Effect of Process Parameters on Volumetric Shrinkage of Plastics via Injection Molding Simulation

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Dedicated To

MUSLIM UMMAH
PALESTINE – SYRIA - KASHMIR

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Abstract

This thesis presents the injection molding (IM) process parameters' optimization to reduce the shrinkage and sink marks from a plastic part through injection molding (IM) simulation. Many researches have been conducted in the past to optimize the effect of process parameters of IM process for different plastic parts. The part selected for this study is wheel cover which is commonly use in the automobiles. The four different materials used in this study for optimization are Acrylonitrile butadiene styrene (ABS), Polybutylene Terephthalates (PBT), Polypropylene (PP) and Acrylonitrile butadiene styrene blend - Polycarbonate (ABS/PC). The parameters selected for this study are melt and mold temperature, injection time, cooling time, packing time and packing pressure. 3D CAD model of the plastic part is made on SolidWorks® Plastics premium 2015 and Autodesk Simulation Moldflow® (ASM) Advisor 2014 is employed to carry out the injection molding simulation. A design of experiment (DOE) approach is used via Taguchi method to examine the effect of various process parameters on volumetric shrinkage and sink marks. An orthogonal array (OA) of L_{27} is applied to conduct the experiments. S/N ratio and analysis of variance (ANOVA) is used to find the quality, significance and percentage contribution of each processing parameter. Results show that ABS/PC material showed least shrinkage and sink marks. Process parameters i.e. melt temperature, mold temperature, packing time and packing pressure have substantial effects on volumetric shrinkage and sink marks. Melt temperature has the highest contribution in affecting both shrinkage and sink marks. Verification tests are being done, which shows that final optimized process parameters significantly reduce the volumetric shrinkage and sink marks for every material.

Keywords:

Design of experiments, Taguchi method, Signal-to-noise ratio, ANOVA, Injection Molding, SolidWorks® Plastics, Autodesk Simulation Moldflow® Advisor.

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Chapter: 01

1 Introduction

The quality of products is very important while producing parts through injection molding process. Many process parameters affect injection molding process. Different types of properties can be obtained by changing parameters like material, design, temperature and pressure etc. The effect of these parameters cause different types of defects in the final end product. This study is to optimize two of the defects caused during injection molding (IM) process i.e. volumetric shrinkage and sink marks. Volumetric shrinkage is caused due to contraction of material's density during cooling phase of mold. Sink marks are the result of that variable shrinkage produced in the final mold. It is important to predict these defects before the manufacturing process. Six parameters will be studied in this study to remove these defects. Parameters are melt and mold temperature, injection time, packing pressure, packing and cooling time. The part will be used in this study is wheel cover. It is most commonly used part in cars, wagons and buses. The design of this part will be made on computer-aided design software according to the latest market designs. Materials used for this study are ABS, PP, PBT and PC/ABS. ABS is mostly used in making wheel covers. Some companies made wheel covers of PP and PBT also. Autodesk Simulation Moldflow® (ASM) Advisor 2014 will be used for simulation according to the experimental methodology devised by design of experiment (DOE) approach.

After optimization, stress analysis will be performed on SolidWorks® Plastics premium 2015 to find out the maximum strength of wheel cover with different materials. Forces will be applied on different sides to find the maximum deformation in it. Stress analysis gives the value of von mises stress and deformation of the part.

1.1 Background of thesis

Injection molding (IM) is most common for the assemblage of plastic parts. The mechanical and physical properties of the products should be good to have a good performance for the customer. These properties can be obtained from a lot of different methods used by manufacturers. Such methods consist of different models of injection process to get valuable products. Manufacturers have to obtain excellent conditions for process parameters before they obtain cheaper and good quality products.

The properties of plastic parts depend on how it is molded (Shoemaker 2006). The quality of product depends on material, design of mold and process conditions (Kumar, Ghoshdastidar et al. 2002). Simulation of the process parameters and design in injection process will provide data for manufacturers to choose the best model for their products. The optimal process parameter setting is the most important step for enhancing the quality of products. Optimization of molding conditions based on simulation will also give information i.e. which material should be used.

A lot of defects are caused as a result of improper injection molding process like blisters, knit lines, flash, sink marks, voids, volumetric shrinkage, weld lines and warpage. These defects depend on material, mold geometry, gates, gate locations and most of all the process parameters (Hakimian and Sulong 2012). Optimization of process parameters can be done by experimenting on machine or through simulations. As simulation is the easiest and cheaper method, therefore for the last decade most of the optimization is performed through computer aided simulations (Kennedy 2008). A number of mathematical models have been recommended and established by researchers for the study of different steps in the process of injection molding (Kumar, Ghoshdastidar et al. 2002). Several simulation studies were implemented to determine possible problems and their cost-effective solutions (Shen, Yeh et al. 2001). For example: Optimum process conditions for thin-wall part i.e. cell phone cover, were determined by Liao, Chang et al. (2004) using taguchi method. They used parameters like melt temperature and mold temperature, packing pressure and injection speed in simulation. Öktem (2012), studied the optimum process conditions to reduce the shrinkage in DVD-ROM cover. The later researcher used taguchi method of L_{27} array, ANOVA and S/N ratio to minimize the shrinkage.

1.2 Study part: Wheel Cover

Wheel covers have become a requirement of automobiles for decoration and to reduce the gathering of dust and clamminess in the hub. Tires look better after covering it with wheel covers. Figure 1.1 shows cars having different styles of wheel covers on their tires. Stainless steel wheel covers were used in the 60s. Plastic was first used in 70s as an experiment which eventually replaced the stainless steel in 80s. ABS is widely used for making wheel covers. It is not only cheap but also tough, long-lasting and very light (Mike 2014). A CAD 3D model of a wheel cover designed for this study is shown in Figure 1.2. This CAD model is designed on SolidWorks® Plastics premium 2015.

Figure 1.1: Cars with latest wheel covers

Figure 1.2: 13" Wheel cover CAD model

1.3 Objectives

The main objective of the thesis is to study the effect of different materials and process parameters on the volumetric shrinkage and sink marks of plastics with the help of an injection molding simulation software (IMS).

I. A CAD model of wheel cover will be generated using SolidWorks® CAE software.
II. Design of experiments (DOE) will be used using taguchi method to develop an experimental matrix and study the effect of various injection molding process parameters.
III. Injection molding simulations will be performed using Autodesk Simulation Moldflow® (ASM) Advisor 2014.
IV. The results obtained from the simulations will be analyzed through S/N ratio and ANOVA to study significance contribution of every process parameter on the volumetric shrinkage & sink marks of the wheel cover.

Chapter: 02

2 Literature Review

2.1 Introduction to Injection Molding

It is a common manufacturing technique for the plastic materials. It is mainly a progressive operation that results in the conversion of plastic pallet into a molded part (Teklehaimanot 2011). Weight of the products may vary from 0.000001 kg to 100 kg (Johansson and Konijnendijk 2007). In almost every field, injection molding products are being used and their sizes may vary from very small to very large. Over the years, plastic injection molding industry has evolved in making a vast variety of products for industries like medical, polymer, automotive and consumer products etc.(Rafidah 2010, Zhou 2013). Injection molding requires plastic material, mold and the molding machine. The plastic is melted in the machine and then in mold it cools down and solidifies. Temperature is high in the machine but mold is cold where under high holding pressure, material is allowed to solidify. Different shapes of mold gives different shapes to that plastic material (Thyregod 2001).

2.1.1 History of Injection Molding

The first man made plastic was invented by Alexander Parkes in Britain, 1851. He called the material “Parkesine” at the 1862 international Exhibition in London. In 1868, John Wesley Hyatt made a plastic material named “Celluloid” have some improvements than the previous one. He patented the first injection molding machine in 1872 in U.S (Murti 2010). It was very simple as compared to now-a-days. James Watson Hendry built first screw injection machine in 1946.(Rafidah 2010, Teklehaimanot 2011)

2.1.2 Injection Molding Process

The process has four main stages: injection, plasticizing, packing and cooling. (Wang, Kim et al. 2014). The process starts with the pallets or granules which are put into the hopper, Figure 2.1. These are then conveyed to the barrel which has a screw inside it. When it rotates, the pallets are melted due to the heat generation by friction of the screw and the barrel. When the injection barrel is occupied with molten plastic, rotation ends and a valve opens into the mold. The melt flows into the mold cavity through nozzle, Figure 2.1. This mold temperature is low, that’s why the melt starts to cool down. Shrinkage occurs when temperature of the material immediately decreases. Packing stage is necessary so that maximum amount of melt enters the mold (Teklehaimanot 2011). When the mold is completely filled, a hold pressure is applied by the screw until the small passage into the cavity solidifies. This small passage is called gate. The cooling channels solidify the plastic. Cooling depends on the thickness of the part. Solidification starts at the surface of the plastic and when it reaches to almost center, (lower than the solidification point) it is ready to be come out.

