	5.10	5.645	9.47	4.988	5.397	12.66	5.41	5.85

Based on the total shrinkage rates, the product initial design can be updated and the mold can be designed accordingly which considers the ejection-induced deformation and air-cooling shrinkage at the initial design stage so that the quality of the part can be ensured in less cycle time. For this case study, the cycle time (filling, packing and cooling time in total) can be reduced to 55s by early ejection upon partial solidification with the product quality still within acceptable limits compared to 110s which the whole product cooled down to the ejection temperature.

5.6 Conclusion and future work

Ejecting molded plastic parts at high temperatures is a common industrial practice to shorten the cycle time and improve productivity. However, when parts are ejected at high temperatures, the product dimensions and warpages are hard to predict and control. Commercial injection molding simulation tools can only simulate the injection molding process up to the end of the in-mold cooling stage and the air-cooling process is ignored. The authors proposed an integrated Moldflow -Ansys simulation method to analyze the entire injection molding process up to the part being cooled to room temperature so that the air-cooling deformation effect can be evaluated at the early mold design stage, and the dimensional and geometrical quality of the part can be ensured in less cycle time. A real industrial case study has been presented using the proposed approach, and the geometric measures obtained from the integrated simulation method show good alignment to the real production result, which is not achievable by using Moldflow simulation alone, especially for plastic parts ejected at a high temperature. In this way, the cost factor for molding production can be accounted for at the mold design stage and a shorter molding cycle time can be achieved due to well-optimized early ejection.

Chapter 6 An Additional Case Study

In order to verify the general application of the proposed method, one more case study was conducted.

6.1 Box product CAD model

A hypothetical case study was carried out to verify that the proposed method can be applied to box products made of polycarbonate (PC) material. The geometry and dimensions of a hypothetical product are shown in Figure 6.1. Six ejection pins are used to eject the product at the end of the in-mold cooling stage. The locations of the ejection pins are shown in Figure 6.1.

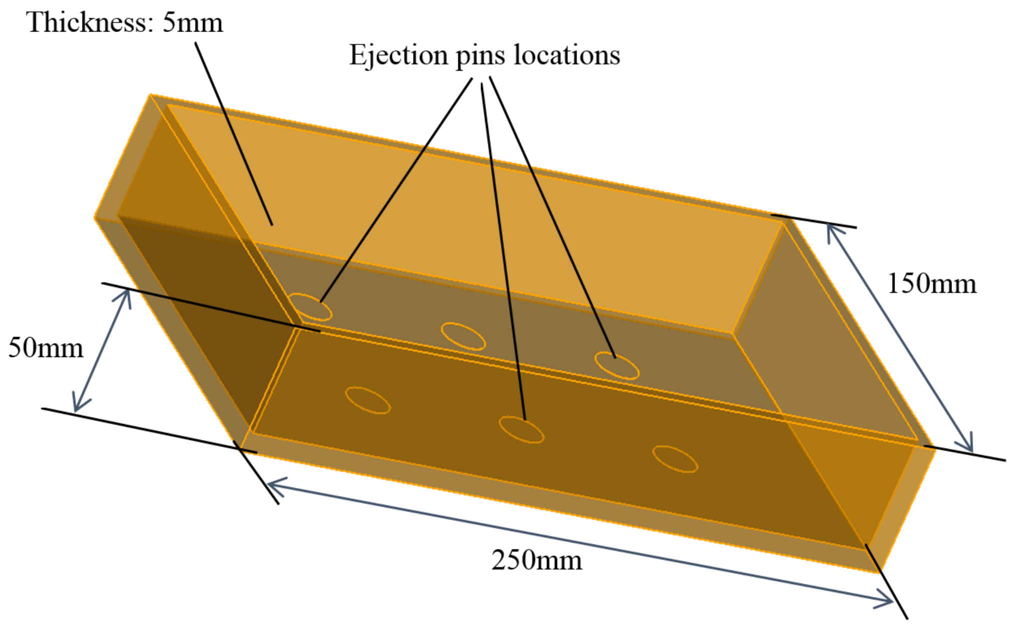


Figure 6.1 Box product CAD model

6.2 Molding simulation

The initial molding simulation was carried out in Moldflow. The process parameters are shown in Table 6.1. The material used for the simulation is generic shrinkage characterized PC and the material properties are shown in Table 6.2. The mold configuration together with the cooling channels and feeding system are shown in Figure 6.2.

