INJECTION MOULDING: WARPAGE REDUCTION BY REDUCING RESIDUAL STRESS

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A project report submitted in partial fulfilment of the requirements for the award of the degree of Masters of Engineering (Mechanical)

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DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **"INJECTION MOULDING: WARPAGE REDUCTION BY REDUCING RESIDUAL STRESS"** was prepared by **VOO CHUANG SHIN**has met the required standard for submission in partial fulfilment of the requirements for the award of Masters of Engineering (Mechanical) at Universiti Tunku Abdul Rahman.

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Date : _________________________

Specially dedicated to

my mother who nagged me all the way to take my masters.

Also to my Bumblebee and Jodyfish.

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ABSTRACT

Injection moulding is one of the most popular methods of processing polymers. It is a versatile process capable of producing high volumes with good dimensional tolerance while maintaining cost effectiveness. Over a third of all plastic products are made using injection moulding while over half of the world's polymer processing equipment is used for injection moulding process. Warping, a major defect in injection moulding is the deformation of a moulded component caused by non-uniform changes in internal stress, differential shrinkage and/or orientation effects. One of the main factors affecting warping is residual stress, the stresses that remains within the moulded part, when there are no external loads applied to the system. In the case study, the part of concern: a faceplate experiences major warping and it affects the assembled end product. Changes are proposed to reduce the residual stress in the part post moulding, which will reduce part warpage as a result. The proposed changes to be studied are gate size, gate quantity, gate location and mould surface temperature. In order to predict and study the effects of these proposed changes to the warping, CAE software Moldflow Plastic Insight (MPI) is used to carry out the simulation. MPI requires no introduction in the field of mould design and optimisation, as it is one of the most widely used CAE solutions in the industry. MPI is a 3D solid-based simulation tool that allows plastic part designers and mould makers to successfully predict design manufacturability and quality during preliminary stages of product development. From the simulation studies, it is concluded that gate size have a minor effect on reducing residual stress and warping while gate quantity and location have a significant impact in reducing residual stress and warpage. Increasing mould surface temperature also reduces residual stress by reducing both flow-induced and thermal-induced residual stress.

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CHAPTER 1

INTRODUCTION

1.1 Background

Injection moulding is one of the most popular methods of processing polymers especially those with complex geometries. Injection Moulding is especially suitable for processing in high volumes with good dimensional tolerance while maintaining cost effectiveness. It is extremely versatile, able to fabricate a wide range of products from small plastic gears to large television panels. Over a third of all plastic products are made using injection moulding while over half of the world's polymer processing equipment is used for injection moulding process (Beaumont, Nagel and Sherman, 2002).

The injection moulding process is basically divided in 5 stages. They are plasticization, injection, packing, cooling and ejection. Though the stages may seem fairly simple, they are actually very complex in nature affected by a myriad of parameters. Hence, part manufacturing defects are common. These defects include warping, weld lines, burn marks, short moulds and streak marks to name a few. Among these, warpage is the most prominent and serious defect as it affects both cosmetic features as well as functional features. Figure 1.1 shows a full injection moulding machine with the mould in place.

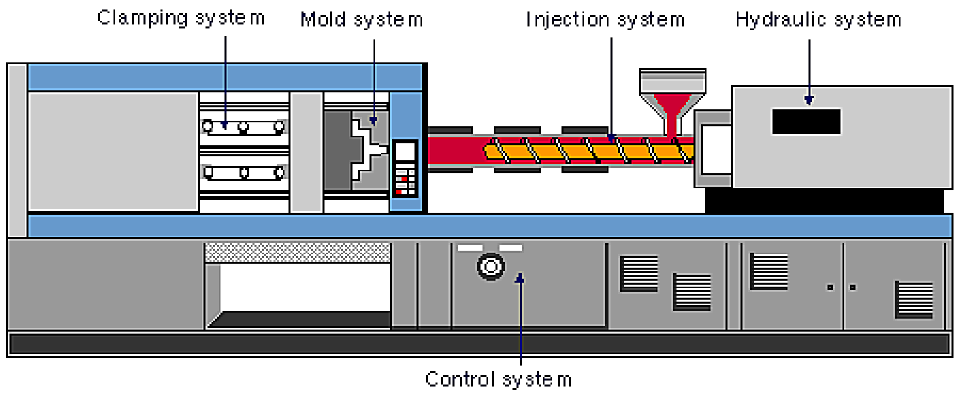

Figure 1.1: Injection Moulding Machine (Source: PMolds Industrial)

1.2 Warping

Warping or warpage is the deformation of a moulded component caused by non-uniform changes in internal stress, differential shrinkage and/or orientation effects (Goodship, 2004). The most influential parameters affecting warpage includes: mould and melt temperatures, design of the injection moulded part, cooling system, length to thickness ratio, packing pressure and time, gate type, dimension and its location (Goodship, 2004). Semi-crystalline plastics are generally more prone to warping than amorphous plastics as they are anisotropic in flow, shrinking contrarily in the direction of flow and transverse to flow (Peacock and Calhoun, 2012). The root cause of warping can be divided into five main groups:

- Incorrect processing parameters
- Mould design issue
- Injection moulding machine problems
- Part design issue
- Poor plastic material selection

With the assumption that the injection moulding machine, part design and material selection are all without problems and constant, that leaves variables of processing parameters and mould design open to changes.

1.2.1 Injection (Filling) Rate

Low injection rates will cause a lower viscosity in the material, requiring higher injection pressures to push the material into the mould cavity. This will leave higher residual stress in the part. High injection rates on the other hand results in high shearing of the material at the gate, adding to internal stress. High filling rates also causes material orientation, resulting in immediate as well as post-moulding shrinkage.

1.2.2 Cooling Rate

Moulded parts that are ejected hot due to short cooling is more likely to warp than a part ejected cold. The part warps due to the asymmetry in heat distribution throughout the ejected part itself, due to differences in geometry or mould wall temperature differences (Bociga et. al, 2010) (Fig. 1.2). The side that is still hot, or cools more slowly will continue to shrink upon cooling whereas the side that has already cooled will stop shrinking or shrink less. Semi-crystalline polymers form larger crystals on the slower cooling side (Paulson, 2015).Large crystals will shrink more than smaller crystal, which makes semi-crystalline materials more prone to warping.

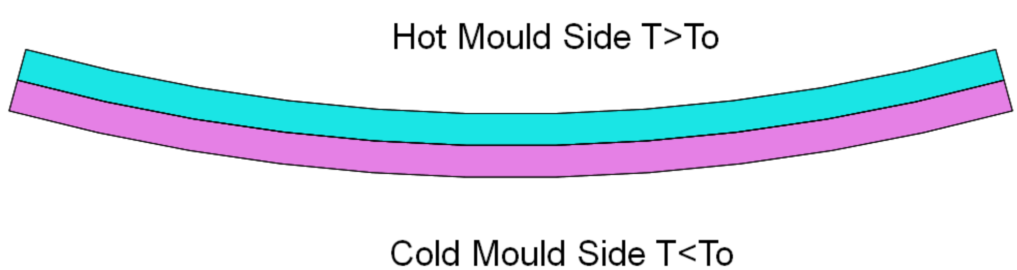

Figure 1.2: Warpage of injection moulded part due to differences in mould wall temperature.

1.2.3 Cavity Pressure

Cavity pressure during injection is always highest closest to the gate. Hence, plastic shrinks less in the gate area than plastic at the end farthest from the gate. Higher packing pressure and holding pressures reduces the mean free volume of the plastic, contributing to lower shrinkage during cooling cycles. With lower overall shrinkage, the warpage of the plastic part can be reduced with increasing cavity pressure. However, higher pressures may contribute to the residual stress in the part which will affect part warpage.

1.2.4 Melting Temperature

Changes within the melt temperature affect all primary variables by change of plastic viscosity. It is always better to follow the recommended melting temperature as provided by the material's Material Safety Data Sheet (MSDS). Low melting temperatures will generally result in higher residual stress in the part post moulding (Paulson, 2015)

1.2.5 Gate Design

Gate location is critical as flow front from the gate should be as uniform as possible. If any portion of the flow front starts to move backwards to the gate instead of away from the gate; weld lines and voids from entrapped air will occur, resulting in extra internal stresses in the part (Tang et. al, 2005). If the gate size is too small, it can also generate large shear stresses within the material as it flows through the gate. The high shear stress will also contribute to warpage of the part.

1.3 Residual Stress

Residual stresses are the stresses that remain within the moulded part, when there are no external loads applied to the system. Internal stresses affects a part similarly to stresses applied externally and is the main cause of uneven shrinkage and warping.There are two types of residual stress in injection moulding process, flow-induced residual stress and thermal-induced residual stress (Östergren, 2013).

1.3.1 Flow-induced residual stress

Flow-induced residual stress occurs when the moulded part solidifies before the long-chain polymer molecules are able to achieve its unstressed and random-coil state of equilibrium. There will be a highly oriented anisotropic frozen layer (skin) on the surface part due to a combination of high cooling rates and high shear stresses of the polymer melt adjacent to the mould wall (Fig 1.3) (Östergren, 2013). The skin forms at the edge of the mould wall because of the metal's good conductivity, which in turn acts as an insulator to the polymer melt in the core. This enables the core polymer to relax to a higher degree and better reach equilibrium, leading to isotropic, low molecular orientation zone

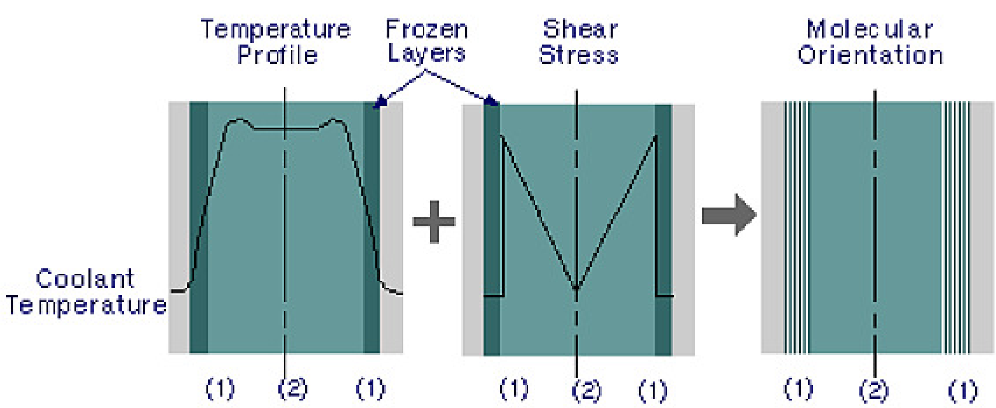

Figure 1.3: Flow-induced residual stresses developed due to a highly oriented solidified polymer molecules. Darker areas represent the frozen layers and (1) high cooling, high shear, and anisotropic oriented zone (2) Low cooling, low shear, and isotropic zone (Source: Östergren, 2013)

1.3.2 Thermal-induced residual stress

Thermal-induced residual stress can occur for several reasons. One of the main factors to it is uneven material shrinkage. At the beginning of the cooling cycle, the external surface close to the mould wall, is the first to cool and shrink forming an outer skin. This leaves the core partially molten and still free to contract. However, the rigid external skin acts as a constraint, limiting contraction when the inner core cools (Fig 1.4). The resulting constrained cooling is thermal-induced residual stress in the part. Compressive stresses develop at the skin as a result while tensile stresses develops in the core, which generally enhances the material's fatigue properties (Östergren, 2013).