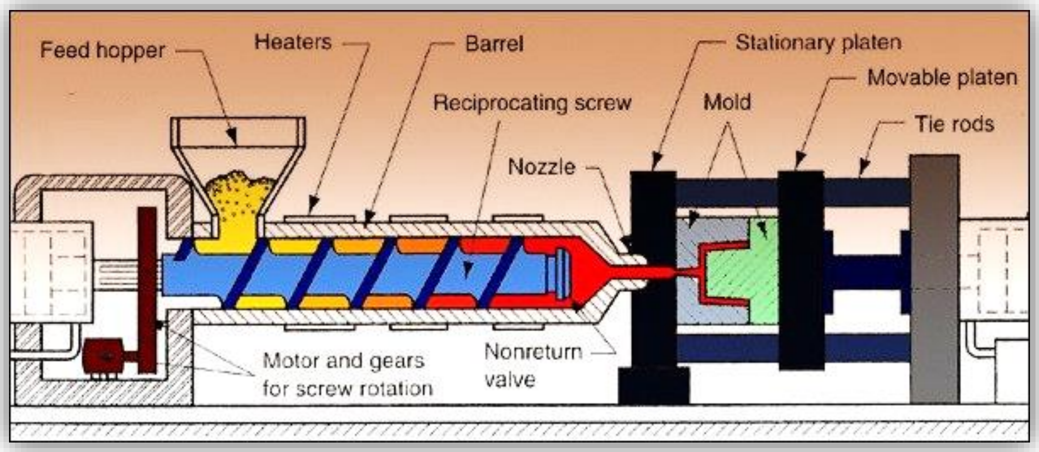


Figure 2.1: Single screw IM machine (mould-technology)

2.1.3 Injection Molding Machine

Injection molding machine (IMM) is used to produce different products of plastics through injection molding. IMM consists of two different main parts; injection unit & clamping unit. The other components are hydraulic system, mold system and control system as shown in Figure 2.2.

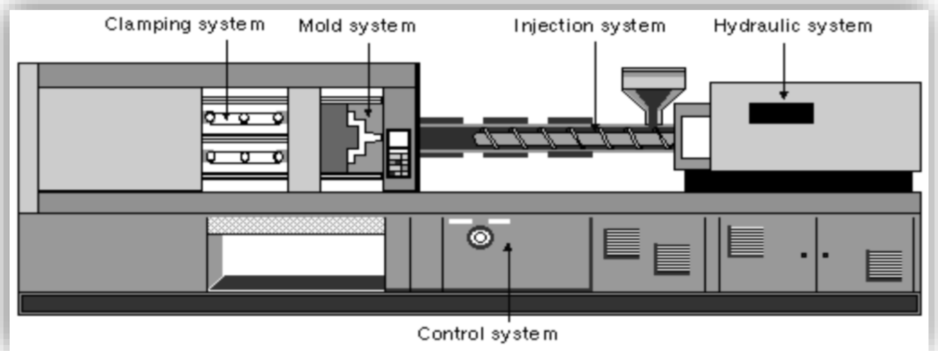


Figure 2.2: IM machine systems (Rafidah 2010)

The clamping unit consists of mold, mold plates and tie bars. It is capable of opening, closing and holding the mold. The injection system consists of hopper, barrel, reciprocating screw and the nozzle.

Hopper holds the small pallets of thermoplastic material. These pallets are fed through hopper into the barrel.

Barrel supports the reciprocating screw which is heated through electric heaters.

Reciprocating screw is used to trample, melt and transport the material. Flight-depth of the screw decreases from feeding zone to the metering zone while diameter remains constant. It has three zones i.e.

i. Feeding zone
ii. Compressing zone
iii. Metering zone

Nozzle connects mold and the barrel through a sprue.

2.1.4 Defects occur in Injection Molding Process

“No operation and process in the industry is 100% perfect”. Injection molding has a lot of problems during process. These problems occur due to the design and process parameters of the injection molding process. It affects the final mold and results in different types of defects in the products. These defects include sink marks, shrinkage, warpage, weld lines, air traps etc. (Guo, Hua et al. 2012). Some common defects causes during injection molding process are given below in Table 2.1. (Rawi 2006, Murti 2010, Teklehaimanot 2011)

Table 2.1: Defects occurs in IM process

	Causes	Solutions
Shrinkage	▪ Low packing pressure ▪ Volume decrease during cooling ▪ Insufficient packing time ▪ Excessive melt temperature ▪ Insufficient cooling time ▪ Small gate size and its location at thin wall	▪ Increase packing pressure and packing time ▪ Decrease melt temperature and mold temperature ▪ Proper gate size and location ▪ Vary the wall thickness ▪ Increase cooling time

Sink marks	▪ Part is not fully filled ▪ High melt temperature ▪ Insufficient residence time ▪ Too hot ejection of part ▪ Gate location	▪ Reduce temperature of barrel ▪ Proper size of gate ▪ Increase packing time ▪ Mold filled sufficiently ▪ Increase cooling time
Weld lines	▪ Wrong location of gate ▪ Low melt and mold temperature	▪ Proper gate location
Warpage	▪ Non uniform shrinkage and stress ▪ Very low melt temperature ▪ Large variation in wall thickness ▪ Part design	▪ Increase melt temperature ▪ Part redesigning ▪ Reduce shot volume and injection pressure ▪ Increase number of gates and proper location
Burning / Burn marks	▪ Too much injection speed ▪ Wrong pattern of filling ▪ Degradation of material due to compressed air	▪ Proper venting ▪ Proper gate size ▪ Reduce melt temperature
Mold sticking	▪ Too much mold temperature ▪ High injection pressure ▪ Over packing ▪ High shrinkage	▪ Proper mold temperature and packing time ▪ Increase cooling time ▪ Increase draft angle
Jetting / flow marks	▪ Low met temperature ▪ Slow injection speed	▪ Increase heating and injection speed
Flashes	▪ Incorrect pattern of filling ▪ Low clamping force	▪ Change location of gate ▪ Increase clamping force ▪ Clean surface of mold
Voids	▪ Excessive shrinkage ▪ Improper filling ▪ Early freezing of flow path	▪ Decrease heating ▪ Increase packing pressure ▪ Proper size of gate
Brittle parts	▪ Insufficient melt temperature	▪ Increase melt and mold

	▪ Erroneous part design ▪ Contamination in material ▪ Degradation of material	temperature ▪ Proper cleaning ▪ Redesigning of part ▪ Increase fill rate
Polymer degradation	▪ Excessive temperature of barrel ▪ High residence time in barrel ▪ High screw speed	▪ Reduce barrel temperature ▪ Proper injection rate

2.2 Parameters affecting Injection Molding Process

Injection molding process is affected by plentiful parameters and it is difficult to single out the effects of all parameters. By changing the value of each parameter, different physical and mechanical properties of products will obtain. Quality of injection molding products affected by main process parameters are injection time, material temperature, melt speed, injection pressure, holding pressure, cooling time, filling time, ejection temperature, material property of melt, mold temperature, mold geometry shape, and action of flow field heat transfer (Shen, Liu et al. 2002). The category of these main parameters are:

- Design parameters
- Process parameters

Design parameters of injection molding process include:

I. Mold design
II. Gate size
III. No. of gates
IV. Runner size etc.

These parameters affect the geometry and shape of the molded products.

Process parameters of injection molding process include:

Table 2.2: Process parameters of IM process

	Temperature related	Time related	Pressure related
	Melt temperature	Injection time	Injection pressure
	Nozzle temperature	Packing time	Plasticizing pressure
	Mold temperature	Cooling time	Packing pressure etc.
		Mold open time	

Optimum process parameters reduce the process time and increase the quality of the main product (Dang 2014). Some process variables are controllable like holding pressure or holding pressure time and some are consequential like melt cushion value. These parameters affect the final mold properties and produce defects like volumetric shrinkage, sink marks and warpage etc. and it's better to choose the best parameters that have considerable good effects on the output. Tsai and Hsieh (2009) studied that the surface curliness of lenses can be better with higher injection and packing pressure, melt temperature and mold temperature. Wang and Zhao (2013) studied that the most effective parameter for warpage is packing time, packing pressure, melt temperature and injection time. Song and Liu (2007) designed an injection mold for plastic parts of ultra-thin wall. Results indicates that injection rate is the principal factor which affects the ratio of filling whether injection pressure & melt temperature are the secondary factors.

2.2.1 Melt temperature

Melt temperature is controlled by the injection machine barrel temperature. The main objective is to ensure a smooth injection molding without any material degradation. Residence time in barrel also affects the melt temperature. The range of melt temperature is broad for amorphous materials and narrow for crystalline materials. It affects melt viscosity, injection pressure and filling. By reducing melt temperature knit lines, burning and weld lines take place, while excessive temperature of barrel results in high melt temperature which cause in the reduction of melt viscosity and stresses(Kumar, Ghoshdastidar et al. 2002). These stresses results in polymer degradation, warping, splay marks and blisters. Chen and Chuang (2009) studied that the packing pressure & melt temperature are the most significant factors to reduce warpage of thin-shell plastic parts made through injection molding process. Teklehaimanot (2011) mentioned that melt temperature and design of mold affects brittleness of product.

2.2.2 Mold temperature

Cooling rate is determined by the mold temperature. Cooling time is inversely proportional to the mold temperature. If we increase the mold temperature, it improves the products of the crystalline plastics, it increases the melt flow, improves the surface quality of the product, and decreases the filling pressure but due to increase in cooling time, productivity of products decreases and the shrinkage increases.

2.2.3 Injection Time

Injection time is totally dependent of injection rate. For thin-wall parts, injection rate should be as high as possible. It should be moderate for thick parts. High shear rate can develop with disproportionate injection rate. This inappropriate injection time and injection rate cause burn marks, discolored flashes, flow marks, jetting and weld lines.

2.2.4 Packing Time

Packing time is the holding time while packing pressure is applied until the freezing of material (Annicchiarico and Alcock 2014). Short period of packing time permit very little time for packing pressure and results in inadequate packing of plastic materials. Insufficient packing time causes sink marks, volumetric shrinkage and weld lines.

2.2.5 Cooling Time

To reach Vicat softening temperature, cooling time is required (Annicchiarico and Alcock 2014). Cooling time is also very important in the whole molding cycle. It mostly depends on the thickness of the molded part. Evenly distribution of the rate of cooling removes the heat from the material and cools down mold properly. If cooling time is short, final product has defects like blisters, sink marks and warpage.