Table 6.1 Moldflow process parameters for box product

Melt temperature	300 ℃	Cooling time	17 s
Injection time	3 s	Coolant	Cold water
Packing time	15 s	Packing pressure	80% of filling pressure

Table 6.2 Mechanical properties of generic shrinkage characterized PC

Elastic modulus (E1)	2280 MPa	Poisson’s ratio	0.417
Elastic modulus (E2)	2280 MPa	Shear modulus	804.5
Coefficient of thermal expansion (α1)	0.000073/℃	Coefficient of thermal expansion (α2)	0.000073/℃

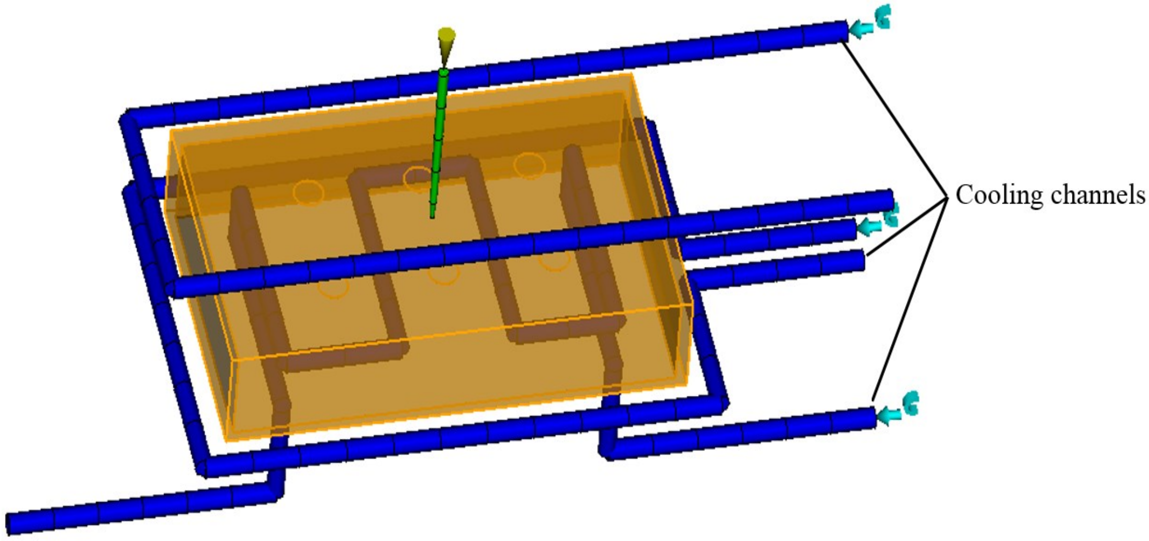


Figure 6.2 Mold configuration for box product

The Moldflow simulation deflection result is shown in Figure 6.3. We can see that the product warpage effect is not significant and is acceptable. The shrinkage rate for the box product is around 1%. More details about the shrinkage rate can be found in Table 6.3.

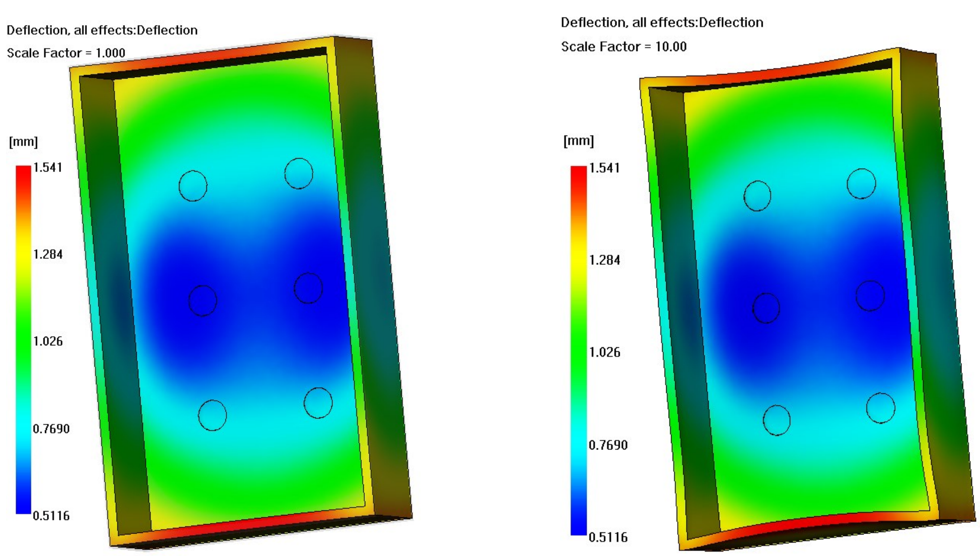


Figure 6.3 Moldflow deflection simulation result for box product

Table 6.3 Box product shrinkage rate from Moldflow simulation

	Length	Width	Hight
Before Deformation(mm)	250	150	50
After Deformation(mm)	247.8	148.7	49.53
Shrinkage (%)	0.87	0.89	0.94

Figure 6.4 shows the box product temperature distribution result at the end of the in-mold cooling. It can be seen that the product is still hot at the moment of ejection. As can be seen from Figure 6.5, the product interior temperature is very high and uneven at the end of the in-mold cooling process, even higher than the Moldflow recommended ejection temperature which is 134 ℃ (Moldflow material library). Further scale down of the temperature result, it is worth to notice that, in the thickness direction, a large portion of the material is hotter than 134 ℃ even after the in-mold cooling process. Therefore, ejection-induced plastic deformation might happen and the air-cooling shrinkage might be significant.