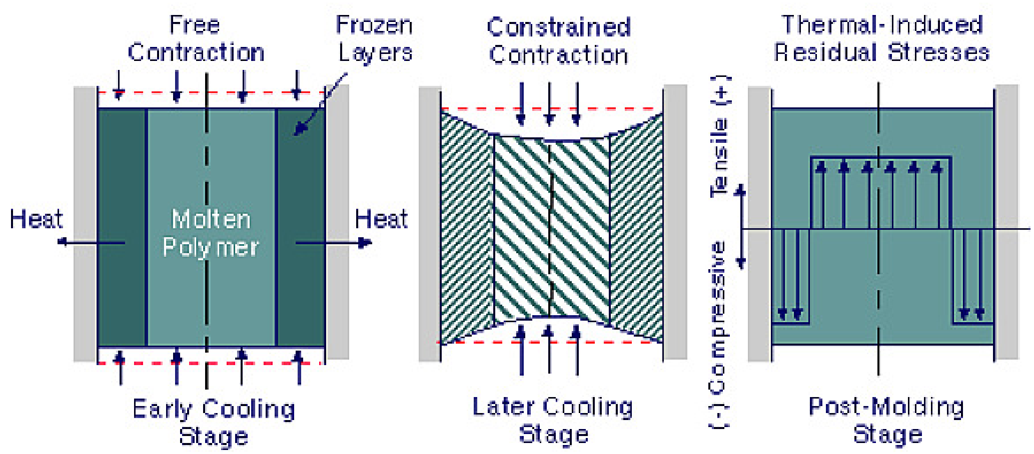

Figure 1.4: Thermal-induced residual stress caused by uneven material shrinkage, creating uneven stress distribution of compressive and tensile stresses in the finish part(Source: Östergren, 2013)

1.4 Rationale

There have been numerous efforts made in the last few years since the beginning of the century to improve warpage control techniques. However, many researchers focused on using numerical methods such as Moldflow simulator combined with statistical methods such as Taguchi orthogonal array and Analysis of Variance (ANOVA) methods. These researchers believe that their studies demonstrate how process parameters can be effectively optimised using Taguchi methods, validated by moldflow software. However, this in turn only widens the gap between academic research and industrial practical applications, due to the impracticability of implementing the studies.

Manufacturers generally do not take these studies seriously as there are many other factors that affect quality. These factors usually ignored in the studies includes: machine tonnage, machine brand, clamping force, surface aspects, cycle time, mould construction and many others. Note that even when there are two identical machines having the same specifications, bought from the same manufacturer; these two machines would in practice produce goods of slightly different quality in respect to each other. Moreover, factories do not generally have the necessary experienced employees, time and resources to carry out such detailed studies especially with complex products like cameras, where they may be over 3 dozen separate plastic components used. It would be extremely time consuming to carry out these studies 36 times, affecting the time to release the goods to market quickly.

Hence, many plastic manufacturers design the moulds and parts based on experience and general plastic design guidelines. This saves time and money and if the designer or tool maker is very experienced, little modifications only need to be made to the moulds in order to achieve good moulded parts. However, this can go awry sometimes and massive tooling modifications are required.

The challenge involved in situations like this is to correct the part defect without increasing cycle time. Sanchez, R., Aisa, J., Martinez, A. and Marcado, D. (2012) like many others found that cooling time is the most significant parameter affecting part warpage. Manufacturers honestly detest and despise recommendations to increase cooling time to improve part quality as it bites into their productivity and ultimately profit margin. Such suggestions are always met with scorn unless it is suggested by the customer itself and the customer is willing to pay the extra costs.

Hence, the focus here is to generate cost effective counter measures to solve the warping problem. As process parameters have already been pushed to the limits in this case, there are only two options: 1. Use a cooling jig or 2. Tooling modifications. Cooling jigs though do not generally affect cycle time, it does make the process more labour intensive. In long terms, this might still cost the plastic moulder higher manufacturing costs. Hence, we have to look into tooling modifications. For tooling modifications one feasible option is to change and optimize the gating type. Senkerik, et al. (2012) attributes built up internal stress within the moulded part as a major contributor to the warping phenomenon and it can be remedied by changing the gating.

As tooling costs are expensive and may take several modification trials and errors before obtaining a solution, it is recommended to use simulation software to first test out the suggested solutions. Injection moulding simulation software like Mouldflow Plastic Insight (MPI) offers an effective solution, allowing the designer to test different gate designs before committing the designs to the tool shop. This in turn saves the moulder money from reduced physical trails.

1.5 Computational Fluid Dynamics

Computational fluid dynamics (CFD) is a branch of fluid mechanics that utilises numerical methods as well as algorithms to analyse and solve problems regarding fluid flow. CFD provides a qualitative method to predict fluid flows by using mathematical modelling (e.g. partial differential equations), numerical methods (e.g. discretisation and solution techniques) and other software tools (e.g. solver, pre/post processing utilities) (Kuzmin, 2012). CFD is based on Navier-Stokes equation that describes correlation of pressure, velocity, temperature and density. CAE is the use of computer software to carry out CFD engineering analysis. The software to be used for injection moulding CFD analysis is Moldflow Plastic Insight from Autodesk.

1.5.1 Moldflow Plastics Insight®

Moldflow Plastic Insight (MPI) requires no introduction in the field of mould design and optimisation, as it is one of the most widely used CAE solutions in the industry. MPI is a 3D solid-based simulation tool that allows plastic part designers and mould makers to successfully predict design manufacturability and quality during preliminary stages of product development. Moldflow enables the users to avoid potential problems downstream which may lead to production delays and costly overruns such as numerous tooling modifications. MPI represents a complete suite of advanced simulation tools for plastic process to predict and eliminate potential manufacturing problems and to optimise mould design, part design, material selection as well as processing parameters.

1.6 Meshing

The first step in CFD is to define a geometry, made up of a series of finite volumes. These finite volumes or elements are referred to as a “mesh” and is normally formed by 2-D or 3-D elements. The main purpose of mesh is to allow for Navier-Stokes discretisation of the partial differential equation, enabling numerical computations (Jaworski, 2004).

After meshing, boundary conditions and the transport properties must be specified including any appropriate turbulence models before a solution can be initialised. Some issues and limitations with CAE software are the need to differentiate and select mesh type, the need to attain convergence results prior to analysis and the need to correctly use appropriate transport and physical properties within the simulation software.There are generally three basic element types in meshing. They are:

- Beam elements (1D) : 2-noded elements used for tasks such as modelling cooling channels and cold runners
- Triangle elements (2.5D) : 3-noded elements used for Dual Domain and Midplane mesh types modelling.
- Tetrahedral elements (3D) : 4-noded elements used for 3D mesh type modelling.

1.6.1 Beam Mesh

Beam elements are basic, one-dimensional (1D) line that connects two nodes with an assigned, cross-sectional area shape (Fig. 1.5) (Jaworski, 2004). They are usually utilised for representation of melt delivery systems such as runners and cooling lines. Beam elements may also be used to represent beam-like part geometry such asscrew boss. In beam elements, the flow is assumed symmetrical about the central axis. The beam should have a length two to three times its diameter.

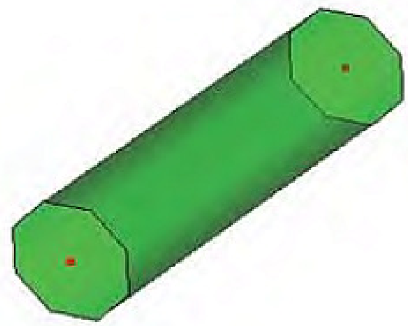

Figure 1.5: Beam element (1D) mesh (Source: Moldflow Tutorial)

1.6.2 Midplane Mesh

A midplane or shell mesh is a representation of a three-dimensional part using two-dimensional plane surface within the centre of the part (Fig 1.6). The place surface is assigned a thickness property, hence the 2.5D terminology. Midplane mesh works best for thin-walled injection moulding applications as to reduce computational time in CAE simulation. In this mesh, it is assumed that the flow length of a cross section is greater than its apparent all thickness, referred to as Hele-Shaw approximation (Jaworski, 2004). Significant errors may occur when midplane mesh is wrongly used for parts not considered thin-walled. As a rule, the minimum average length should be four times greater than the local thickness. A more conservative rule exists, where the minimum width to local thickness ratio should not be less than 10:1. The more a model digresses from these guiding principles, the greater the potential of error in analyses. This is an issue with beam shapes such as air vents and grills.

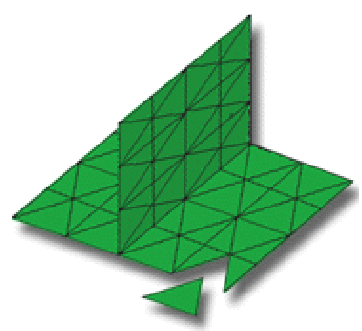

Figure 1.6: Midplane element (2.5D) mesh (Source: Moldflow Tutorial)

1.6.3 Dual-Domain Mesh

A Dual-Domain mesh is a three-dimensional part represented by using skin mesh or two-dimensional boundary of the outside surface of a part, translated from Computer Aided Design (CAD) models such as STL or IGES format (Fig 1.7) (Jaworski, 2004). The dual-domain mesh is similar to the shell mesh except the boundary shell is aligned and matched for the outer surfaces. The part thickness is defined by the distance between the mesh surfaces. Mesh density plays an important role in determination of geometries with varying thickness such as hinges or drafted ribs. The same limitations in thickness ratio that applies to midplane mesh also applies to dual-domain, it is more suitable for thin-wall parts.

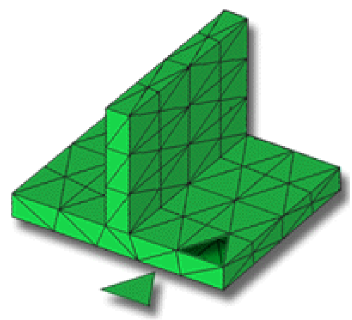

Figure 1.7: Dual-domain (2.5D) mesh (Source: Moldflow Tutorial)

1.6.4 Tetrahedral Mesh

A tetrahedral mesh, is a four-node element gives a 3D representation of the part by filling the volume of the model (Fig 1.8). 3D mesh works well with any geometry or part that does not adhere to the thickness-limitation ratios as in midplane mesh. As tetrahedral utilises Navier-Stokes equations rather than Hale-Shaw approximations, the 3D analyses requires extra computational time to complete. This makes 3D mesh suitable for thick models with complicated geometries.

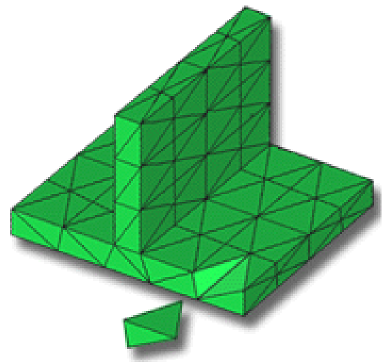

Figure 1.8: Tetrahedral (3D) mesh (Source: Moldflow Tutorial)

1.6.5 Computational Time

Computational solution time is an important consideration when choosing a mesh type for analysis. As multiple iterations or trials are required for successful simulation study in a work environment, carrying out simulations that require longer times will pile up and cost significant amount of time. The total solution time consists of model preparation (mesh repair, set constraints, boundary conditions) time and analysis calculation time. These are reliant on the model's element type and sum, complexity and user selected analysis option. In general, Moldflow recommends dual-domain mesh as it provides the best combination of model preparation time and the time for analysis for most simulations (Fig. 1.9).

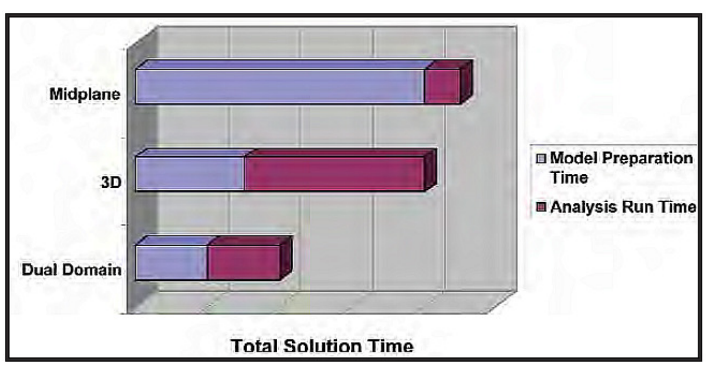

Figure 1.9: Total Solution time for three different mesh types. (Source: Moldflow Tutorial)

1.7 Case Study

The part in focus for this study is a faceplate (Fig 1.10), part of a decoder from Lifesize Communications. The faceplate forms the front cover and is made of Infrared transmitting polymer, PC Lexan 940A from Sabic. The main problem with the faceplate is part warping, causing poor fit with the main housing (Fig 1.11) creating a cosmetic defect. The part has a total part length of 330mm and width of 35mm, which makes it highly susceptible to warpage due to its high length to width ratio. The part warpage is up to 2mm total and in order to obtain a good fit, it must be brought down to less than 1mm.