2.2.6 Injection Pressure

Injection pressure is the minimum amount of pressure required to fill the mold cavity. Flow ability of the material is increased if the injection pressure is high. It may cause overflowing, and flashing. But if the injection pressure is low, flow ability decreases which cause bubbles, voids, sink marks, shrinkage and partial parts. Hotter materials require low injection pressure.

2.2.7 Plasticizing Pressure

It is also called screw back pressure. By increasing the plasticizing pressure, shear effect increases which produces heat and hence results in the increase in melt temperature. Also residence time increases by increasing this pressure which results in the improvement of the quality of plastics. But too much increase in the pressure cause indoor leakage, decrease amount of plastics, increase power consumption and degradation.

2.2.8 Packing Pressure

This pressure is required to finish the filling of mold by packing its molecules until the freezing of gate. If the holding pressure is low, then there will be insufficient pressure left for packing which cause sink marks, voids and shrinkage in the mold. High holding pressure results in overflowing and flashes.

2.3 Volumetric Shrinkage

2.3.1 Shrinkage

It is the reduction in the mold part size and it occurs when mold part is ejected from the mold. All polymeric materials shrink when cooled to solid form. Shrinkage is very important for designers for the designing of different products. It changes along flow and across flow directions (Pontes 2002).

2.3.2 In-Mold shrinkage

It occurs due to the variation in the density of the polymer from processing temperature to the room temperature. It is caused by shape, size and wall thickness of the part, size of the gate and nozzle and the process parameters. If the mold cavity is being forced by maximum amount of material for a long time until material become hard due to high pressure, then the shrinkage will be low (Fischer 2003). Mold shrinkage will be high when density is high and crystalline areas are more. It can be reduce by reducing specific volume. Phases in injection molding which affects volume are shown in Table 2.3 (Industria 2005).

Table 2.3: Effect of phases of IM on volume

Steps	Phase of Molding	Temperature	Pressure	Volume
1	Filling start	Melt temperature	Atm. Pressure	Highest expansion
2	End of filling - Holding start	Constant	Constant	Little decrease
3	Maximum pressure reached – solidification start	Constant	Quickly increase	Decrease quickly
4	End of packing – cooling start	Decreases	Quickly decrease	Little decrease
5	End of cooling – pressure reduce to atm.	Decreases	Atm. Pressure reached	Decreases
6	Ejection of part	Decreases	Atm. Pressure	Decreases
7	Final product	Room temperature	Atm. pressure	Final

2.3.3 Volumetric shrinkage

It is the result of thermal expansion and contraction (Rännar 2008), cross-linking, reordering of molecules and orientation of fibers and fillers. It is a driving force for linear shrinkage. Almost every plastic has approximately 25% volumetric shrinkage when cool from melt to solid state without any pressure (Shoemaker 2006). When amorphous and semi-crystalline materials are in melted state, their volume is linearly dependent on the temperature. It can be shown in Figure 2.3 the where for different pressure values, specific volume behavior versus temperature is shown (Rännar 2008).

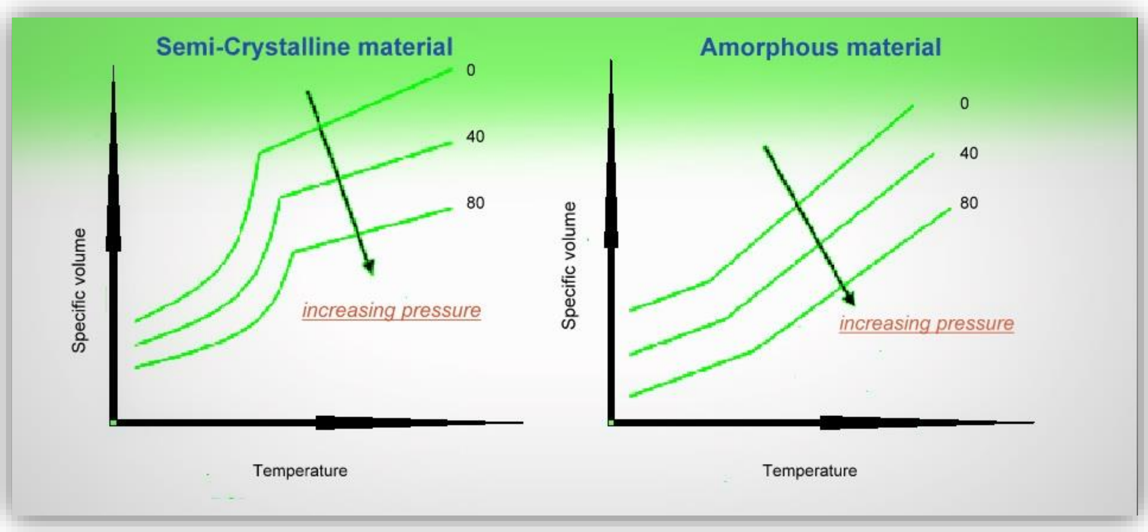


Figure 2.3: Effect of temperature-pressure on specific volume

Isayev and Hariharan said that models relating pvt behavior of the material can predict volumetric shrinkage, but it can’t accurately predict shrinkage because these are attained from those tests which are conducted in equilibrium conditions and not describe the material performance in actual processing environments (Pontes 2002).

The variation in the specific volume for amorphous and semi-crystalline materials is shown in Figure 2.4 (Center 2006) at altered cooling rates:

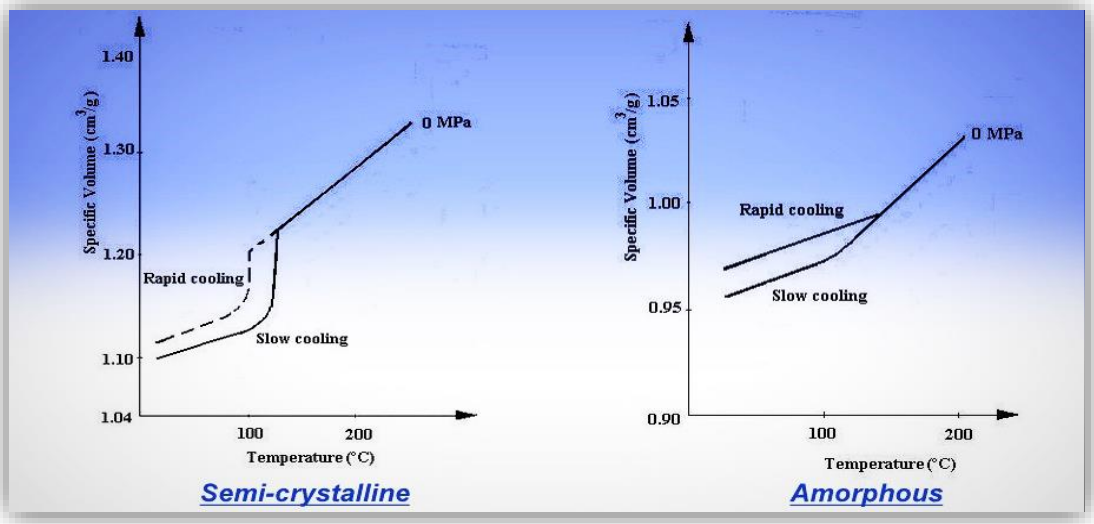


Figure 2.4: Variation of specific volume in different materials

It shows that for amorphous polymers, by increasing cooling rate, transition of melted state to solid state is accelerate while for crystalline polymers, it delayed.

2.3.4 Volumetric shrinkage in molded part

Volumetric shrinkage in molded part is an unwanted thing in the injection molding process. It occurs during the packing phase in injection molding process. In packing stage, it occurs due to change in temperature and high pressure (Choi and Im 1999). Plastic material is injected into the mold cavity, holding pressure is applied to the melt until gate freezes. Holding pressure keeps the material tight to avoid any shrinkage in the mold, but the part continuously shrinks even after the freezing of gate. Extent of shrinkage is directly related to how the holding pressure is applied on the part through gate and runner system (Fischer 2003). Those areas have lower shrinkage where more pressure is applied like areas near the gate. Shrinkage increases toward the edges of the part.

2.4 Factors affecting Volumetric Shrinkage

Polymer’s density variations from process temperature to room temperature cause shrinkage. In IM process, high amount of volumetric shrinkage occurs when mold is being injected with insufficient material and pressure is applied for very short period of time for packing. On the other hand, material shrinks very less when mold is being injected with maximum amount of material and have long period of time for packing. Many factors can also affect volumetric shrinkage such as if machine is small; it'll provide insufficient clamping pressure resulting in shrinkage. Also, geometry of the part, runner, gates, and wall thickness of the part affect volumetric shrinkage (Fischer 2003).

2.4.1 Effect of Part Design on Volumetric Shrinkage

Part design and its geometry has a significant effect on volumetric shrinkage.

Wall thickness has the direct relation to the volumetric shrinkage show in Figure 2.5 (Industria 2005) and it increase constantly as the thickness of the part increases (Fischer 2003). The part having variation in the wall thickness exhibits different shrinkage at different sides. As the thick portion retain more heat than the thin portion, that's why it take long time to cool and contract much more than thinner portion. The result of this is dimensionally distorted part.