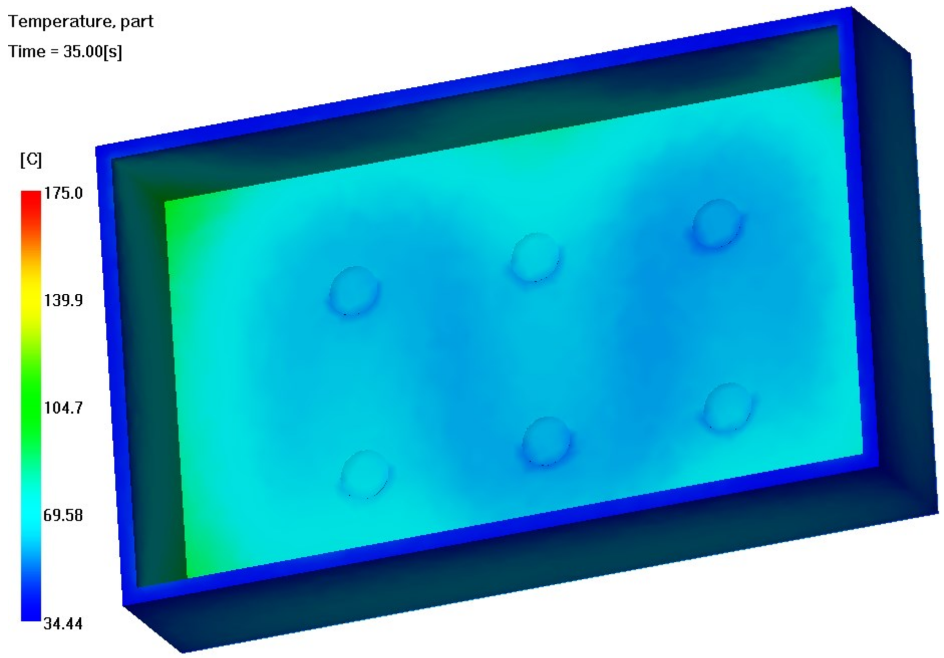


Figure 6.4 Box product temperature result

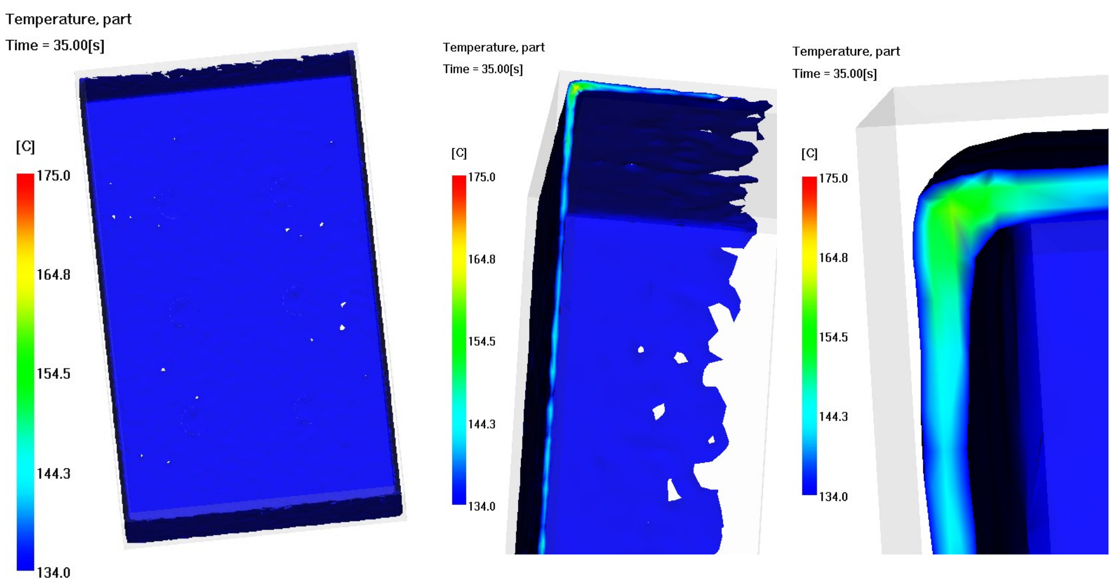


Figure 6.5 Box product interior temperature result

6.3 Ejection simulation

Using the method mentioned above in chapter 4, Moldflow-Ansys integrated simulation is carried out to evaluate the ejection-induced deformation. The PC comprehensive mechanical properties at different temperatures are estimated based on the literature (Yu, et al., 2015) and Moldflow material library. The ejection force is around 900N. The ejection-induced plastic deformation is shown in Figure 6.6. We can see from Figure 6.6 that the localized plastic deformation does happen during the ejection process. However, it does not influence the critical dimensions we are interested in which are length, width and height. Therefore, the product can still maintain its structural integrity and the ejection process will not seriously deform the box product, so that the product can be ejected even though the center of the product is still at a high temperature level.