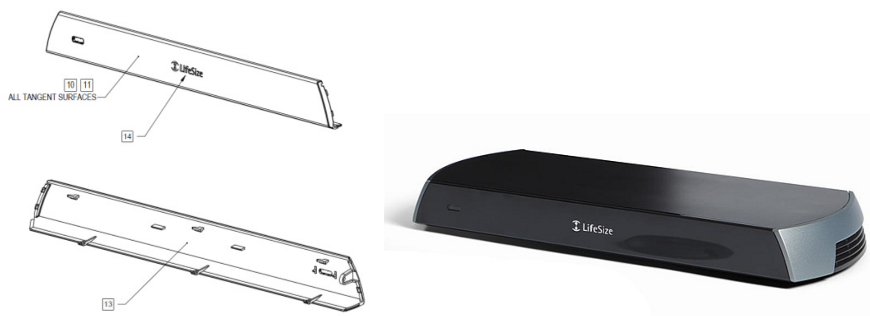

Figure 1.10: Faceplate of the decoder. (Source: Lifesize)

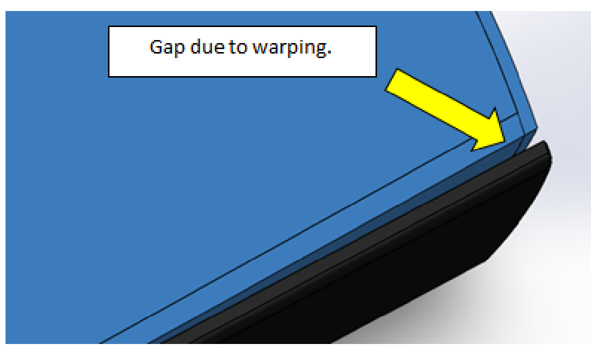

Figure 1.11: Poor fitting of the faceplate and the decoder.

Due to market pressure that requires immediate release of the product to capture the market, production continued with help of cooling jigs and increased injection moulding cooling time which contributed to higher overall costs. Defect rates were also high, adding to the production scrap costs.

1.8 Aims and Objectives

The aim of this project is to:

- Reduce the warping of the faceplate to a value less than 1.0 mm without changes to the part design and without increasing production cycle time.

The objectives of this study are to:

- To reduce warping in the faceplate to a value less than 1.0mm.
- To offer a cost effective solution that does not increase cycle time.
- To reduce residual internal stresses through optimised gate design.
- To determine the optimum gating layout, type and size for this case study.
- To simulate and verify design effectiveness.
- To optimise simulation mesh and constraints to obtain low and efficient computational time without sacrificing accuracy.
- To study the effects of mould surface temperature on the residual stress

1.9 Problem Statement

<u>Question to statement on hand:</u>

How can the warping from an injection moulded plastic part be minimised or eliminated by reducing the residual stresses?

Problems:

i. Warpage occurs post moulding and the final moulded part has poor fit with the main housing unit
ii. Process parameters have been pushed to the limits and warping still occurs
iii. Cycle time must not be increased to make manufacturing cost effective
iv. Part geometry of the face plate is long and moderately thin
v. Mould have been tooled, with both core and cavities finished
vi. Too late to change part geometry and design post tooling

1.10 Proposed Solution

The proposed probable solution to the problem statement is in the flow chart as below (Fig 1.12)

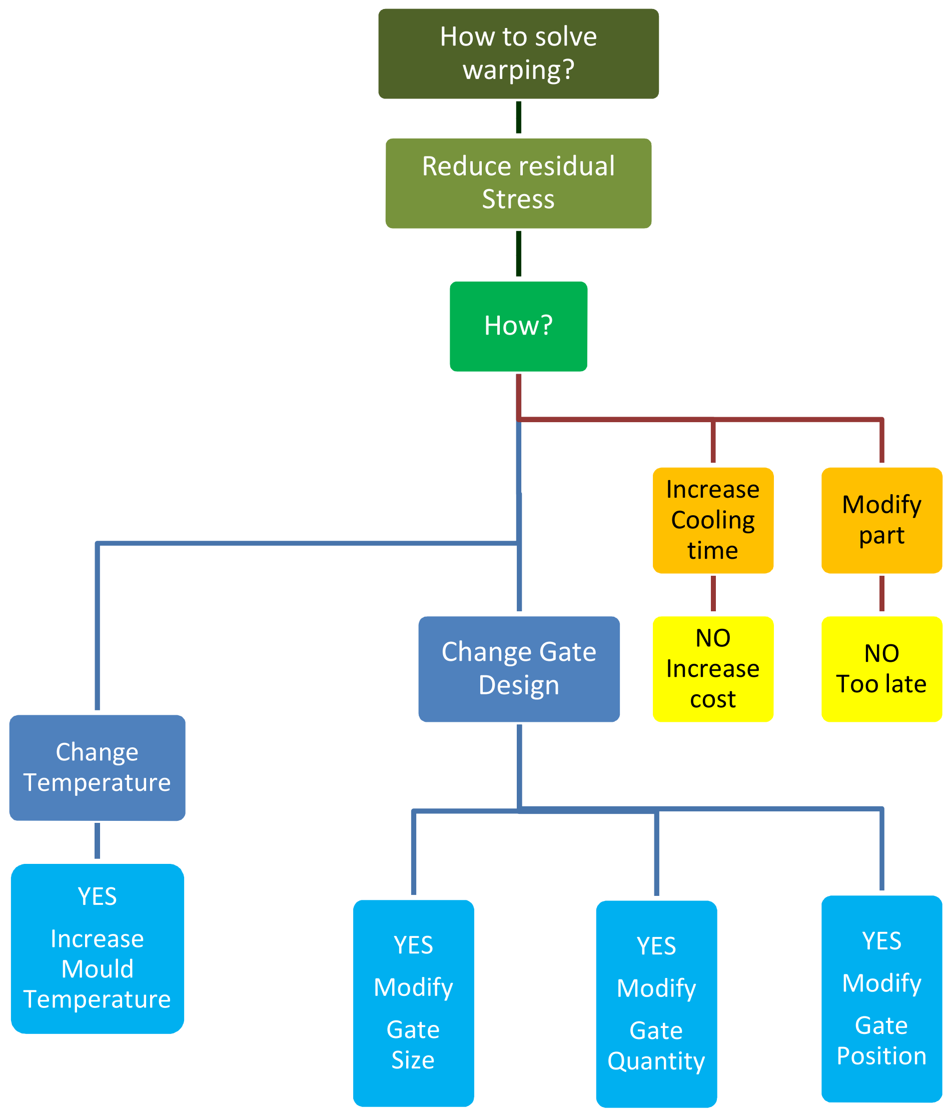

Figure 1.12: Process flow chart to determine probable solutions to the warpage problem.

CHAPTER 2

LITERATURE REVIEW

2.1 Process Parameters Optimisation: Taguchi Method

Warping defects in injected moulded part are generally attributed to unfavourable process conditions. The effects of processing conditions on the properties of the injected parts have been investigated by several studies. Reddy, et al. (2009) carried out studies to predict warpage of injection moulded parts through soft computing methods, namely artificial neural networks and support vector machines. The control parameters were optimised using Taguchi's orthogonal array, a method proven popular amongst those investigating injection moulding due to numerous processing conditions that exists. Reddy et al. compared artificial neural network (ANN) model against support vector machine (SVM) model to judge its ability and efficiency of the models to predict absolute relative error warpage values. From their studies, it was concluded that ANN model predicts with higher accuracy as opposed to SVM.

Tuncay and Babur (2006) looked into minimising warpage and sinkage index in injection-moulded thermoplastics by Taguchi optimization method. In the study, Tuncay and Babur used process parameter ranges recommended from Mouldflow Plastic Insight (MPI) software. The parameters studied included mould temperatures, polymer melt temperatures, packing pressure and the focus of the study, the rib cross-section types as well as the rib layout angle. In order to reduce time and cost to evaluate the moulding conditions with MPI, Taguchi was used to reduce the number of testing simulations required. The confirmation test for optimal process parameters conducted indicates the effectiveness of the Taguchi optimization method.

Many researchers use Taguchi to first obtain optimal processing conditions before further analysis of the hypothesis on hand. This kind of method is not without limitation as the search space is limited. The so called ‘optimum’ process conditions are actually just best case for the specified set of parameters. It may not be considered optimum at all as too many parameters were ignored, simplified or simply disregarded by the researcher.

2.2 Effects Of Temperature and Pressure on Warpage

Temperature and pressure differences along the mould cause local shrinkage and the resulting internal stresses induces warping. Sanchez, et al. (2012) Studied the relationship between cooling setup and warpage effects. The research presented warpage values obtained from non-contact laser scanning apparatus while varying only cooling parameters; temperature, cooling time and cooling flow rate. The experimental process was clearly expounded and designed as the samples were injected and carefully stored for stability of each set. Cooling time was found to be the most significant parameter affecting warpage while melt temperature is less important and coolant flow rate is almost negligible. As mentioned previously, plastic manufacturers rarely if ever favour long cooling rates. Manufacturers would lose significant production time from increasing its cooling time especially with high order volumes. An increase of 10s cycle time per part would undoubtedly require 28 hours extra per 1000pcs moulded, not including rejected parts. Such studies are actually quite useless in the industry but Sanchez et al. did propose to further test cooling position effect as it might be a debatable point for mold-makers and plastic moulders.

Mould temperature difference can in some cases can be the major contributing factor to inner stress over other factors. Unequal mould temperatures may lead to thermokinetical asymmetry of the melt flow, leading to disproportionate structure development. The resulting dissimilar localised stresses in the parts cross section results in part warpage. Bociga, et al. (2010) investigated the effects of warpage of injection moulded parts results of mould temperature differences. Bociga et al. confirmed that it is very important to assure uniform cooling of the moulded part by proper design of the cooling system else it would lead to internal stresses in the part from unequal mould temperature from their cross-section studies of the moulded plastics. However in practice, there are other factors influencing development of internal stress such as polymer flow, different wall thickness along the part, part geometry, ejection forces and many others.

Kovacs and Siklo (2011) investigated cooling effects at the corners of injected moulded parts by comparison of mathematical versus simulation models. Kovac and Siklo designed the mould with variable cavity and interchangeable gate inserts. This is a very clever design as it allows cost effective study to be conducted from various angles by rotating the cavity inserts or changing the gating position and even type. Like Sanches et al. and Bociga et al., Kavacs and Siklo analysis showed that significant temperature difference between the two sides of the moulds from asymmetrical cooling caused anisotropic shrinkage; the main cause in corner deformation, mechanisms similar to warpage.

Wang, Zhao and Wang (2013) studied reduction of sink marks and warpage for rapid heat cycle moulding process (RHCM). These two defects were found to be more prominent in RHCM over conventional injection moulding (CIM) due to the large temperature difference between the mould core and cavity plates. As the cavity side is usually the cosmetic side of the moulded part, only the cavity side is heated and cooled rapidly while the core side is cooled through conventional coolants. The significant temperature difference leads to serious non-uniform cooling of the plastic parts resulting in much larger warpage in the final part. Wang et al. resolved the issue by design of new screw stud structures accompanied with external gas assisted packing developed to reduce sink marks. First-step packing time and cooling time were found to have most significant contributions to reduction of warpage. However such conditions are not favourable in factory settings as increase in packing time as well as cooling time affects cycle time and ultimately productivity.