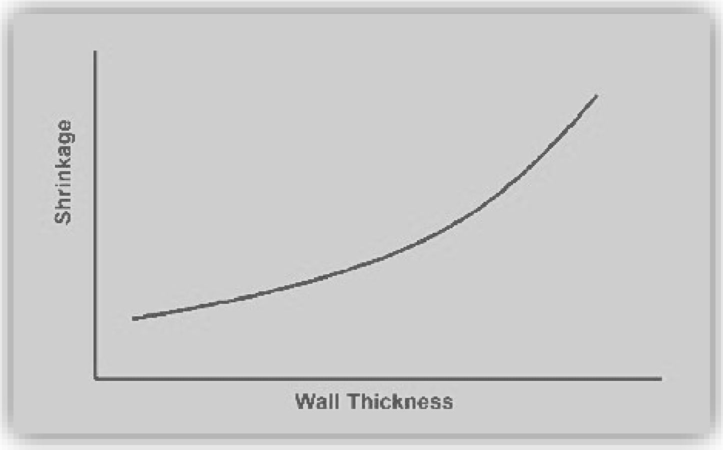


Figure 2.5: Effect of wall thickness on shrinkage

Ribs: Due to the ribs, flow pattern of the material may interrupt. Their presence may cause the variation in the thickness of the part. Improper location and thickness of the ribs causes shrinkage in the final mold part.

Gate: Dimensions, warpage, shrinkage and strength of the part also affected by gate. Different types, sizes and shapes of gates like sprue gates, pinpoint gates, submarines gates, edge gates, fan gates, film gates, ring gates and tab gates etc. are used for different materials and sizes of products and each have separate effect on the final molded part. To uphold constant shrinkage, minimize the space between gate and edges of the part. Multiple gates are used so the filling ability of the molder is improved with reasonable temperature and pressure. (Fischer 2003). Gate size should be large enough so that packing of the material completely done until gate freezes.

Gate location: prominently affects the flow of material (Murti 2010), final mold shrinkage and dimension of the part. Proper gate location provide balanced flow. Residual stresses and over packing can be reduce by balanced flow (Seow and Lam 1997). It also affects the orientation of fibers, number of weld lines and warpage of the product. Gate should be positioned, where distance from each edge to the gate is almost same and it should be the thickest area of the part. Figure 2.6 and Figure 2.7 shows the different flow patterns due to different gate locations. It shows that fill time increases when the gate is located at the thin edges of the part.

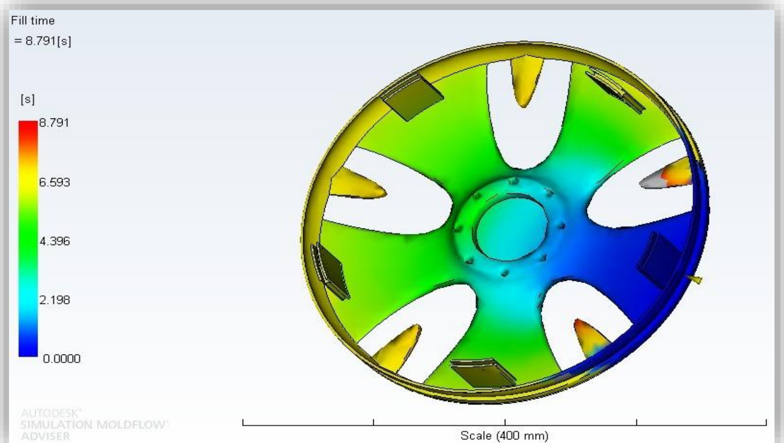


Figure 2.6: Fill analysis with gate on the thin wall

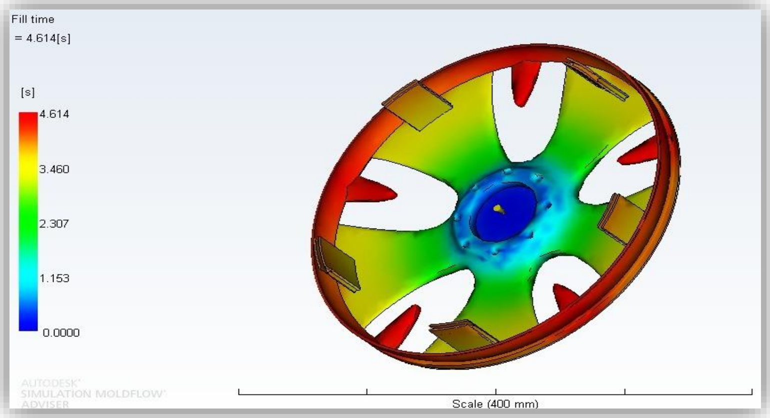


Figure 2.7: Fill analysis with gate on the center of part

2.4.2 Effect of Material on Volumetric Shrinkage

Material is the basic constituent in injection molding process which is used to make a specific product of specific properties. Final product is totally dependent on, which type of material is used and in which composition it is used. Feedstock composition plays an important role in the success of injection molding. Selection of material and its composition is an intricate task and includes many consideration such as: materials chemical resistance, temperature for thermal stress, assembly, standardization, finishing, cost and conditions like mechanical, electrical stress and colors etc. (R. Surace 2012). Polymer rheological properties should be taken into consideration for IM simulation process (Shin and Park 2013). A failure to optimize composition could result in the formation of defects for example shrinkage and warpage during injection molding process (Kate, Enneti et al. 2013). Tursi and Bistany found that mold material significantly affects the sink marks in final mold product (Tursi and Bistany 2000). Many process parameters like injection pressure and cooling time depends on composition of the materials used. Changing the compositions, vary the viscosity of the material and its rheological properties which ultimately affects the process and mold. Sin, Rahman et al. (2012), used same material of different composition in their study and found that composition having high specific volume has greater volumetric shrinkage than composition having low specific volume. Mostly in plastics industry, two types of materials are used for injection molding process

I. Amorphous polymeric materials
II. Semi-crystalline polymeric materials

2.4.2.1 Amorphous polymeric materials:

These materials usually produce isotropic shrinkage which is equal in both in-flow and cross-flow direction. Acrylonitrile butadiene styrene (ABS), Polyvinyl chloride (PVC), Polystyrene (PS) and Polycarbonate (PC) are the examples of amorphous materials having isotropic shrinkage. Chang and Faison (2001), concluded that amorphous materials i.e. GPS and ABS shrinks less than the semi-crystalline material HDPE.

Table 2.4 shows the flow directional shrinkage values of these materials:

Table 2.4: Shrinkage values of Amorphous polymeric materials (Plastic Products , Fischer 2003)

	% Shrinkage
ABS	0.3-0.8
PPE	0.4-0.8
PC	0.5-0.7
PS	0.5-0.7
PVC (rigid)	0.2-0.4

2.4.2.2 Semi-crystalline polymeric materials:

Parts made from these materials have anisotropic shrinkage which is different in both in-flow and cross-flow direction. Polypropylene (PP), Polyamide (PA), High density polyethylene (HDPE) and Acetal are the examples of semi-crystalline materials. Table 2.5 shows the shrinkage values of these materials:

Table 2.5: Shrinkage values of Semi-crystalline polymeric materials (Plastic Products , Fischer 2003)

	% Shrinkage
PP	1.0-3.0
HDPE	1.5-4.0
PA (Nylon 6-6)	0.8-1.5
Acetal	2.0-3.5

2.4.3 Effect of Processing Condition on Volumetric Shrinkage

Processing conditions have the most significant effect on volumetric shrinkage during injection molding process. Melt and mold temperature, injection and packing pressure, injection time, holding and cooling time are the main process variables which have direct or indirect effect on shrinkage in the final mold (Wu and Huang 2007, YING 2010). From all of these parameters, melt temperature and packing pressure are the dominant factors in influencing shrinkage in a molded part (Kurt, Kaynak et al. 2010, Alireza Akbarzadeh and Sadeghi 2011). While (Mehat, Kamaruddin et al. 2013) studied the performance of gears and optimize the parameters using grey-based taguchi optimization and present that melt temperature and packing time are the only two most dominant parameters reducing shrinkage.

Shrinkage can be reduce through fillers but it can be reduce to an adequate value by carefully selecting the best process parameters (Hakimian and Sulong 2012). Process parameters that have a significant effect on volumetric shrinkage are shown in Figure 2.8 (Fischer 2003, Industria 2005).

Loh and German (1996), studied the shrinkages in the direction of thickness, length and width and found that hold temperature, heating rate and hold time are affecting width and thickness shrinkage. They concluded that by decreasing hold time and increasing heating rate shrinkages decreases. Also, shrinkage can be reduced by increasing injection plunger speed (Chen, Ho et al. 2004). In 1998, (Jansen, Van Dijk et al.) described that shrinkage decreases with the increase in packing pressure and melt temperature, whereas injection velocity and mold temperature have less and diverse effect for different materials. Also (Jialing and Pengfei) in the year 2005, used seven process parameters to reduce volumetric shrinkage in IM process through orthogonal experimental design and have almost the same results. Hassan, Regnier et al. (2010) studied the effect of cooling system on rate of distribution of shrinkage and Liu, Zeng et al. (2012) studied effect of processing factors on shrinkage & warpage and both found that cooling effect could not achieve optimum shrinkage all through the product. But in study of optimizing shrinkage of DVD-ROM cover, Öktem (2012) concluded that cooling and injection time has more effect on shrinkage as compared to melt and mold temperature.

Azaman and Sapuan (2013) evaluated volumetric shrinkage with different process conditions using Autodesk MoldFlow® Insight. Results showed that packing pressure and mold temperature had significant while packing & cooling time had less significant effect on shrinkage. Process conditions including non-uniform pressure distribution and low cooling cause volumetric shrinkage and when it is high, it cause dents/depressions on plastic part called sink marks (Wang, Zhao et al. 2013).