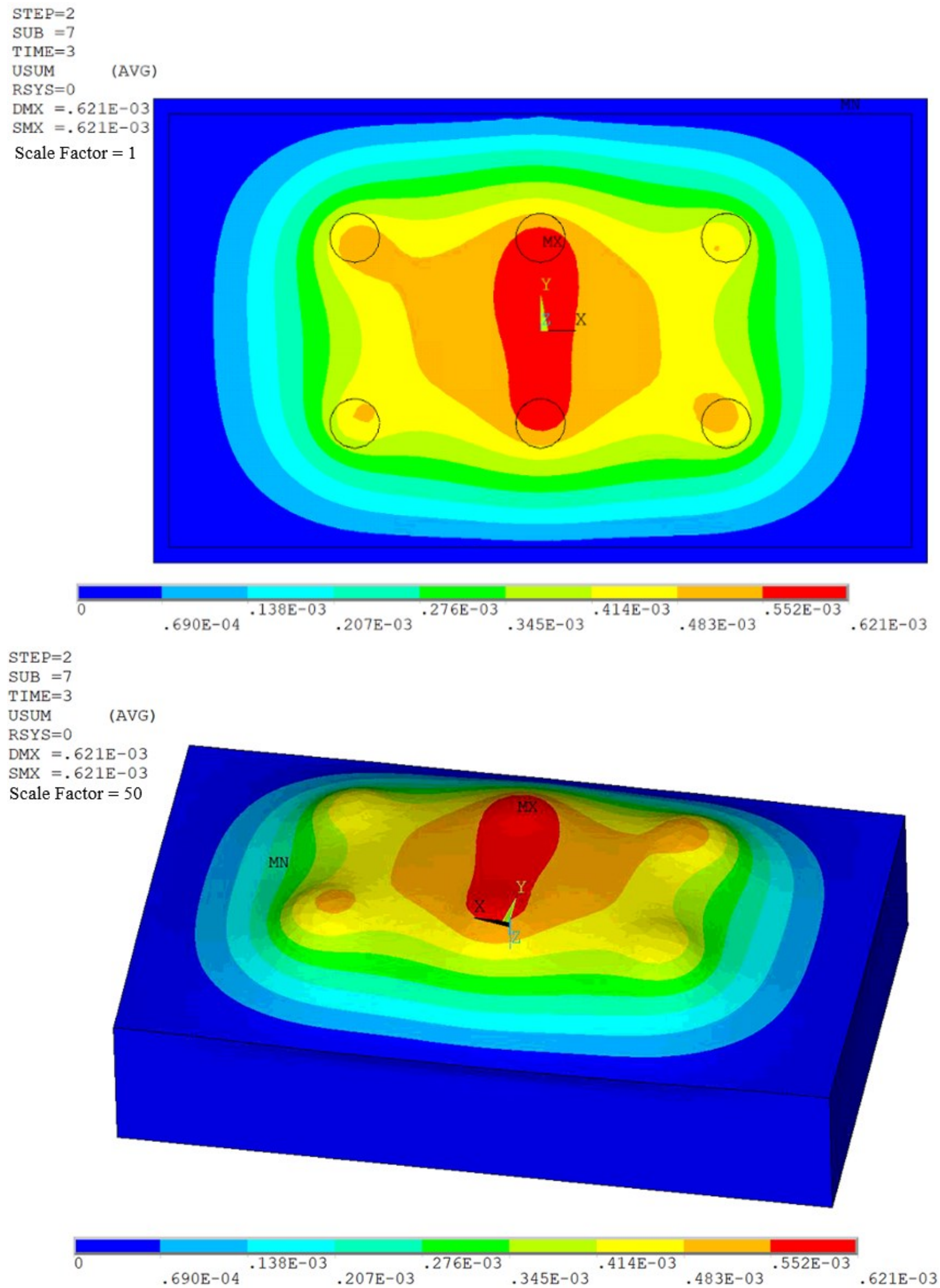


Figure 6.6 Ejection-induced plastic deformation for box product

6.4 Air-cooling simulation

After being ejected, the product is still at a high temperature and will continue to be cooled down to the room temperature in the open air with no mold constraints. Using the method mentioned above in chapter 5, Moldflow-Ansys integrated simulation is carried out to evaluate the in-mold cooling and air-cooling shrinkage. The simulation result is shown in Figure 6.7.