Le, et al. (2011) investigated the influence of pressure on the crystallization kinetics during the injection moulding process. Using an embedded thermocouple probe, the temperature of the cavity centre is measured. The measured temperature curves shows plateau shaped relation to the crystallisation phenomenon. Measurements done at other various pressures on the other hand shows an increase in crystallisation plateau temperature depending on pressure cavity. Thoroughly understanding crystallisation may be the correct step towards controlling warping and may lead to effective control of internal stresses that develop during moulding process. However much work will need to be done to translate findings herefor practical applications in injection moulding.

Postawa and Kwiatkowski (2006) examined residual stress distribution in injected moulded parts using a photoelastic method making use of the double refraction passing through a transparent medium. The study focus on effects of post filling pressure and effects of injection temperature. The analysis was carried out to point out the area of stress distribution along the transparent part. However, such an analysis requires fundamental knowledge of properties in the resulting images that appears on the screen and requires skills and considerable experience to interpret the results. Postawa and Kwiatkowski's acknowledge that there is no possibility to perform such analyses in industrial manufacturing. However, this may not be solely true as many lens and transparent covers are plastic injection moulded these days as they are no longer solely glass. The analyses may be carried out during tool testing to enable further optimisation of the mould. There may actually be potential for application in the moulding industry with further research, albeit limited to transparent materials only.

2.3 Material Strength versus Warpage Resistance Relationship

Babur and Ibrahim (2009) studied warpage and structural analysis of thin shell plastics. Babur and Ibrahim also first used Taguchi to first optimised their choosen process parameters before proceeding with the core analysis. Their analysis shows that Glass fibre reinforced PC/ABS warped significantly less than virgin unreinforced polymers of either PC, ABS or PC/ABS blend. The authors linked material strength to resistance to warpage. With light correlation, they found that materials with higher tensile strength as in the fibre reinforced polymer tends to have less warping in the selected z-axis direction as opposed to softer, lower tensile strength polymers.

Senkerik, et al. (2013) also relates piece stiffness to warpage resistance. Their main focus however is on the different gating layout as well as cooling layout to reduce part warpage. Validated by MPI simulation software, Senkerik et al found optimal injection gating locations as well as better cooling channel layouts reduced part warping. This analysis is actually practical and is feasible for use in injection moulding companies, straight forward and can be easily applied by the manufacturers. Studies like this serves to narrow the gap between academia and industry instead of distancing it apart

2.4 Gate and Runner Designs

Kima and Im (2003) investigated the effects of gate location design for an automobile injection box with integral hinges. It was found that properly determined gate location leads to better resin flow and significantly reduced hesitation time. As result, part has reduced weld lines and no short moulds. However, as seen in many studies, the researches ignored more complex interactions from both the machine parameters as well as the mould tooling itself. Kima and Im could consider further research with gas assisted compression injection moulding, which is especially recommended for thin-walled parts and optical application parts. The reason to this is because the parts manufactured this way have very low internal stresses (Oswald, 2001).

Demirer, Soydan And Kapti (2007) carried out an experimental investigation on the effects of hot runner systems versus conventional cold runner systems in injection moulding process. Demirer et al. Took careful steps to eliminate noise as much as possible by using the same mould to conduct both studies. First using it with hot runner system (HRS) then converting it to cold runner system (CRS) by necessary tooling modifications. The study showed that HRS can be performed at lower processing temperatures and lower packing pressures as opposed to CRS because CRS have problems with the gate freezing. This means that less energy is consumed by the moulding process and hence smaller machines may be utilised for relatively larger components. It was also found that HRS results in less part shrinkage from better influential packing stage from late solidification of the gates, lower heat requirements, lower pressure losses and better fluidity of the molten polymer. Demirer et al. did fail to consider the installation costs of HRS in terms of money and technical resources. If hot runner systems are allegedly said to be superior as in most academic studies, questions arise to why it is still not a common practice among plastic manufacturers and why are CRS systems prevalent. HRS are generally not used for lower volume plastic parts as there is no cost justification for installing the heaters. In this case, the material wastage from runners are still cheaper than the HRS set-up.

2.5 CAE and Other Numerical Methods

Computer aided engineering, CAE have been recommended as an effective method to test designs and improve it before carrying out costly and mostly irreversible fabrication of the injection moulding tool. However, depending on the experience of the user carrying out the simulation, a large number of trial and error iterations may be required to come up with an acceptable solution. Simulation software such as Moldflow Plastic Insight (MPI) may be computer hardware intensive especially for complicated and or large geometries as well as complex simulation models, requiring hours at times just to run one simulation model.

Deng, Zhang and Lam (2010) used hybrid optimization method for minimizing warpage of injection moulded parts. Zhang et al. proposed a combines mode-pursuing sampling method with conventional optimization algorithm to examine for ideal moulding process parameters. Kriging surrogate modelling strategy was used as a means of substitute to computationally intensive CAE software. A case study using a plastic food tray was presented with variable injection time,packing pressure, melt temperature and mould temperature as design variables. The case study as whole showsthat the proposed optimization method is able to reduce warpage effectively in an efficient computationally manner. Though this sounds favourable to the plastic industry of being able to carry out optimization more efficiently, it should however be noted that the method presented is not for the average Joe. In layman’s terms, it’s just too freaking hard to be understood and used by the plastic moulders unless it came in a nice cute little software package that runs and calculates the models with a click of the mouse.

Dang (2013) also concerned on more efficient optimization processes. Dang's paper on the general frameworks for optimization of the process parameters in moulding seeks to accelerate the optimization process and seamlessly integrate it into CAE, to speed up the moulding design process and still ensure quality of the moulded parts. Dang carefully discussed the advantages, disadvantages and scope of application for the optimization methods and from the results obtained from the case studies. It was concluded that genetic algorithm is the best choice for problems requiring low simulation cost or for simple moulded parts. Direct gradient method on the other hand is recommended for low nonlinear problems while metamodel based optimization methods are best suited to problems with low nonlinear behaviour regardless of single or multi-objective optimization. Dang rightfully acknowledge the gap between simulation and physical experimentation due to limitation in simulation techniques, their simplification assumptions and approximation errors. End of the day, simulation optimization is only a reference data and should be verified by physical testing.

Courbebaisse (2005) looks into pre-modelling concept and the numerical simulation of the moulding process. Courbebaisse noticed a lack of pre-modelling tools which allows for estimation of an effective solution. Optimization is seen in this paper as a fast algorithm for propagation simulation of molten polymer within the mould and requires best positioning of injection gate points during mould filling to minimize the end-filling pressure. The validation is done by Aronsson's model and leads to a fast Borgefor's algorithm. However Courbebaisse lets it rest to the industries to carry out case studies to cofirm the robustness of the methods proposed in the paper as it is an original approach.

CHAPTER 3

METHODOLOGY

3.1 Research Scope

Methodology; a description of a process or expanded to include philosophical coherent collection of ideas, concepts or theories as they relate to a particular field or discipline of inquiry (Discoll, 2004). The methodology will include the principles of procedures, rules and postulates employed in the implementation of the research project to carry out CAE simulation using Moldflow.

3.2 Resources Required

The following resources are required for the successful completion of the simulation project:

- Autodesk Moldflow Plastic Insight® CAE Program
- Solidworks CAD Program
- Original 3D files of part
- Sample (physical) part
- Feeler Gauge
- Computer workstation (gaming unit)
    - Processor : Intel-i5 3550
    - GPU : GeForce GTX 650
    - RAM : 8GB

3.3 Simulation Methodology

3.3.1 CAD – Geometry Preparation

The purpose of the geometry preparation is to manually draw in the gate to be used for the simulation study. As Moldflow can only specify gating injection points, not gating type, the gate type, design and dimensions have to be drawn manually in to the part. Solidworks CAD program is used for modification of the part geometry.

The inner face of the part is selected as the plane for sketching. A horizontal reference line in then drawn about the central axis. This reference point is used to determine gate locations. A r = 1 mm radius circle is drawn at the most right position of the inner face, on the reference line (Fig. 3.1). This most right position is determined as the datum and original point of the gate. The circle is then extruded to form a 10 mm long direct sprue gate. The file is saved as stl. (stereolithography) format for simulation purposes. The steps above are then repeated for different gate sizes and/or positions. The listed methodology for CAD – geometry preparation is found in Appendix A.

Figure 3.1: A direct sprue gate extruded from the sketch located on the guide line.

3.3.2 CAE – Moldflow Simulation

Moldflow Plastic Insight program is used for injection moulding simulation study. A new project is created, givena project name and the stl. file from Solidworks is then imported as geometry.In the import menu, Solid 3D mesh type is selected and the units of measurement millimetres (mm) are selected as default.The part is then meshed as 3D, tetrahedral.Under mesh density options, the mesh size is set to 5mm, merge tolerance set to 0.1mm and the global edge length set to 1mm.The mesh is then fixed using repair wizard, using default recommendations.

The type of moulding is selected as “Thermoplastic Injection Moulding”. The type of analysis sequence is set as “Fill+Pack+Warp”. The material is selected as the original, PC Lexan 940 from Sabic Innovative Plastics from the material list.The injection location is then specified at the gate location drawn previously.The process settings are set, with Mould Surface Temperature = 80^{o}C and Melt Temperature = 320^{o}C.The filling control, Velocity/Pressure switches over and Packing/Holding controls are selected as auto. For simplicity’s sake, most settings are selected as default as tempering with such settings require significant knowledge and experience for Moldflow. The cooling time is specified as 25s and the analysis is started.

The results are exported once the simulation is done and tabulated.The deflection (warpage) results of the physical part is measured using a feeler gauge and compared with the simulation results.The process is repeated and the steps above repeated with different mesh sizes, gating size, gating positions and different mould surface temperature. The listed form of the CAE – Moldflow Simulation methodology is found in Appendix B.

3.4 Simulation Variables

The variables concerned in this study are listed as follow:

i. Mesh Type (Tetrahedral vs Dual-domain)
ii. Mesh Size (1mm-9mm)
iii. Gate size (Radius, r=1mm to r=5mm)
iv. Gate quantity (n=1,2,3)
v. Gate position From Datum =0 (in %)
    n=1, 0, 10, 20, 30, 40, 50
    n=2, 0-100, 20-80, 30-70, 40-60
    n=3, 0-50-100, 10-50-100, 30-50-100, 40-50-60
vi. Mould surface temperature (T=80^{o}C to 140^{o}C, every 20^{o}C)

3.5 Desired Result Output

There are two results that are of concern in this study:

1. Deflection (warpage) in the z-axis direction
2. Pressure at end of fill (residual stress)

For the deflection readings, the total deflection is obtained by summing the deflections of the positive components from the datum, z=0, and deflections of the negative components from datum, z=0 (Fig 3.2).

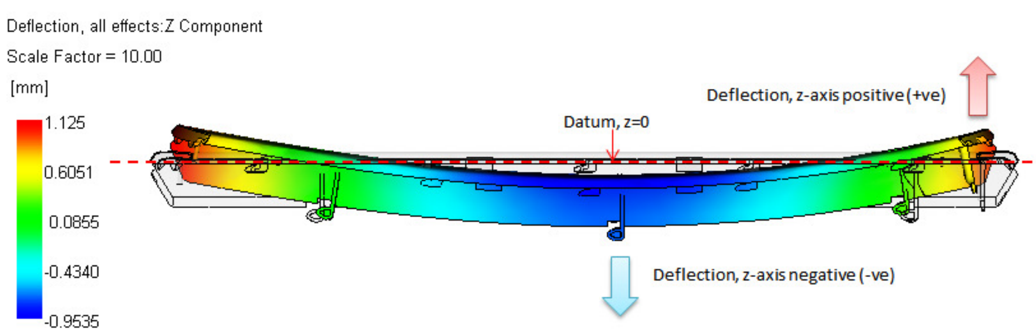

Figure 3.2: Diagram showing warping deflection in the z-axis. Positive deflections are in red and yellow shades while negative deflections are in blue shades. The diagram is not to scale, exaggerated for clarity.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Simulation Pre-Study

Before the actually simulation study may be carried out, an optimisation simulation pre-study is first carried out to determine the optimum mesh type and size to be used in order to minimise computational time in terms of analysis time and memory usage. This is extremely important as several iterations or studies need to be carried out per part. If the simulation is not optimised to reduce computational time, the design engineer would waste several hours for nothing. This translates into increased costs due to increasing man-hour as well as delayed time to modification improvement and ultimately affects production schedule.