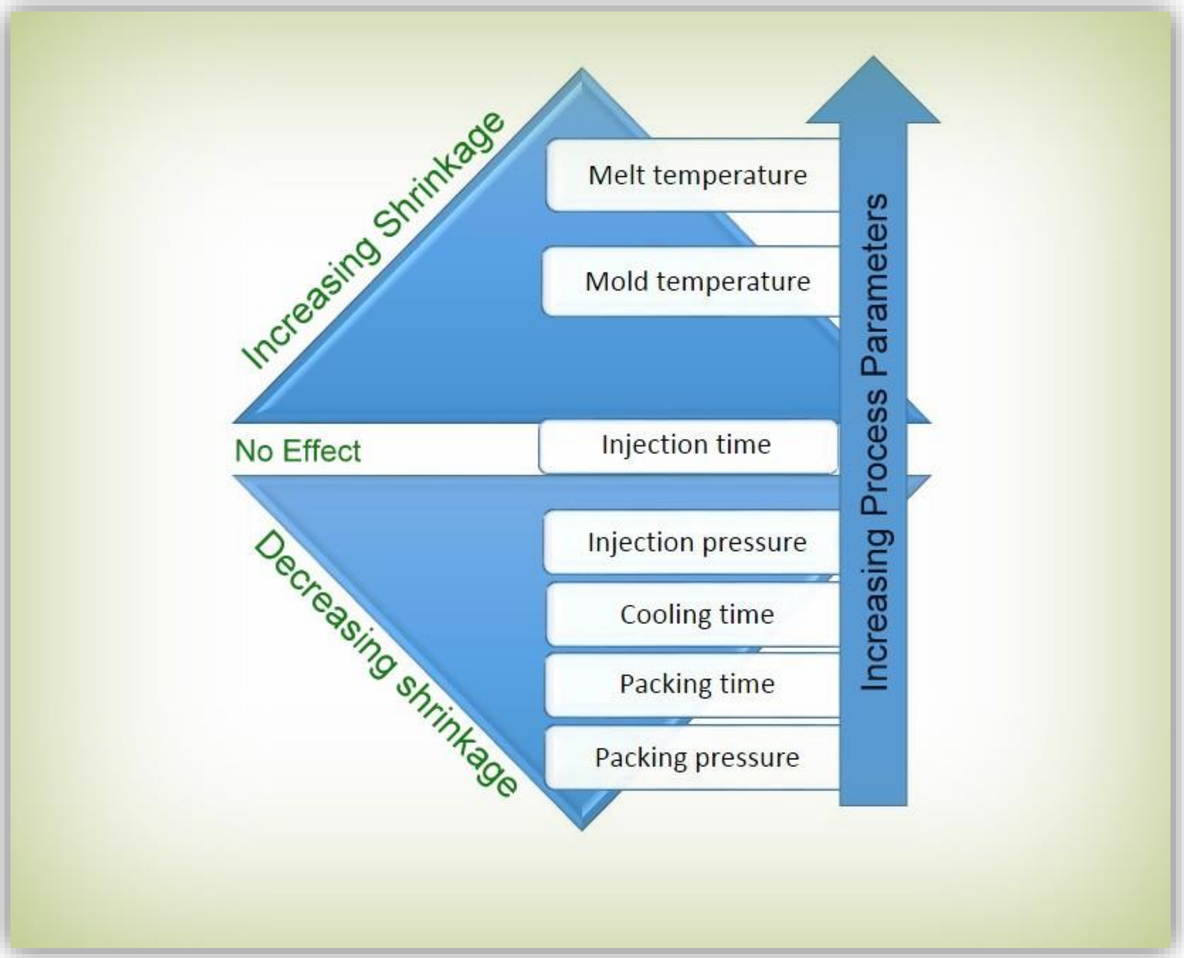


Figure 2.8: Effect of process parameters on volumetric shrinkage

2.5 Sink Marks

Sink marks looks as depressions on the mold surface. They are small but quite visible because of the reflection of light (Erzurumlu and Ozcelik 2006). These develop in the thicker sections like ribs, bosses and fillets. These areas shrink more than the adjacent side due to uneven removal of heat. Figure 2.9 shows the sink marks (Center 2006).

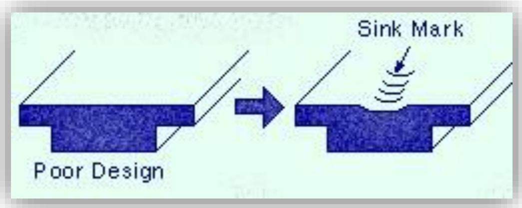


Figure 2.9: Sink marks

Sink marks has the direct relation with the volumetric shrinkage, hence almost every factor which affects shrinkage also affect sink marks. To reduce the sink marks, Erzurumlu and Ozcelik (2006) and Shen, Wang et al. (2007) did simulations using taguchi method and find that packing pressure, melt and mold temperature are the most significant factors affecting sink marks. Zhang and Jiang (2007) also did research to reduce sink marks using taguchi optimization technique and found that melt temperature is the most imperative factor affecting sink marks in dustpan. As sink marks are the result of volumetric shrinkage, hence to minimize the shrinkage, Mirigul (2010) did research and found that melt temperature and packing pressure significantly decrease shrinkage in PS and PP moldings. As the packing pressure decreases and the thickness of the ribs increase, the depth of sink marks also increases (Fischer 2003). Kusić and Kek (2013) studied that packing time and packing pressure are the most overruling parameters which affect post molding shrinkage. Wang and Zhao (2013) studied that the most effective parameter for sink marks is external gas assisted packing pressure.

2.6 Optimization of Injection Molding Process

In optimization, precise techniques are used to determine the best cost effective and effectual solution to a project for a process (YING 2010). It is very difficult task to understand the relationship between processing variables and the quality of the products using experiments in polymer processing. That’s why computer aided engineering (CAE) has developed the simulation of molding through different software and become more successful in the last two decades (Kennedy 2008). These software analysis helps to choose suitable feeding dimensions to improve IM process for better quality products (YING 2010). To check the results of the impact of materials, process variables and mold design on the product requires a lot of experiments. These trial-and-error experiments are very costly because for the optimization of each factor, experiments may become more than hundreds. But simulation is very cheap as compared to experiments as it is just perform through some software and it can easily omit risk of experimentations (Galantucci and Spina 2003). It not only gives the results but also provide the opportunity for evaluation of those results and their optimization. Without CAE, we can’t get the information like location of weld lines and air trap; required injection time and pressure; final shape of the product and its deformations and many more (Shoemaker 2006). Many engineers had worked on the optimization of injection molding as well as simulation of effect of process parameters on it. Their basic aim was to improve the injection molding process and the properties of the final mold. Computer aided simulation is widely used for the optimization of injection molding process. Dairanieh (1996) presents a computer simulation of weld lines in part made through IM. They used a tool to predict the final part to save time and resources by performing trial and error experiments. He used old version Moldflow® simulation software to simulate the weld lines in polymer part. Shen and Liu (2002) used Moldflow® to analyze the results with different materials, different process parameters and different thicknesses in injection molding. Koszkul and Nabialek (2004) used altered rheological models for a treated polymer and presented numerical simulation results of the IM process by using Moldflow®. Dimla and Camilatto (2005) determined an optimum and efficient design for conformal cooling channels using FEA analysis on Moldflow®. To obtain the minimum residual stress dissemination on thin walled parts, Azaman and Sapuan (2014) optimize the mold temperature, packing pressure, cooling time and packing time. Wan Abdul Rahman, Sin et al. (2008), used SolidWorks® to design CAD model of window frame and then used Moldflow® for the IM process simulation.

2.6.1 Design of Experiments Technique

Due to time consumption and high cost, the trial and error method is not appropriate for multifarious process in determining the optimal injection molding process parameters (Y. C. Lama 2007). Thus, Design of experiments technique is used to optimize the process parameters at low cost and obtain best product performance (Rännar 2008). Design of Experiments can direct to select the right control variables and adequate ranges for the setting and alteration of those variables. First we have to identify the problem and after that the response variables (continuous or discrete). These variables are the factors which can affect the process. After that, selection of levels is another critical part. Levels should be distant but not too much that they become inappropriate. Experimental design depends on how much factors and levels selected for experiments (Rännar 2008).

Each process parameter has different effect on the final mold properties. Chen and Chuang (2009) studied that the packing pressure & melt temperature are the most significant factors to reduce warpage of thin-shell plastic parts made through injection molding process. Kusić and Kek (2013) studied that packing time and packing pressure are the most overruling parameters which affect post molding shrinkage. Wang and Zhao (2013) studied that the most effective parameter for warpage is packing time, packing pressure, melt temperature and injection time. Azaman and Sapuan (2013) calculated volumetric shrinkage and warpage with different process conditions using Autodesk MoldFlow Insight®. Results showed that packing pressure and mold temperature had significant while packing time and cooling time had less significant effect on shrinkage and warpage.

The Taguchi method, genetic algorithm (GA) and artificial neural networks (ANNs) are mostly applied to optimize and achieve better quality product (Hasan O 2006). Shen, Wang et al. (2007), used ANN/GA combined-method to optimize the process conditions to reduce shrinkage. When the parameters values are discrete with the least experiment, Taguchi method can competently find the best certain process parameters level combination. It is based on the matrix experiments to determine the optimal parameters (Wang YQ 2012). Y.K.Shen, P.H.Yeh and J.S.Wu (2001) used the Moldflow® software to simulate thin wall cases of fiber-reinforced thermoplastics. They used different process parameters, fiber and ratios. Taguchi method is being used to get optimal results. Ozcelik (2011) implemented Taguchi's orthogonal array (L_9) design to optimize IM process parameter's effect and weld lines on the mechanical properties of PP moldings.