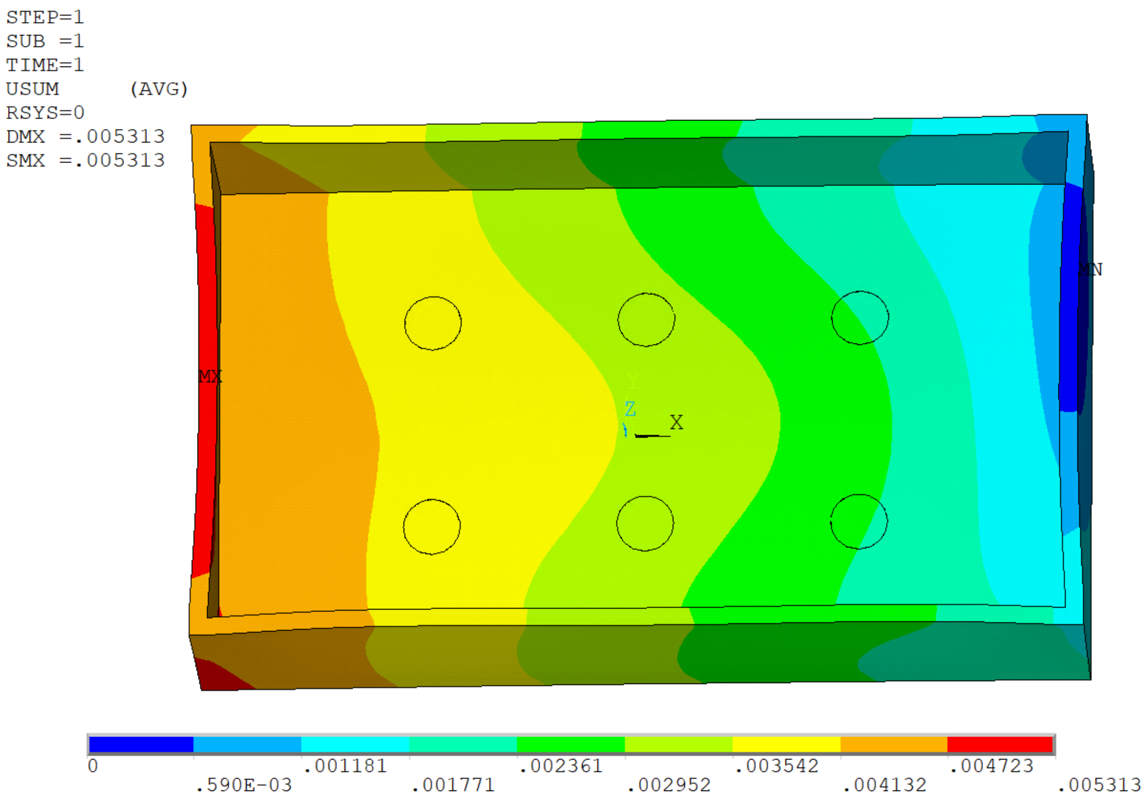


Figure 6.7 Deformation of box product with in-mold cooling and air-cooling

The total shrinkage rates after the products cool down to the room temperature are shown in Table 6.4.

Table 6.4 Box product final shrinkage rate

	Length	Width	Hight
Before Deformation(mm)	250	150	50
After Deformation(mm)	246.53	147.89	49.22
Shrinkage (%)	1.388	1.41	1.56

The air-cooling induced shrinkage rate is shown in Table 6.5. The air-cooling induced shrinkage rates are comparable to the shrinkage rates we got from the Moldflow simulation. Therefore, we can conclude that the air-cooling shrinkage is significant and cannot be ignored for the early-ejected partial solidified parts.

Table 6.5 Box product air-cooling induced shrinkage rate

	Length	Width	Hight
Air-cooling induced deflection(mm)	1.27	0.81	0.31
Shrinkage (%)	0.518	0.52	0.62

Based on the product total shrinkage rates, the product initial design can be updated and the mold can be better designed accordingly which accounts for both the in-mold cooling shrinkage and air-cooling shrinkage at the initial design stage, so that the product quality can be ensured in less cycle time by ejecting out the product at a high temperature level. In this way, the cost factor can be considered at the mold design stage and a cost-effective injection mold design can be achieved. For this case study, the cycle time (filling, packing and cooling time in total) can be reduced to 35s by early ejection upon partial solidification with the product quality still within acceptable limits compared to 43s which the whole product cooled down to the ejection temperature.