4.1.1 Mesh Type

Moldflow Plastic Insight 2013 allows three mesh types, 1) midplane, 2) Dual-Domain and 3) Tetrahedral. In this case only Dual-Domain and Tetrahedral are tested as the geometry is too complex to form midplane mesh. The pre-simulation is carried out with 1mm mesh size and 1mm radius direct gate. The results of concerned are: deflection along z-axis, simulation time and mesh time. Deflection is in millimetres while time is in hours, minutes and seconds.Numbers in bracket represents percentage deviation from physical readings.

With reference to Table 4.1, as expected the mesh time for tetrahedral is significantly more than 2D Dual Domain. Mid Plane was not included as it has significant problems generating the mesh. The mesh generated is full of gaps and mismatched ratios. The geometries generated were poorly represented with features missing (Fig 4.1).

Table 4.1: Simulation results for varying mesh type with mesh size=1mm, Gate radius = 1mm.

Mesh Type	Deflection (z-axis +)	Deflection (z-axis -)	Deflection Total (mm)	Simulation Time	Mesh Time
Actual (Physical)	1.200	1.000	2.200	-	-
3D Tetrahedral	1.220 (+1.67%)	0.820 (-18.03%)	2.040 (+7.27%)	1:32:54	0:05:59
2D Dual Domain	1.432 (+19.33%)	0.790 (-20.98%)	2.222 (+1.00%)	0:49:35	0:02:30
2D Mid Plane	-	-	-	-	-

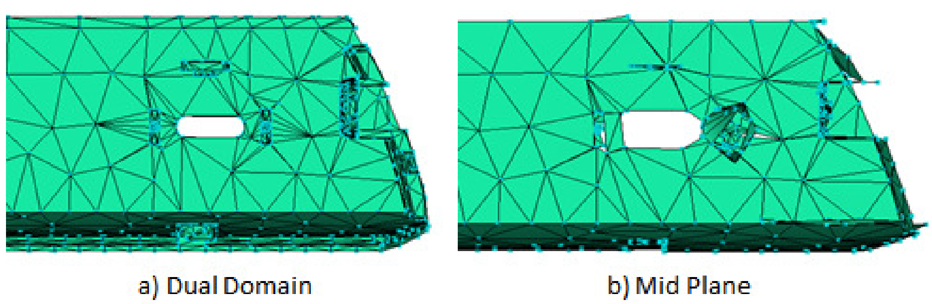

Figure 4.1: Mid Plane mesh (b) as opposed to Dual Domain (a). The features in Mid Plane are distorted and gaps appear in the mesh.

The total computational time for the simulation is significantly lower for Dual Domain at 49mins and 35secs compared to tetrahedral at 1hour 32mins and 54 secs. Dual Domain mesh uses 43mins less computational time for simulation than tetrahedral meshing, gaining an efficiency advantage of 87% faster simulation time. This is expected as 3D analyses require extra computational time to complete (Mitchell and Vavasis, 2002).

In terms of deflection along the z-axis, dual-domain seems to have a simulated result closer to actual physical parts. The percentage difference for dual-domain is +19.33% for z-axis positive and -20.98% for z-axis negative while for tetrahedral is +1.67% for z-axis positive and -18.03% for z-axis negative. Overall deflection, Dual Domain has a total deviation of +1.00% as opposed to tetrahedral with 7.27%. This means that in this case, dual-domain meshing actually yields better results and has shorter simulation time. Both mesh types were noted to over predict deflection in the positive direction while under predicting deflection in the negative direction. The total z-axis deviation is the main concern in this study.

4.1.2 Mesh Size

A total of 9 mesh sizes (global edge length) were selected for the pre-simulation study. From 1mm-9mm mesh sizes. The gate size is 1mm radius for the study while the mesh type used is Dual Domain. Dual Domain is selected as it has significantly lower simulation time over 3D Tetrahedral and better accuracy, with lower deflection deviations compared to the physical readings.

The simulation was run with varying mesh sizes and the results are tabulated in Appendix C. Included in the table is the percentage (%) difference of the simulated results versus physical results.

From the results obtained, the simulation time reduces as the mesh size increases (Fig 4.2). However as the mesh size increases, the accuracy of the result decreases (Fig 4.3). Finer mesh sizes tends to provide better results, giving higher accuracy of deflection warping predictions (Mitchell and Vavasis, 2002). As such, a mesh size of 5mm is selected as the standard to be used further in the study as it has significantly low simulation time requirement of 2.5mins while still maintaining an acceptable deviation accuracy of only -3.00%. When compared with fine mesh size of 1mm, this saves 47mins per simulation or a 94.9% simulation time reduction.

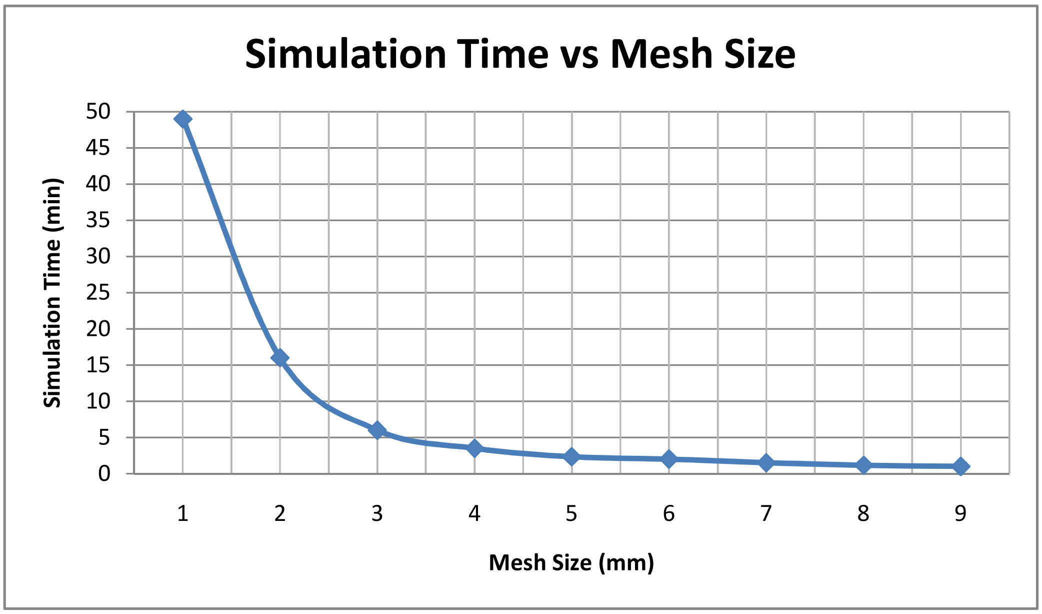

Figure 4.2: Graph of simulation time (mins) versus the Mesh size (mm). Simulation time decreases exponentially with decreasing mesh size.

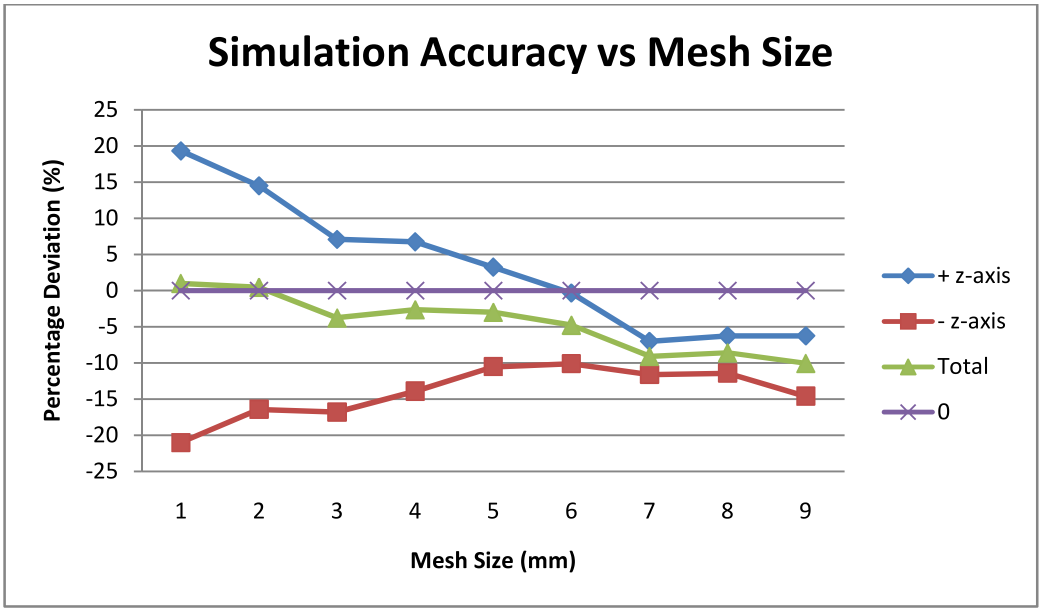

Figure 4.3: Graph of simulation accuracy (Actual-simulation) in percent % versus the mesh size. Total deflection accuracy (green line) decreases with increasing mesh size.

4.2 Gate Study

With the mesh type and size determined by the pre-study to be Dual Domain and 5mm respectively, the main study shift focus to the gate. The factors that were studied are gate size, quantity and location. The main focus of this study is to determine if varying gate designs have an effect on both the warping and the residual stress distribution. The results of concern are the z-axis deflection and pressure measured at the end of the injection moulding filling cycle. Pressure is in Mega Pascals (MPa).

4.2.1 Gate Size

The gate used was a direct sprue gate (Fig. 4.4). Direct sprue gates allow for direct material flow, experiencing minimal pressure loss and reduces material shear (Goodship, 2004). However, the gate runs the risk of high stress concentration caused by material freeze off, prematurely blocking the material flow due to frozen polymer. There is also need for gate removal once the part is ejected from the mould.

The gate sizes to be studied varies from gates with radius, r=1mm to gates with radius, r=5mm. The gate drawn into the model is only part of it, with a height of 10mm. The results from the simulation are recorded in Table 4.2.

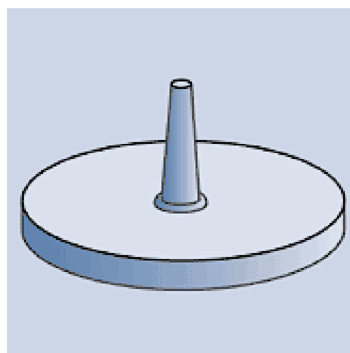

Figure 4.4: Direct sprue gate (Source: BH Molds)

Table 4.2: Simulation results for varying gate size with mesh size = 5mm, mesh type = Dual Domain

Radius, r (mm)	Deflection (z-axis +)	Deflection (z-axis -)	Deflection Total (mm)	Min. Pressure (MPa)	Max. Pressure (MPa)
1	1.239	0.895	2.134	15.4	65.1
2	1.212	0.915	2.127	0	82.4
3	1.225	0.925	2.150	15.7	65.9
4	1.221	0.918	2.139	0	82.7
5	1.228	0.926	2.154	0	81.7

From the results shown in Table 4.2, no significant changes in total part deflection (z-axis) can be observed for changes to the gate size. This shows that gate size is not a major factor in reducing the warpage of the part. Concern however shifts towards the pressure results obtained. The results gathered were erratic and inconsistent for Dual Domain meshing. It seems that 2D mesh is poor at simulating pressure flow distribution hence the simulation for pressure have to be redone with 3D tetrahedral mesh and tabulated in Table 4.3.

Table 4.3: Simulation results for varying gate size with mesh size = 5mm, mesh type = Tetrahedral.