For determining the quality characteristics and specify the effect of process parameters on optimization process, Taguchi endorses the use of S/N ratio and ANOVA (Wang, Kim et al. 2014). ANOVA is performed using general linear model and find degree of freedom, variance, sum of squares, F & P tests and percentage contribution of every parameter (Mehat, Kamaruddin et al. 2013). In study by Ozcelik and Ozbay (2010), Taguchi's L_9 orthogonal array design was used for the experiment and altering of mechanical properties of Acrylonitrile Butadiene Styrene was optimized through ANOVA analysis and regression analysis. Chen, Huang et al. (2013), used 9 process parameters to optimize the shrinkage and warpage of a digital camera thin cover using L_{27} array of taguchi method and ANOVA. Mirigul (2010) proposed optimal IM conditions for minimum shrinkage by the Taguchi method and ANOVA methods. Wang and Kim (2014) used number of gates, gate size, molding temperature, resin temperature and curing time for optimizing the injection molding process to make a brake booster valve body. They used L_{18} orthogonal array for the DOEs based on Taguchi method. S/N ratio and the analysis of variance are used to find the optimal injection molding process parameters. In Kusić and Kek's (2013) study changing in mechanical properties of Acrylonitrile Butadiene Styrene (ABS) was optimized by ANOVA analysis and regression analysis. While carrying out experimental tests on a PP material with 40% calcium carbonate using Taguchi method, it was found that packing time and pressure are the most dominant parameters which affect post molding shrinkage.

2.6.2 Taguchi Method

Design of experiments (DOE) is used to quantitatively study the influence of process parameters on volumetric shrinkage. Taguchi method is used because of its simplicity and effective method for optimization. It consists of three stages:

I. System design
II. Parameters design
III. Tolerance design

Application of scientific knowledge and engineering used in making of end product is included in system design. To find the optimal process parameters and better product quality, parameter design is used. It makes correlation between process parameters and end product performance. While the tolerance design analyze and determine the tolerance for optimum parameters combinations recommended by parameter design. (Barghash and Alkaabneh 2014, Gu, Hall et al. 2014).

Chen, Lee et al. (1997) and Zhang and Jiang (2007) optimized the manufacturing process of PC/PBT bumper and PP dustpan by applying taguchi method of L_{18} and L_{27} array respectively to optimize the process conditions. Hakimian and Sulong (2012) investigated the effect of process parameters on shrinkage & warpage properties by numerical simulation using Taguchi method. Chang and Faison (2001) and (Alireza Akbarzadeh and Sadeghi 2011) used taguchi method and study the effect of process parameters on the shrinkage of (HDPE, ABS, GPS) and (PP, PS) respectively. (S.Rajalingam, Awang Bono et al. 2013) studied the effect of shrinkage on the cell phone shell by using taguchi DOE technique. For determining the quality characteristics and indicating the influence of process parameters on optimization process, Taguchi recommends the use of signal-to-noise (S/N) ratio and analysis of variance (ANOVA) (Wang, Kim et al. 2014). The effect of different parameters on different grades of PP is studied by Mehat and Kamaruddin (2011) using taguchi method and S/N ratio. ANOVA and F-test is used by Loh and German (1996) to find the most significant factors affecting shrinkages in different direction of the product.

2.6.3 CAD Simulation Software

Computer modeling has played a critical role in the quality control of injection molding. Prediction and optimization of the product quality has now become conceivable at low cost. All the design variables including material selection, mold design and product quality can be set on computer. Processing variables can be changed to get the best result in quality variables. In early stages, few mathematical models were developed for describing the IM process. These models are limited to one dimensional geometry. But now many mathematical models have been developed to simulate the process behavior of injection molding. Simulation can be performed comparatively cheap in the initial stages of mold design and suggest the ability to evaluate different design possibilities in terms of part, material and mold design. Computer Aided Engineering (CAE) simulation tools and Design of Experiments (DOE) almost replaced the traditional trial-and-error method and help to select material, designs the product and the mold. It also assists to set-up the molding conditions in more operative manner. As the use of computer aided simulation is increasing, hence the commercially available software also increased in the market (Seow and Lam 1997). CAE simulation includes commercial software like Moldflow®, SolidWorks® plastics, Moldex® 3D and HSCAE. These CAE software's models provide the developer with very effective tools.

Moldflow® Insight/advisor is the most widely used process simulation tools to forecast and remove possible manufacturing malfunctions and optimize mold design, part design and the IM process. It can simulate the stages of filling, packing and cooling of the thermoplastic injection molding process (Moldflow-Corporation 2001).

2.6.3.1 Autodesk Moldflow® Plastics Advisor/Insight

Autodesk Moldflow plastics software offers advanced process simulation tools to forecast and remove possible manufacturing problems & optimize part and mold design and the IM process (Murti 2010, Teklehaimanot 2011). It can simulate the filling stage, packing stage and cooling stage of the thermoplastic injection molding process (Moldflow-Corporation 2001).

2.6.3.2 SolidWorks® Plastics

SolidWorks® Plastics simulates melt plastic flows during the IM process which predict production related flaws on parts and molds. It can design 3D models of mold. It can simulate the effect of all process parameters on injection molding process. Its SimulationXpress tool can be used for the stress analysis of materials.

Chapter: 03

3 Methodology

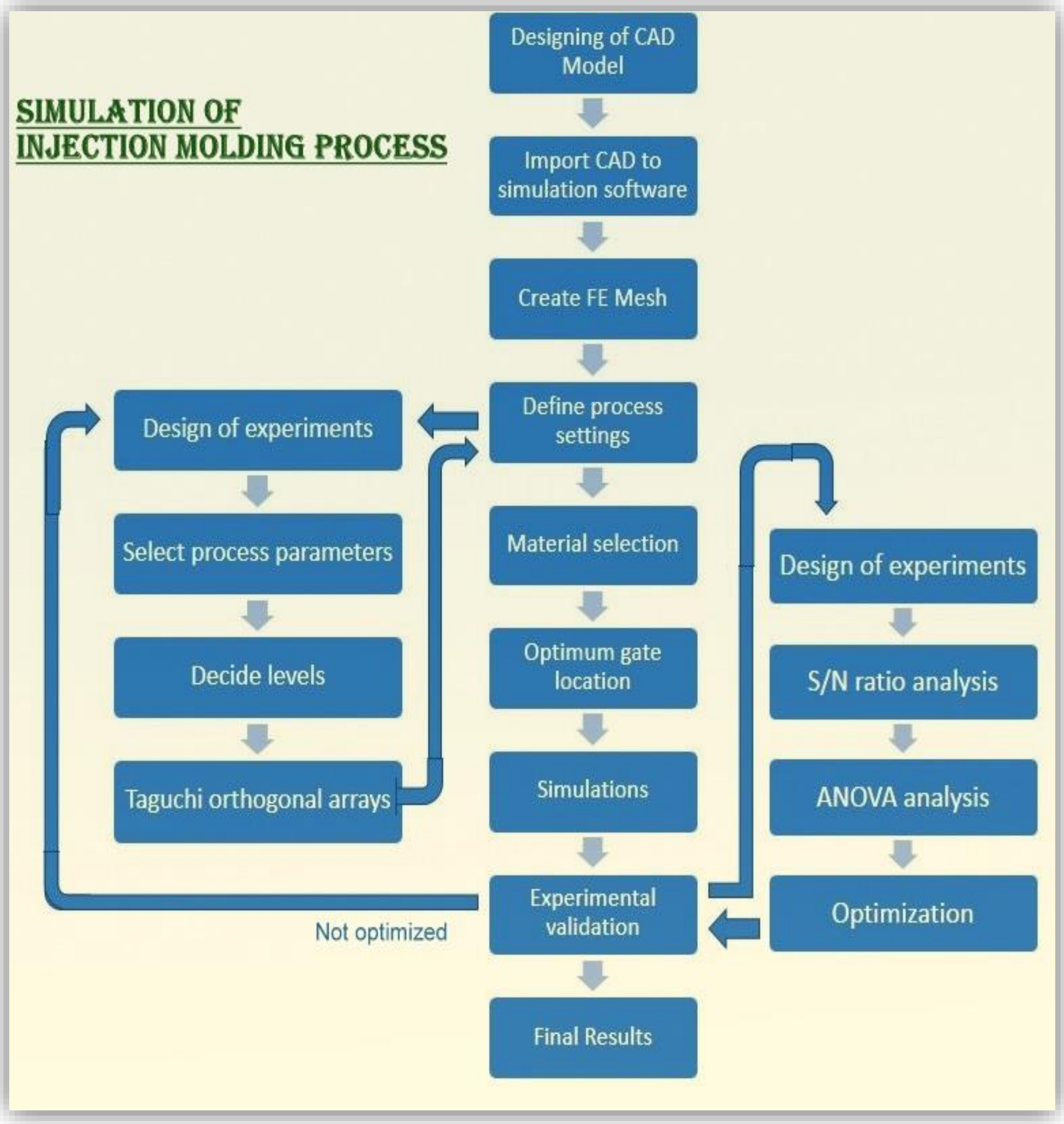


Figure 3.1: Optimization process using Simulation software and Taguchi method

3.1 Computer-Aided Design (CAD)

A new 13 inches wheel cover design according to the latest trend in the market was made on the SolidWorks plastics premium 2015 as shown in Figure 1.2 used as a model. Dimensions are (72.41 x 321.51 x 321.48) mm and part geometry is shown in the Figure 3.2. Finite element analysis (FE) of that mold body is performed using the same software. FE model used in this study corresponded to the real dimensions of the product and number of gates for this particular product.