6.5 Cycle time optimization

The bottom surface flatness is crucial for the box product quality. As shown in Figure 6.6, the ejection induced residual plastic deformation for the bottom surface is around 0.6mm when the cycle time is 35s. If the customers require the ejection induced residual plastic deformation for the bottom surface is less than 0.5mm, how to determine the cycle time becomes a question. Using the method mentioned in Chapter 4, several simulations are carried out to evaluate the relationship between the cycle time and ejection deformation. The ejection deformations at several given cycle times are shown in Table 6.6 and Figure 6.8. The formula reveals the relationship between the cycle time x and the ejection deformation y can be expressed as:

$$y = 6 * 10^{-5}x^2 - 0.0143x + 1.0499 \quad (6.1)$$

Using this formula, we can know that the cycle time should be longer than 49s if the ejection induced plastic deformation is less than 0.5mm.

Table 6.6 Ejection deformation VS Cycle time for the box product

Cycle time x (s)	Ejection deformation y (mm)
35	0.621
43	0.552
45	0.533
50	0.489
55	0.445
60	0.412
65	0.379
70	0.353

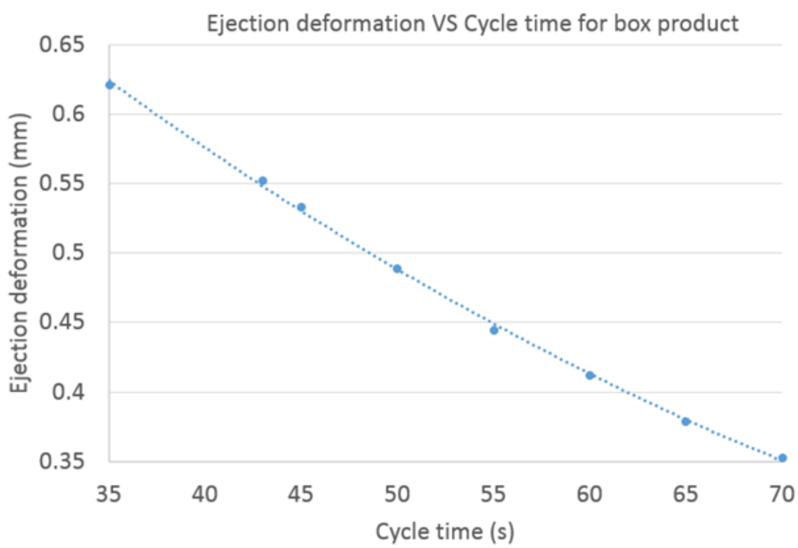


Figure 6.8 Deformation of box product with in-mold cooling and air-cooling

Moldflow-Ansys integrated simulation is carried out to verify the ejection induced residual plastic deformation is less than 0.5mm when the cycle time is 49s. The simulation result is shown in Figure 6.9. We can see that, the ejection induced plastic deformation is 0.498 mm when the cycle time 49s, which meets our expectation.