Radius, r (mm)	Deflection (z-axis +)	Deflection (z-axis -)	Deflection Total (mm)	Min. Pressure (MPa)	Max. Pressure (MPa)
1	1.116	0.987	2.103	16.7	44.5
2	1.021	0.915	1.936	20.5	43.6
3	1.027	0.925	1.952	21.5	43.6
4	0.946	0.918	1.864	21.2	43.1
5	0.8616	0.926	1.7876	13.1	42.9

The study is redone in tetrahedral meshing. As such there is a need for revalidation of the mesh used. Previous studies for mesh size optimisation is still valid for tetrahedral as long as mesh density is the same. Hale (2014) showed that the stress sensitivity of a simulation is logarithmically related (y=ln[x]) to the mesh density (Fig 4.5). Hence, using a 5mm mesh size in tetrahedral would have a similar simulation time and accuracy in relation to other mesh sizes.

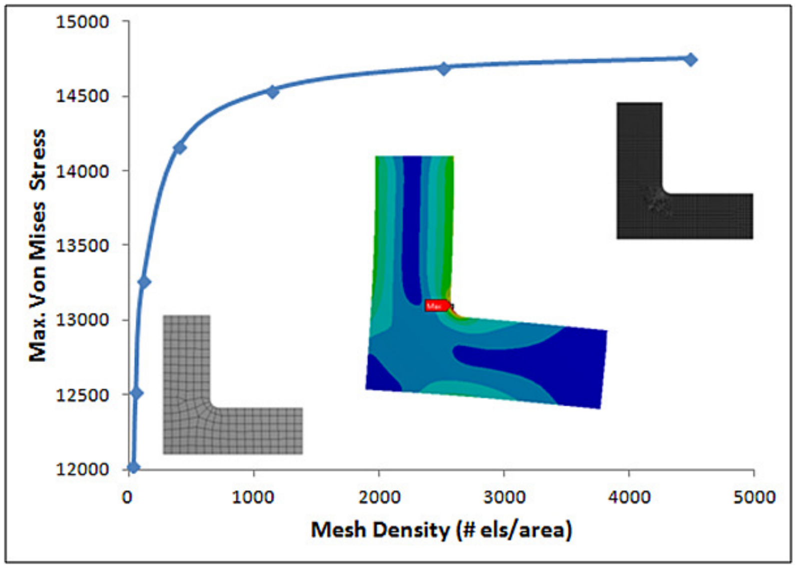

Figure 4.5: Graph showing stress sensitivity increases with mesh density and levels out. Accuracy is increases with increasing mesh density till a saturation point. (Source: Hale, 2014)

With data from Table 4.3, the total deflection in the z-axis value is 2.103mm, which is a -4.4% deviation from the physical results of 2.200mm. Therefore the accuracy of tetrahedral meshing is acceptable. The simulation time obtained for tetrahedral 5mm mesh size is 6mins, a 140% increase of the simulation time required by Dual Domain with same mesh size. However, 6mins is still an acceptable simulation time.

The pressure distribution did not show significant changes until the gate radius size reaches r=5mm. However from the pressure distribution diagram (Fig 4.6), it is noted that the stress is more even out. The red areas where pressure is highest, initially limited to the gate spreads out further into the part as the gate size increases. Smallest gate size, r=1mm is noted to have lower minimum pressure than sizes 2 to 4. This may be due to the gate size being so small it acts as a choke point, allowing less material flow into the moulded part.

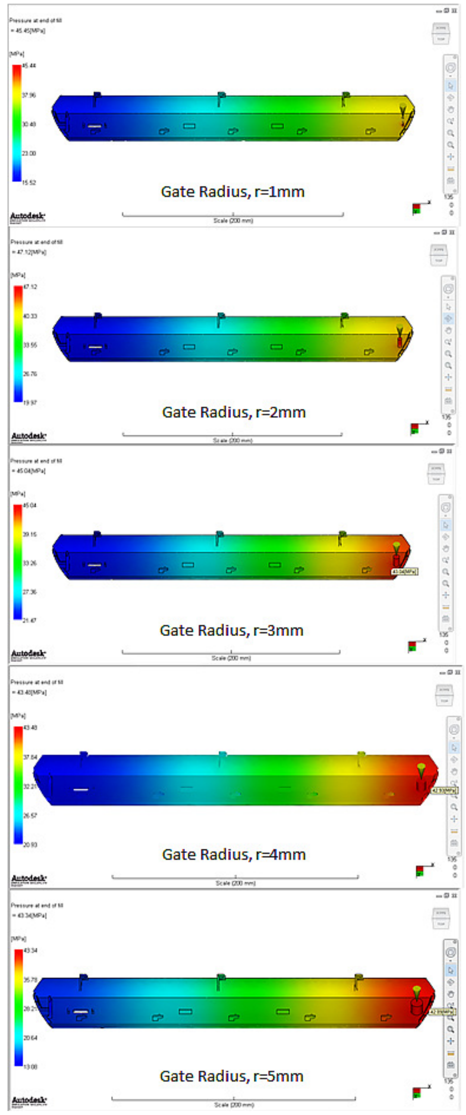

Figure 4.6: Simulated results showing the pressure distribution at end of fill. First result shows pressure for gate size r=1mm and last result shows pressure for r=5mm. The red spot (where pressure is highest) noted to spread out with increased gate size.

4.2.2 Gate Quantity

From the previous data obtained, Dual Domain is unable to effectively calculate and predict the pressure distribution for this part geometry. Hence from this point onwards, the mesh type used will be Tetrahedral. This is so the deflection results obtained may be directly linked to the pressure distribution. If the deflection data is by Dual Domain meshing while the pressure data is in Tetrahedral meshing, this will cast doubts on the validity of the data obtained.

The next part of the study was to determine effects of gate quantity on the warpage and pressure distribution of the moulded part.

Table 4.4: Simulation results for varying gate quantity with mesh size = 5mm, mesh type = Tetrahedral.

Gate quantity, n	Deflection (z-axis +)	Deflection (z-axis -)	Deflection Total (mm)	Min. Pressure (MPa)	Max. Pressure (MPa)
1	1.116	0.987	2.103	16.7	44.5
2	0.755	0.675	1.430	10.3	19.6
3	0.616	0.680	1.296	6.1	10.3

Increasing the number of gates shows promise as the warpage is seen to decrease as shown in Table 4.4. The pressure distribution also decreases significantly with increasing gate quantity (Fig 4.7). The maximum pressure decreases from 44.5MPa to 19.1MPa (57% reduction) when the number of gates increase to two. It further reduces to 10.3MPa (77% reduction) when the gate quantity is increased to three. The minimum pressure also reduced from 16.7MPa to 10.3MPa with two gates and 6.1MPa with 3 gates.

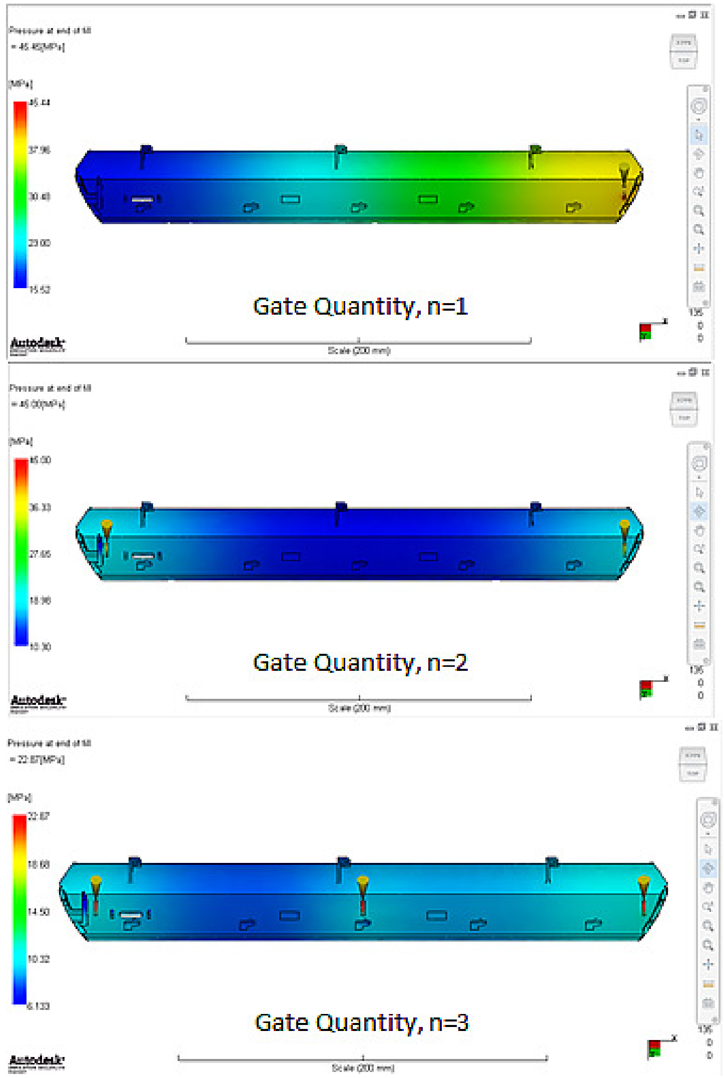

Figure 4.7: Simulated results showing the pressure distribution at end of fill. First result shows pressure for gate quantity,n=1 and last result shows pressure for n=3. The pressure reduces significantly and is dark blue for n=2 and light blue for n=3.

The part deflection also shows significant reduction with increase in number of gates. With one gate, the total deflection is 2.103 mm reduced to 1.430 mm (32% reduction) with two gates. With three gates the total deflection is reduced to 1.296 mm (38% reduction). Though the reduction is significant from one gate to two, the reduction from two to three is not much, only an extra 6%.

Increasing gate size affected the pressure distribution only slightly, therefore there was no significant results in deflection change. By increasing the gate number, the pressure measure at end of filling cycle within the part significantly decreases; hence the residual stress post moulding should be reduced accordingly. As residual stress have strong correlation with part warpage (Postawa, and Kwiatkowski, 2006), the reduction in residual stress will directly reduce warping of the part post moulding.

4.2.3 Gate Position, Gate =1

The gate position was studied to determine if it would affect both warping and pressure distribution. As the interacting effects are hard to predict and ascertain, the position study was repeated for all three gate quantities, n=1,2,3. First, the effects of gating position were determined for singular gate count. The position is calculated as percentage (%) distance from datum point, where: 0% is the start of the part and 100% is end of the part (Fig 4.8).

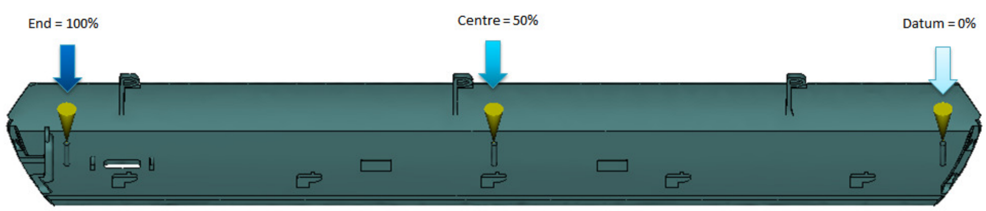

Figure 4.8: Gate position in terms of percentage (%) from datum.

Table 4.5: Simulation results for varying gate position with mesh size = 5mm, mesh type = Tetrahedral, gate quantity = 1.

Gate Position (%)	Deflection (z-axis +)	Deflection (z-axis -)	Deflection Total (mm)	Min. Pressure (MPa)	Max. Pressure (MPa)
0	1.116	0.987	2.103	16.7	44.5
10	1.044	0.963	2.007	24.5	39.8
20	1.027	0.919	1.946	23.6	35.8
30	0.934	0.858	1.792	18.6	28.5
40	0.989	0.996	1.985	17.2	28.9
50	0.875	0.902	1.777	12.8	18.4

The results from the positional studies shown in Table 4.5 indicate that the gate position is a critical factor. As the gate moves closer to the centre balancing the material flow, the total deflection consistently decreases. This might be due to the fact that from the centre, the material is able to flow both direction unimpeded in comparison to gate position at datum, where the material can only flow from 0% to 100%. Correct placement of gate location leads to better resin flow and reduced residual stress (Kima and Im, 2003).