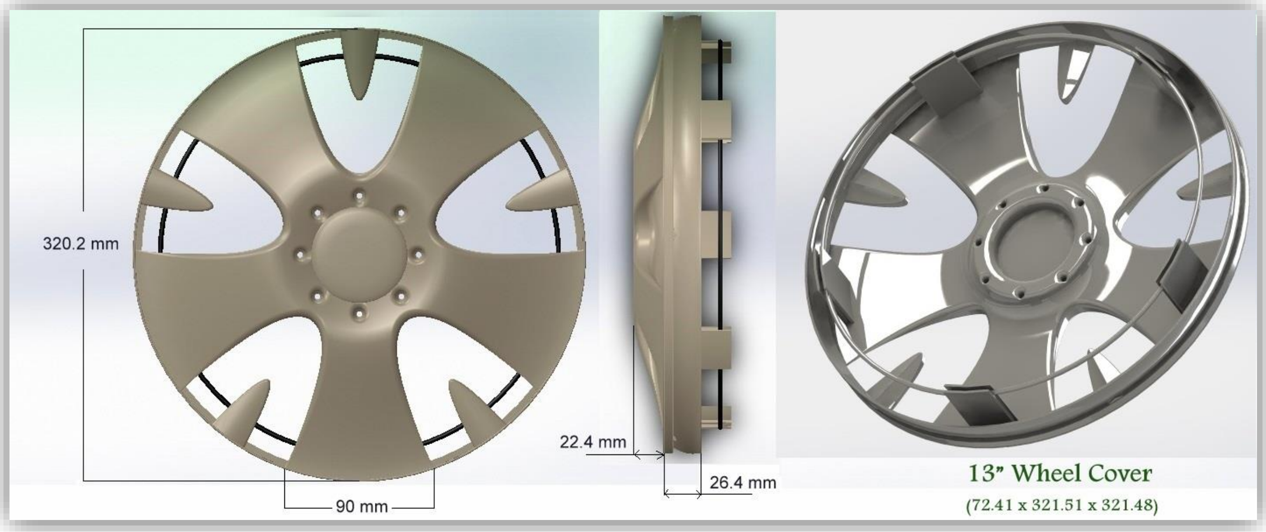


Figure 3.2: Geometry of CAD model

3.1.1 Meshing

After designing, CAD model is imported in the simulation software Autodesk Simulation Moldflow (ASM) Advisor 2014. Now we have to mesh the part with any finite-element mesh models. There are two types of meshing in ASM Advisor 2014:

I. Dual Domain Mesh
II. 3D Technology Mesh

Dual Domain mesh is best for thin-wall parts while 3D technology mesh is recommended for parts having thick geometry (Moldflow-Corporation 2001, Shoemaker 2006). Also Dual Domain mesh requires very less time as compared to 3D mesh. Hence, the initial geometry of the CAD model is meshed by recommended Dual-domain mesh.

3.2 Materials for simulation

The thermoplastic materials used for the analysis are Acrylonitrile butadiene styrene (ABS), Polybutylene Terephthalates (PBT), Polypropylene (PP) and blend of Acrylonitrile butadiene styrene and Polycarbonate (ABS/PC). ABS is the most widely used material for wheel covers (Mike 2014). PBT and ABS/PC can also be used to make wheel covers (plastics) while PP is mostly used in Pakistan. Detailed properties of the materials shown in Table 3.1-3.4.

Table 3.1: Specifications and properties of ABS material.

Material	**Acrylonitrile butadiene styrene (ABS)**
Material structure	Amorphous
Manufacturer	Monsanto Kasei
Elastic modulus	1200 MPa
Poisson's ratio	0.43
Specific heat	2400 J/kg°C
Shear modulus	419.6MPa
Thermal Conductivity	0.18 W/m°C
Maximum shear stress	0.28 MPa
Maximum shear rate	1200 1/s

Table 3.2: Specifications and properties of PP material.

Material	**Polypropylene (PP)**
Material structure	Crystalline
Manufacturer	Generic Default
Elastic modulus	1340
Poisson's ratio	0.392
Specific heat	2740 J/kg°C
Shear modulus	481.3
Thermal Conductivity	0.164 W/m°C
Maximum shear stress	0.25 MPa
Maximum shear rate	100000 1/s

Table 3.3: Specifications and properties of PBT material.

Material	(PBT)
Material structure	Crystalline
Manufacturer	Moldflow Corporation
Elastic modulus	2600 MPa
Poisson’s ratio	0.4
Specific heat	2358 J/kg°C
Shear modulus	929 MPa
Thermal Conductivity	0.2255 W/m°C
Maximum shear stress	0.4 MPa
Maximum shear rate	50000 1/s

Table 3.4: Specifications and properties of PC/ABS material.

Material	(PC/ABS)
Material structure	Amorphous
Manufacturer	Moldflow Corporation
Elastic modulus	2780 MPa
Poisson’s ratio	0.4
Specific heat	2133 J/kg°C
Shear modulus	992.9 MPa
Thermal Conductivity	0.24 W/m°C
Maximum shear stress	0.4 MPa
Maximum shear rate	40000 1/s

3.3 Gate Location

Location of gate is most important in the filling stage; it not only affects the filling pattern but also has a substantial effect on volumetric shrinkage and sink marks. Location of gate is selected after “best gate location analysis” on ASM advisor$^{®}$ 2014, Figure 3.3.

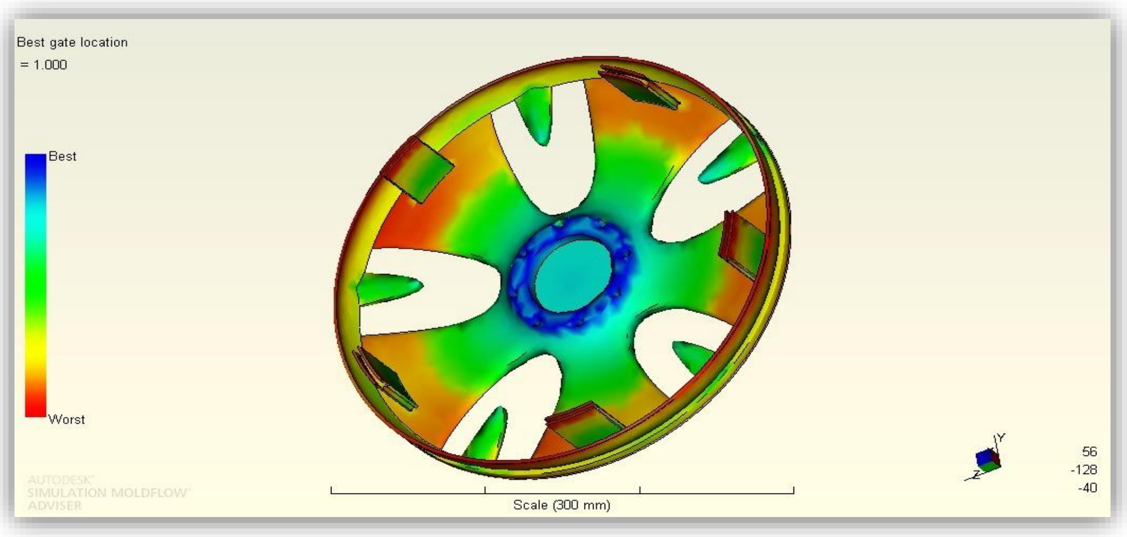


Figure 3.3: Best gate location analysis

3.4 Process Parameters

Process parameters considerably change the volumetric shrinkage and sink marks in plastics. Important and influential factors which affect volumetric shrinkage are packing pressure, melt temperature and mold temperature respectively (Wang, Zeng et al. 2012), while external gas pressure considerably affects sink marks(Wang, Zhao et al. 2013). In this study, the parameters i.e. melt temperature, mold temperature, injection time, cooling time, packing time and packing pressure are selected. According to the standard materials properties range 3 levels of these parameters are also selected shown in Table 3.5**.** Level 1 was selected according to standard values of materials in default values of SolidWorks® Plastic Premium 2015. Injection time was selected through fill analysis in ASM advisor® 2014. Parameters in Level 2 and 3 were varied to get optimal process parameters.

Table 3.5: Process parameters and their levels.

No.	Symbols	Process parameters	Level 1	Level 2	Level 3
1	A	Melt temperature (°C)	240	250	260
2	B	Mold temperature (°C)	40	50	60
3	C	Injection time (s)	4	5	6
4	D	Cooling time (s)	10	20	30
5	E	Packing time (s)	10	15	20
6	F	Packing pressure (% at the end of fill)	40	80	120

3.5 Simulation using ASM Advisor 2014

The simulations were done on Autodesk Simulation Moldflow (ASM) Advisor 2014. Recommended Dual-domain mesh was used. Default values for injection machine are used from ASM advisor 2014 shown in Table 3.6. The analysis used for simulations is Fill + Pack analysis. Taguchi method, S/N ratio and ANOVA is used using statistical software Minitab v.16.

Table 3.6: IM machine default values.

Ejection temperature	88°C
Machine clamp open time	5 s
Maximum machine injection pressure	180 MPa
Velocity/pressure switch-over	Automatic

3.6 DOE via Taguchi Method

An orthogonal array (OA) of L_{27} (3**6) is selected for conducting experiments as shown in Table 3.7-3.8 after considering the levels and parameters S/N ratio is used to succeed the quality characteristics contradictory from the preferred value. To calculate it, three objective functions are there: smaller is better, larger is better and nominal is best. As our aim is to minimize the volumetric shrinkage, hence smaller-is-better objective function is selected. ANOVA "General linear method (GLM)" is applied to detect the effect of each process parameter.