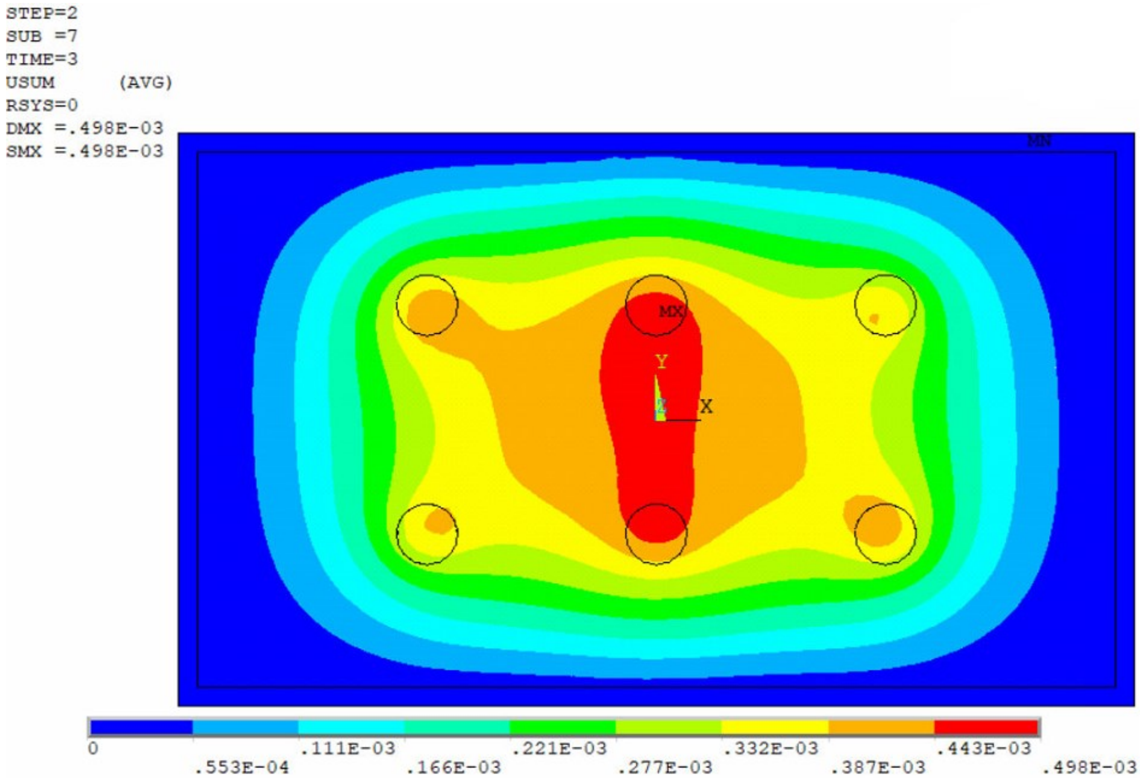


Figure 6.9 Ejection-induced plastic deformation for box product at 49s

Chapter 7 Conclusion and Future Work

7.1 Conclusion

Product quality and productivity are vital to the injection molding process. However, they are conflicting requirements in most cases and cannot be optimized simultaneously. Warpage, a common quality problem for injection-molded plastic parts, is hard to avoid. This is true even with the help of the advanced CAE technology, especially in scenarios in which a mold has already been made. Cycle time is vital for the injection molding process, as the latter involves mass production; hence every second counts. The early ejection upon partial solidification method to shorten cycle time has not yet been carefully studied, and the current available technology cannot predict final dimensions of the product accurately. This is because the temperature distribution is uneven, the material mechanical properties are transitional, and the ejection process involves complex non-linear plastic deformation.

This thesis proposes (1) a workflow to address the warpage problem when the mold has been made using the advanced CAE simulation package and (2) a new method to shorten the cycle time by ejecting the partially solidified product earlier. Further, a model is proposed to predict the localized and transitional mechanical properties of the plastic parts. In this way, the non-uniform and non-linear ejection deformation and air-cooling shrinkage can be predicted under transitional cooling conditions with highly non-uniform and temperature-dependent mechanical properties. A new mold design strategy is proposed to account for ejection deformation and air-cooling shrinkage at the mold design stage so that only partial solidification is needed and the cycle time can be further reduced while maintaining the product quality within acceptable limits.

My work facilitates both the prediction of the final dimensions of the early-ejected partially solidified plastic product and conformation of whether product quality is within acceptable limits. It paves the way for the optimization of the best ejection time, which can reduce the cycle time significantly while ensuring product quality. In addition, when potential early ejection deformation and corresponding air-cooling shrinkage at the mold design stage are accounted for, the product can be ejected when it is only partially solidified. The cycle time can thus be further reduced while maintaining product quality within acceptable limits. In this way, transitional solidification physics can be incorporated into the intelligent mold design and analysis process, and the proposed method has the capability to provide a trustable prediction of the best ejection time. Therefore, the cost factor can be considered at the mold design stage and a cost-effective injection mold design can be achieved. Hence, the part and mold design will be enhanced to better support early ejection upon partial solidification and ensure final product quality and molding productivity.

In summary, this study has considered ejection-induced deformation and air-cooling shrinkage for partially solidified products upon early ejection. The simulation result is close to that of the real product, which has proven that the proposed methodology is feasible and could generate a reasonable result for the targeted problem.

The exploration of the proposed method is complex and requires a good understanding of the CAE software and material properties. Compared to the trial-and-error method, it is more complicated and requires much more time. My work facilitates the semi-automation of the method.

7.2 Contributions

The contributions of this research are as follows:

1. Investigated the feasibility of an early ejection upon partial solidification molding quality assurance method to shorten the cycle time and while controlling deformation.
2. Proposed a new ejection criterion which ensures quality requirements are met and yet allows controlled plastic deformation during the ejection process.
3. Made new efforts to develop a theoretical model of ejection deformation involving the transitional mechanical properties of plastic parts.

4. Suggested a simulation method to analyze the deformations caused through the whole injection molding process including the in-mold cooling, ejection and air-cooling stages. Carried out non-uniform and non-linear ejection deformation FEA simulation.

5. Proposed a method to determine the optimal ejection time.

6. Proposed a new mold design strategy to better support early ejection upon partial solidification by incorporating ejection deformation at the mold design stage.