4.2.4 Gate Position, Gate =2

For study of position with two gates, the position selected is similar to the study of one gate except it is a mirror image. Position 10%-90% is omitted because of the light pipe feature (hole) that is in the way, hence a gate may not be placed there. The results are tabulated in Table 4.6.

Table 4.6: Simulation results for varying gate position with mesh size = 5mm, mesh type = Tetrahedral, gate quantity = 2.

Gate Position (%)	Deflection (z-axis +)	Deflection (z-axis -)	Deflection Total (mm)	Min. Pressure (MPa)	Max. Pressure (MPa)
0-100	0.755	0.675	1.430	10.3	19.6
15-85	0.762	0.678	1.440	11.1	15.6
20-80	0.724	0.670	1.394	7.9	15.6
25-75	0.831	0.755	1.586	14.1	20.3
30-70	0.838	0.765	1.603	14.4	17.5
35-65	0.852	0.769	1.621	15.1	19.6
40-60	0.907	0.891	2.191	16.1	20.4
45-55	1.020	0.960	1.980	12.1	23.9

For gate quantity n=2, the total deflection does not continuously reduces when the gate position approaches the centre. The optimum position is found to be at the 20-80 percent point (Fig 4.9). Beyond that, the deflection increases instead of decreases as the gate position gets close to the centre of the part. This may be due to the material flowing from each gate, due to their close proximity creates a back flow pressure when meeting each other. When the portion of the flow front starts to move backwards to the gate instead of away from the gate; weld lines and voids from entrapped air will occur, resulting in extra internal stresses in the part (Tang et. al, 2005).The pressure readings also support this theory showing that the pressure rises for positions such as 40-60and 45-65 (Fig 4.10). Pressure is highest at the point closest to the gates.

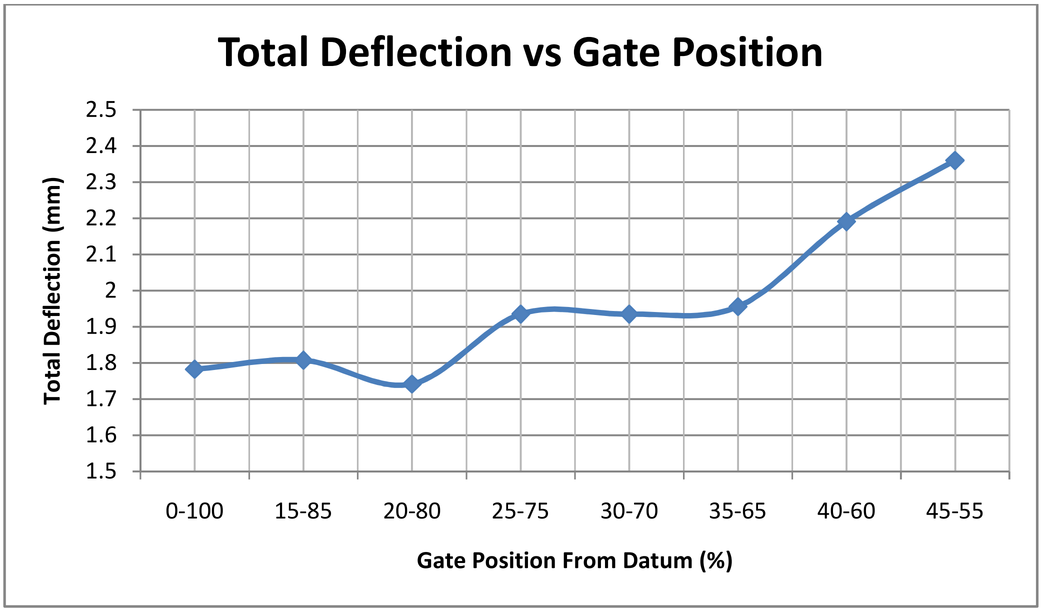

Figure 4.9: Graph of total deflection (mm) versus gate position from datum (%). Total deflection is lowest for position 20-80.

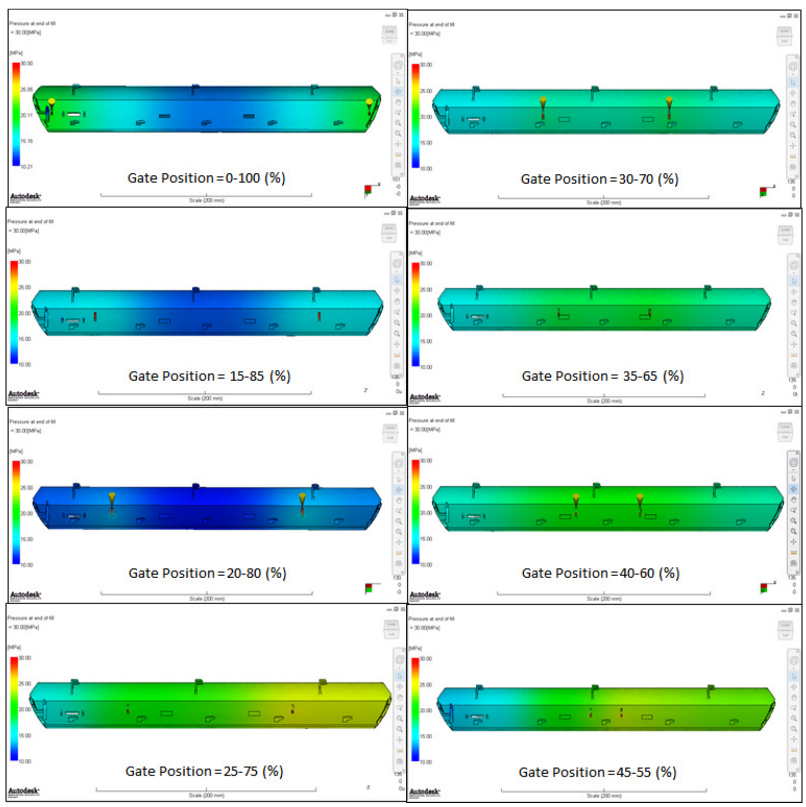

Figure 4.10: Pressure at end of fill for different gating locations. Pressure is lowest for position 80-20.

Gate positions with lower pressure distribution have lower z-axis deflection. This study further enforces the fact that lower pressure within the part translates to lower part warpage; while higher pressure translates to more warpage as in Figure 4.10 above.

4.2.5 Gate Position, Gate =3

The gate quantity is increased to three for position study. Position 10-50-90 is not carried out due to light pipe hole feature in the way. This study is a combination of single gate position study and dual gate position study. Results are shown in Table 4.7.

Table 4.7: Simulation results for varying gate position with mesh size = 5mm, mesh type = Tetrahedral, gate quantity = 3.

Gate Position (%)	Deflection (z-axis +)	Deflection (z-axis -)	Deflection Total (mm)	Min. Pressure (MPa)	Max. Pressure (MPa)
0-50-100	0.616	0.680	1.296	6.1	12.6
20-50-80	0.718	0.679	1.397	13.3	21.4
30-50-70	0.846	0.761	1.607	15.9	21.6
40-50-60	0.901	0.915	1.816	11.1	17.8

As expected, gate position 0-50-100 shows the least warping. The previous two studies on gating position have shown that gates that are evenly spaced out are the ones with low pressure distribution and low warpage. With optimum three-gate 0-50-100 configuration, the total deflection obtained is lowest so far at 1.296mm. The lowest value obtained with optimum dual-gate 20-80 configuration is 1.394mm total deflection. The differences between these two configurations are 0.098mm.

The initial simulated total deflection using tetrahedral mesh with single gate is 2.103mm. Changing only the gate position and quantity may reduce the value to 1.296mm with tri-gate 0-50-100 configuration. However, the specifications set by Lifesize require that the warping be limited to 1mm maximum. Changing the gate design alone will not help meet the standards required.

From all three gate quantity studies, it is observed that generally the lower the pressure (i.e. lower internal stress), the lower the part z-axis deflection (i.e. less warpage). Note that the pressure for single gate is 44.5MPa at datum location and reduces to 18.4MPa at central position (50% from datum). For dual-gate, taking the 20-80 position as example, the pressure peaks at only 15.6MPa while for three-gate 0-50-100 position, the maximum pressure is only 12.6MPa. From this we can conclude that pressure (at end of filling cycle) have a very strong effect on the part z-axis deflection.

4.3 Mould Temperature

The last focus is on reducing the residual stress of the moulded part. Increasing the mould surface temperature prevents flow-induced residual stress (Östergren, 2013). The increased temperature allows for relaxation of the long-chain polymer molecules; allowing it to achieve its unstressed state of equilibrium. Increasing the mould surface temperature will also prevent premature freezing at the mould-polymer interface. This prevents formation of an insulating skin layer, thus avoiding thermal-induced residualstress (Östergren, 2013).

Moldflow allows for changes in the process settings to alter the mould surface temperature in the simulation. The temperature will be increased from 80^{o}C to 140^{o}C in 20^{o}C increments. The limit is set at 140^{o}C as the Vicat Softening Temperature for PC Lexan 940 is 152^{o}C (Sabic Innovative Plastics, 2015). Increasing the temperature any further will cause distortion to the part. As the material would be soft above the Vicat Softening Temperature, the ejector pins will for sure damage the part during the ejection cycle.

4.3.1 Temperature Change – Original Gate Design

The test for increasing mould temperature is first carried out with original gating design, where gate radius = 1 mm with position at 0% datum. The purpose of the study is to act as a control sample and to gauge the effects of heat alone, if it is significant enough to reduce warping. The result of the study is tabulated in Table 4.8.

Table 4.8: Simulation results for varying mould surface temperature with original gating, radius = 1 mm, position = datum, gate quantity = 1

Temperature (^oC)	Deflection (z-axis +)	Deflection (z-axis -)	Deflection Total (mm)	Min. Pressure (MPa)	Max. Pressure (MPa)
80	1.116	0.987	2.103	16.7	44.5
100	0.871	0.804	1.675	18.2	33.4
120	0.703	0.643	1.346	13.0	31.2
140	0.525	0.493	1.018	13.2	30.5

From the results shown in Table 4.8, it is found that mould temperature plays a most significant role in reducing warping. It is observed that the total z-axis deflection of the part decreases with increasing mould surface temperature. Without changing the gate design, part deflection is reduced to a low of 1.018 mm at 140^oC, almost meeting the requirements set forth by Lifesize. It is clear that although temperature is the alpha factor in warping, unfortunately it alone is not enough to meet the requirements by the customer.

One thing of note is that pressure distribution is actually higher than in this case when compared to the 2-gate optimised design. Although it has significantly less deflection than the 2-gate design, it has higher pressure distribution. This may be due to the increasing mould temperature reduces the effects of thermal induced residual stress and other stress factors are contributing to the pressure distribution.

4.3.2 Temperature Change – Optimised Gate Design

The optimised dual-gate configuration will be used instead of tri-gate to reduce the amount of gates and runners used. As the gate is discarded and not recycled, larger more complex gates translate to increased production costs.

Table 4.9: Simulation results for varying mould surface temperature with mesh size = 5mm, mesh type = Tetrahedral, gate quantity = 2.

Temperature (^{o}C)	Deflection (z-axis +)	Deflection (z-axis -)	Deflection Total (mm)	Min. Pressure (MPa)	Max. Pressure (MPa)
80	0.724	0.67	1.394	11.5	15.6
100	0.688	0.567	1.255	11.3	13.9
120	0.587	0.525	1.112	10.4	12.5
140	0.476	0.456	0.932	9.6	11.5
140 (Tri-Gate)	0.441	0.4655	0.907	5.4	10.1

From the results shown in Table 4.9, it is observed that the total z-axis deflection of the part decreases with increasing mould surface temperature. The total z-axis deflection reduced from 1.394mm at 80^{o}C to 0.932mm at 140^{o}C, a significant 33% decrease in warping. Pressure distribution also decreases throughout the part.

For comparison, a simulation is added using three-gate system at 0-50-100 position. The result from the two-gate and three-gate simulations at 140^{o}C shows that at higher temperatures, there is only a minor difference. The difference between these two is only 0.025mm, a 2.6% difference. As the difference is minor and negligible, the two-gate system at position 20-80 is the best optimum configuration for reducing warping. This will reduce the material required for the gate and runners for two-gate over the three-gate system.

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CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In conclusion, the objectives are met with the final design. A total z-axis deflection of 0.932mm is obtained by using two gates with radius, r=1mm and located at positions 20-80% from datum. Mesh type used is tetrahedral and mesh size is 5mm, giving results within 4.4% error of margin. Reducing the pressure at the end of injection moulding fill reduces the z-axis total part deflection.

Three main design changes were proposed for the gating system. Increasing gate size had only a minor effect on the part deflection post moulding. Adding extra gates have a significant effect in reducing the part deflection. The position of the gates also plays an important role in reducing the part warpage and there is an optimum location for the gates. The gates must not be too near to each other else the build-up of pressure between two gates and the gates must not be too far, else there will be significant differences between the minimum and maximum pressure distribution of the part.

Hence, the final recommended design and parameter changes for optimised part warping reduction are summarised in Table 5.1.

Table 5.1: Recommended final design and parameters

Parameter		Value	Unit
For Simulation	Mesh Type	Tetrahedral	-
	Mesh Size	5	mm
For Gating Design & Process Parameters	Gate Size (Radius)	1	mm
	Gate Quantity	2	-
	Gate Position	20-80	% from Datum
	Mould Temperature	140	^{o}C

Final result of 0.932mm is less than warping tolerance of 1mm provided by Lifesize Communications. Main objective is met.

The main contribution of this study is to prove that warping problems may be solved with minimal changes and without increasing production direct costs. The most labour intensive part of the solution is the study itself, beyond that little work is needed to modify the gating. Increasing the mould temperature is easy as it only requires an external heater with hot oil. No major changes were required to the part design or geometry and no major changes were required for the tooling. The most important contribution is there is no increase in production cycle time to solve the problem.

5.2 Recommendations

It is recommended to further increase the scope of study for future study in the following:

i. Effects of cooling channel locations on the part warpage
ii. Effects of injection rate on the part warpage
iii. Effects of post filling (packing) pressure on part warpage
iv. Correlation of part volume shrinkage to the internal pressure

It is recommended for future studies to look into other factors that affect warpage, especially those directly related to internal pressure or residual stress. Knowledge in controlling and minimising residual stress will allow for moulding of parts with minimal warping without sacrificing production output.

REFERENCES

Beaumont, J.P., Nagel, R., Sherman, R. (2002). Successful Injection Molding, Hanser Publishers, Munich,

Goodship, V. (2004). Practical Guide to Injection Moulding. Rapra Technology Limited and ARBURG Limited, 193-194.

Peacock, A.J. & Calhoun, A. (2012). Polymer Chemistry: Properties and Application. Carl Hanser Verlag GmbH & Company KG.

Paulson Plastic Academy. (2015). Injection Molded Part Problems & Solutions. Paulson Training Programs

Tang, S.H. et al. (2005). Design and thermal analysis of plastic injection mould. Journal of Materials Processing Technology 171 (2006) 259–267

Östergren, A. (2013). Prediction of residual stresses in injection moulded parts. Department of Applied Mechanics Division of Material and Computational Mechanics Chalmers University of Technology. GöteborgSweden

Sanchez, R., Aisa, J., Martinez, A. And Marcado, D. (2012). On The Relationship Between Cooling Setup And Warpage In Injection Molding. *Journal of Measurement,* 45 (1) 1051–1056

V. Senkerik, M. Stanek, M. Manas, D. Manas, A. Skrobak, J. Navratil (2012). Gate Location and Cooling System Optimization. *International Journal of Mathematics and Computers in Simulation*,6 (6)

Kuzmin, D. (2012). Introduction to Computational Fluid Dynamics. Institute of Applied Mathematics University of Dortmund.

Jaworski, M. (April, 2004). Flow Front. Moldflow Corporation. Vol. 4, Issue 1 2004 MF-FF06-0404.

Reddy, B.S., Kumar, J.S., Reddy, V.J., Padmanabhan, G. (2009). Application of Soft Computing for the Prediction of Warpage of Plastic Injection Molded Parts. *Journal of Engineering Science and Technology Review,* 2 (1) 56-62.

Tuncay, E., Babur, O. (2006). Minimization Of Warpage And Sink Index In Injection-Molded Thermoplastic Parts Using Taguchi Optimization Method. *Journal of Materials and Design,* 27 (1) 853–861

Wang, X.X., Zhao, G.Q., Wang, G.L. (2013). Research On The Reduction Of Sink Mark And Warpage Of The Molded Part In Rapid Heat Cycle Molding Process. *Journal of Materials and Design,* 47 (1) 779–792

Babur, O., Ibrahim, S. (2009). Warpage And Structural Analysis Of Thin Shell Plastic In The Plastic Injection Molding. *Journal of Materials and Design,* 30 (1) 367–375

Kima, H.S., Im, Y.T. (2003). Gate Location Design In Injection Molding Of An Automobile Junction Box With Integral Hinges. *Journal of Materials Processing Technology,* 140 (2003) 110–115

Osswald, T.A., Turng, L.S., Gramann, P.J. (2001). Injection Molding Handbook, Hanser Publishers, Munich, Hanser Gardner Publications, Inc., Cincinnati.

Demirer, A., Soydan, Y., Kapti, A.O. (2007). An Experimental Investigation Of The Effects Of Hot Runner System On Injection Moulding Process In Comparison With Conventional Runner System. *Journal of Materials and Design,* 28 (1) 1467–1476

Bociga, E., Jaruga, T., Lubczynska, K. and Gnatowski, A. (2010). Warpage Of Injection Moulded Parts As The Result Of Mould Temperature Difference. *Archives of Material Science and Engineering*, 44 (1) 28-34

Kovacs, J.G., Siklo, B. (2011). Investigation Of Cooling Effect At Corners In Injection Molding. *International Communications in Heat and Mass Transfer,* 38 (1) 1330–1334

Deng, Y.M., Zhang, Y., Lam Y.C. (2010). A Hybrid Of Mode-Pursuing Sampling Method And Genetic Algorithm For Minimization Of Injection Molding Warpage. *Journal of Materials and Design,* 31 (1) 2118–2123

Dang, X.P. (2014). General Frameworks For Optimization Of Plastic Injection Molding Process Parameters. *Journal of Simulation Modelling Practice and Theory*, 41 (1) 15–27

Courbebaisse, G. (2005). Numerical Simulation Of Injection Moulding Process And The Pre-Modelling Concept. *Journal of Computational Materials Science,* 34 (1) 397–405

Le, M.C., Belhabib, S., Nicolazo, C., Vachot, P., Mousseau, P. Sarda, A., Deterre, R. (2011). Pressure Influence On Crystallization Kinetics During Injection Molding. *Journal of Materials Processing Technology* 211 (1) 1757– 1763

Postawa, P., Kwiatkowski, D. (2006). Residual Stress Distribution In Injection Molded Parts. *Journal of Achievements in Materials and Manufacturing Engineering,* 18 (2)

Discoll, S.B., (2004). The Basics of Testing Plastics: Mechanical Properties, Flame Exposure and General Guidelines. American Society For Testing and Materials (ASTM), Mayfield P.A.

Mitchell, S.A. and Vavasis, S.A. (2002) Quality Mesh Generation in Three Dimensions. Eighth Annual Symposium on Computational Geometry.

Hale, S. (2014). Engineer’s Guide to Finite Element Analysis of Part-to-Part Connections. CAE Associates.

PC LEXAN™ Resin MSDS - SABIC Innovative Plastics. Retrieved from: plastics.ulprospector

APPENDICES

APPENDIX A: CAD – Geometry Preparation

1. The CAD program Solidworks is first start-up.
2. The 3D file for the faceplate, 413-00211-901 is then imported to Solidworks.
3. The inner face is selected as the plane for sketching.
4. A horizontal reference line is then drawn about the central axis.
5. A R=1mm radius, is drawn at the most right position of the inner face (datum).
6. The circle is then extruded to form a 10mm direct sprue gate.
7. The file is saved as stl. (stereolithography) format.
8. Steps 4-6 are repeated for gates of different sizes and positions.

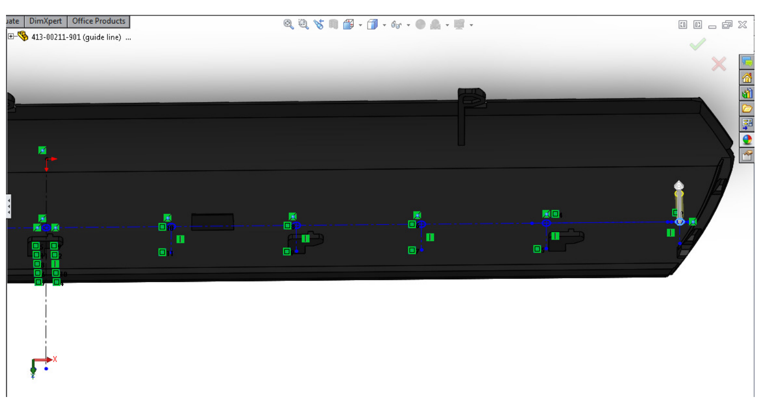

Figure 3.1: A direct sprue gate extruded from the sketch located on the guide line.

APPENDIX B: CAE – Moldflow Simulation

1. The Moldflow Plastic Insight program is first start-up.
2. A new project is created and given project name.
3. The stl. file from Solidworks is then imported as geometry.
4. In the import menu, Solid 3D mesh type is selected and the units of measurement millimetres (mm) are selected as default.
5. The part is then meshed as 3D, tetrahedral.
6. Under mesh density options, the mesh size is set to 5mm, merge tolerance set to 0.1mm and the global edge length set to 1mm.
7. The mesh is then fixed using repair wizard, using default recommendations.
8. The type of moulding is selected as “Thermoplastic Injection Moulding”
9. The type of analysis sequence is set as “Fill+Pack+Warp”
10. The material is selected as the original, PC Lexan 940 from Sabic Innovative Plastics from the material list.
11. The injection location is then specified at the gate location drawn.
12. The process settings are set, with Mould Surface Temperature = 80^{o}C and Melt Temperature = 320^{o}C.
13. The filling control, Velocity/Pressure switches over and Packing/Holding controls are selected as auto.
14. The cooling time is specified as 25s.
15. The analysis is started.
16. The results are exported once the simulation is done and tabulated.
17. The deflection (warpage) results of the physical part is measured using a feeler gauge and compared with the simulation results.
18. The process is repeated and the steps above repeated with different mesh sizes, gating size, gating positions and different mould surface temperature.

APPENDIX C: Simulation results for varying mesh size with gate radius = 1mm, mesh type = tetrahedral.

Mesh Size (mm)	Deflection (z-axis +)mm	% Difference	Deflection (z-axis -)mm	% Difference	Deflection Total (mm)	% Difference	Simulation Time	Mesh Time
Actual	1.200	0	1.000	0	2.2	0	-	-
1	1.432	19.33	0.79	-20.98	2.222	1.00	0:49:35	0:01:31
2	1.374	14.5	0.836	-16.4	2.210	0.45	0:15:55	0:00:38
3	1.285	7.08	0.832	-16.8	2.117	-3.77	0:06:05	0:00:20
4	1.281	6.75	0.861	-13.9	2.142	-2.63	0:03:32	0:00:12
5	1.239	3.25	0.895	-10.5	2.134	-3.00	0:02:31	0:00:10
6	1.196	-0.33	0.899	-10.1	2.095	-4.77	0:01:58	0:00:08
7	1.116	-7.00	0.884	-11.6	2.000	-9.09	0:01:35	0:00:06
8	1.125	-6.25	0.886	-11.4	2.011	-8.59	0:01:12	0:00:05
9	1.125	-6.25	0.854	-14.6	1.979	-10.05	0:01:03	0:00:05