7. Proposed a new molding process design strategy to shorten cycle time by early ejection.

8. Demonstrated a Moldflow and Ansys integrated simulation solution (by programming in Ansys).

9. Proposed a theoretical model of transitional mechanical properties of plastic parts.

7.3 Possible design guidelines for engineers:

Due to the complexity of material transition from molding temperature to room temperature, designers have very limited knowledge about how plastic parts will deform and eventually how much the potential warpage will be. Further, it is even more difficult for designers to estimate how much in-mold cooling time is required as the optimum process setting. Due to the lack of such knowledge, designers are not able to determine the actual shrinkage and warpage patterns for the product based on the current technology. In addition, it is impossible for designers to design the cooling channels in an intelligent way to address such problems. With the work proposed by our research, a numerical simulation solution will help designers to gain such knowledge and enhance the design of the cooling channels as well as the distributions of the ejection pins. Based on the simulated cooling effect, designers can be confident in assessing the cooling effect during molding, and in estimating the actual warpage after ejection with both ejection deformation and air-cooling shrinkage considered. By incorporating the ejection deformation and air-cooling shrinkage at the design stage, they can ensure that early ejection is feasible upon partial solidification while maintaining product quality within acceptable limits.

7.4 Benefits to the injection molding industry

Producing high quality plastic parts efficiently with low cost is still hard to achieve due to the complex nature of the molding process. My work facilitates the accurate simulation of the whole molding process from the filling stage up to the plastic parts are molded and fully cool down to the room temperature. In this way, we can evaluate the product final dimensions with different process settings no matter the parts are fully solidified before ejection or not. Potentially, the plastic parts can be ejected earlier upon partial solidification so that the cycle time, as well as the molding cost, can be reduced. Further, by incorporating the partial solidification early ejection results at the mold design stage, the mold can be better designed to support early ejection so that the cycle time can be further reduced.

7.5 Future work

7.5.1 Investigating the mechanical properties of plastic material

The mechanical properties of plastic material change significantly with the temperature. Young's modulus, Poisson's ratio, yield strength etc. at different temperatures are needed in order to predict ejection deformation more accurately. However, the study of these properties at different temperatures is still not mature. Therefore, further research is needed from material scientists to report the plastic material stress-strain curves at different temperatures. In addition, aspects of the optimization of the ejection system, such as the ejection pin locations, have been left for others to study due to time limitations.

7.5.2 Applications for fiber reinforced material in different manufacturing methods

As shown in Figure 7.1, tough grips tend to break when a rod is inserted into them. Fiber-reinforced plastic materials generally have a better mechanical performance and may offer a way to improve the mechanical performance of any product. They have been widely used in light-weight parts, offering them superior mechanical properties (Dhand, et al., 2015; Liu, et al., 2015; Park and Dang, 2011).

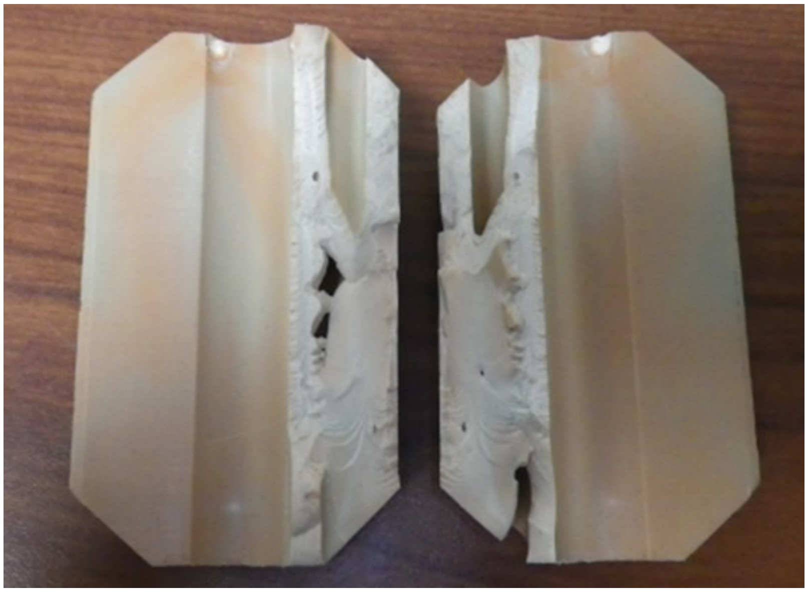


Figure 7.1 Failure example of a tough grip

There are generally two manufacturing techniques for fiber-reinforced plastic products: injection molding and 3D printing. As mentioned previously, due to the injection induced fiber orientation, the mechanical properties of fiber-reinforced injection-molded plastic parts are influenced by the molding process, and are hard to predict.

3D printing has aroused a lot of attention, as it is an additive manufacturing method which can precisely control the composition and properties of a product (Kalsoom et al., 2016). Therefore, the fiber orientation can be accurately controlled and aligned along the force direction. However, because the bond between the plastic matrix and the fiber is not perfect due to the manufacturing technique, it may undermine the mechanical properties of the product (El Refai, 2013; Rong, et al., 2001).

The author aims to compare the fiber-reinforced product manufactured using these two different techniques in terms of mechanical performance, cost, productivity, etc. It can potentially provide engineers a feasible way to choose a suitable manufacturing method for fiber-reinforced products.

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