Table 3.7: Orthogonal array (OA) L_{27} (3**6) of Taguchi method for volumetric shrinkage

No. of Exp.	Melt Temp °C	Mold Temp °C	Injection Time(s)	Cooling Time(s)	Packing Time(s)	Packing Pressure (% at the end of fill)	Volumetric Shrinkage %			
	(A)	(B)	(C)	(D)	(E)	(F)	ABS	PP	PBT	PC/ABS
1	240	40	4	10	10	40	9.311	16.52	15.55	8.285
2	240	40	4	10	15	80	8.925	16.29	14.01	7.587
3	240	40	4	10	20	120	**8.822**	**16.10**	13.80	**7.468**
4	240	50	5	20	10	40	9.061	16.56	14.74	7.771
5	240	50	5	20	15	80	8.959	16.41	13.96	7.613

6	240	50	5	20	20	120	8.864	16.20	**13.60**	7.502
7	240	60	6	30	10	40	9.486	16.59	14.27	8.196
8	240	60	6	30	15	80	9.000	16.40	14.29	7.646
9	240	60	6	30	20	120	8.911	16.18	13.69	7.541
10	250	40	5	30	10	80	9.469	16.56	14.77	8.171
11	250	40	5	30	15	120	9.349	16.30	14.57	8.032
12	250	40	5	30	20	40	9.941	16.73	15.10	**8.846**
13	250	50	6	10	10	80	9.501	16.78	14.85	8.192
14	250	50	6	10	15	120	9.388	16.35	14.67	8.063
15	250	50	6	10	20	40	9.418	17.03	15.44	7.799
16	250	60	4	20	10	80	9.632	16.89	15.09	8.318
17	250	60	4	20	15	120	9.528	16.75	14.76	8.196
18	250	60	4	20	20	40	9.818	16.95	15.74	8.204
19	260	40	6	20	10	120	9.895	16.87	15.47	8.615
20	260	40	6	20	15	40	10.320	17.00	16.05	8.327
21	260	40	6	20	20	80	9.589	16.86	14.76	8.197
22	260	50	4	30	10	120	10.030	17.10	15.68	8.741
23	260	50	4	30	15	40	**10.520**	**17.21**	**16.25**	8.764
24	260	50	4	30	20	80	9.743	17.09	15.58	8.352
25	260	60	5	10	10	120	10.060	17.15	15.70	8.766
26	260	60	5	10	15	40	10.150	17.20	16.12	8.619
27	260	60	5	10	20	80	9.785	17.09	15.31	8.388

Table 3.8: Orthogonal array (OA) L27 (36) of Taguchi method for sink marks**

No.	Melt Temp °C	Mold Temp °C	Injection Time(s)	Cooling Time(s)	Packing Time(s)	Packing Pressure (% at the end of fill)	Sink marks (mm)			
	(A)	(B)	(C)	(D)	(E)	(F)	ABS	PP	PBT	PC/ABS
1	240	40	4	10	10	40	1.194	2.532	1.577	0.7788
2	240	40	4	10	15	80	1.168	2.438	1.551	0.7596

3	240	40	4	10	20	120	**1.146**	**2.410**	1.521	**0.7392**
4	240	50	5	20	10	40	1.197	2.557	1.577	0.7769
5	240	50	5	20	15	80	1.172	2.454	1.548	0.7587
6	240	50	5	20	20	120	1.154	2.443	1.518	0.7429
7	240	60	6	30	10	40	1.204	2.517	1.573	0.7788
8	240	60	6	30	15	80	1.183	2.476	1.565	0.7625
9	240	60	6	30	20	120	1.164	2.449	**1.511**	0.7477
10	250	40	5	30	10	80	1.282	2.614	1.758	0.8457
11	250	40	5	30	15	120	1.254	2.518	1.725	0.8225
12	250	40	5	30	20	40	1.207	2.442	1.600	0.7741
13	250	50	6	10	10	80	1.285	2.638	1.745	0.8469
14	250	50	6	10	15	120	1.258	2.537	1.716	0.8255
15	250	50	6	10	20	40	1.211	2.459	1.593	0.7777
16	250	60	4	20	10	80	1.347	2.642	1.866	0.9132
17	250	60	4	20	15	120	1.320	2.579	1.840	0.8901
18	250	60	4	20	20	40	1.273	2.495	1.718	0.8442
19	260	40	6	20	10	120	1.367	2.689	1.899	0.9149
20	260	40	6	20	15	40	1.311	2.558	1.791	0.8596
21	260	40	6	20	20	80	1.289	2.549	1.775	0.8402
22	260	50	4	30	10	120	1.441	2.765	2.022	**0.9822**
23	260	50	4	30	15	40	1.386	2.594	1.917	0.9287
24	260	50	4	30	20	80	1.361	2.564	1.903	0.9070
25	260	60	5	10	10	120	**1.448**	**2.787**	**2.027**	0.9781
26	260	60	5	10	15	40	1.392	2.618	1.921	0.9230
27	260	60	5	10	20	80	1.372	2.583	1.912	0.9040

Chapter: 04

4 Simulation Results

4.1 Signal-to-noise ratio

Products performance and quality after the effect of different process parameters during Injection Molding process can be evaluate through S/N ratio (Mirigul 2010, Barghash and Alkaabneh 2014). Its measured values are shown in Table 4.1-21. Quality function of smaller-is-better is used. S/N ratio is:

$S/N = -10 * \log [\Sigma (Y^2)/n)]$

"n" is the number of observations on the particular product.

"Y" is the respective characteristics

To find the best set of process parameters, highest values of each parameters from the S/N ratio graphs of all materials are selected which are shown in Figure 4.1-4.8 respectively. Highest value of Delta (difference) Δ shows the factors which affected more during the molding process and ranked accordingly.

4.1.1 S/N ratio graph for ABS

Table 4.1: Response table-S/N ratio of ABS for shrinkage

Level	Melt Temp. (A)	Mold Temp. (B)	Injection Time (C)	Cooling Time (D)	Packing Time (E)	Packing Pressure (F)
1	-19.12	-19.56	-19.63	-19.53	-19.65	-19.80
2	-19.61	-19.54	-19.56	-19.56	-19.60	-19.46
3	-20.01	-19.63	-19.55	-19.64	-19.48	-19.48
Delta Δ	0.89	0.09	0.08	0.11	0.16	0.34
Rank	1	5	6	4	3	2

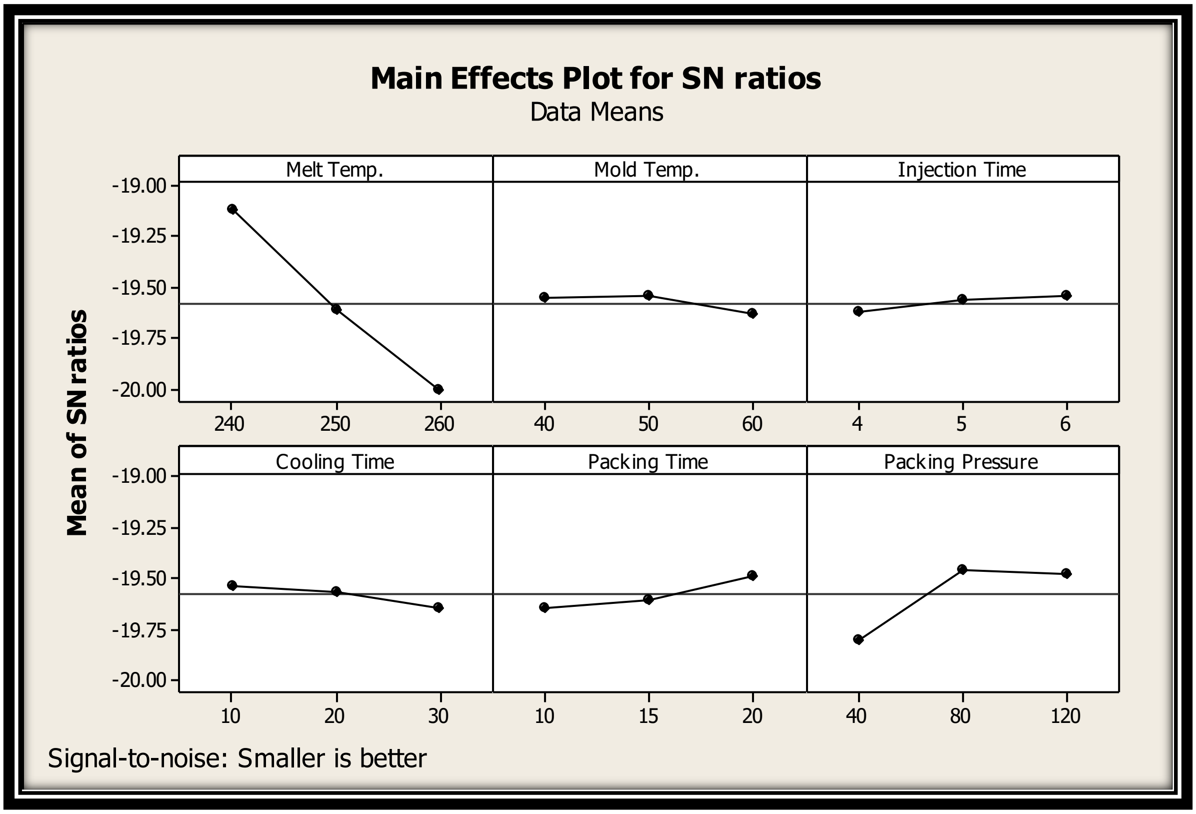


Figure 4.1: S/N ratio graph of ABS for shrinkage

Table 4.2: Response table-S/N ratio of ABS for sink marks

Level	Melt Temp. (A)	Mold Temp. (B)	Injection Time (C)	Cooling Time (D)	Packing Time (E)	Packing Pressure (F)
1	-1.405	-1.900	-2.206	-2.082	-2.305	-2.019
2	-2.076	-2.078	-2.086	-2.061	-2.069	-2.082
3	-2.755	-2.258	-1.944	-2.093	-1.863	-2.136
Delta Δ	1.349	0.358	0.262	0.031	0.441	0.117
Rank	1	3	4	6	2	5

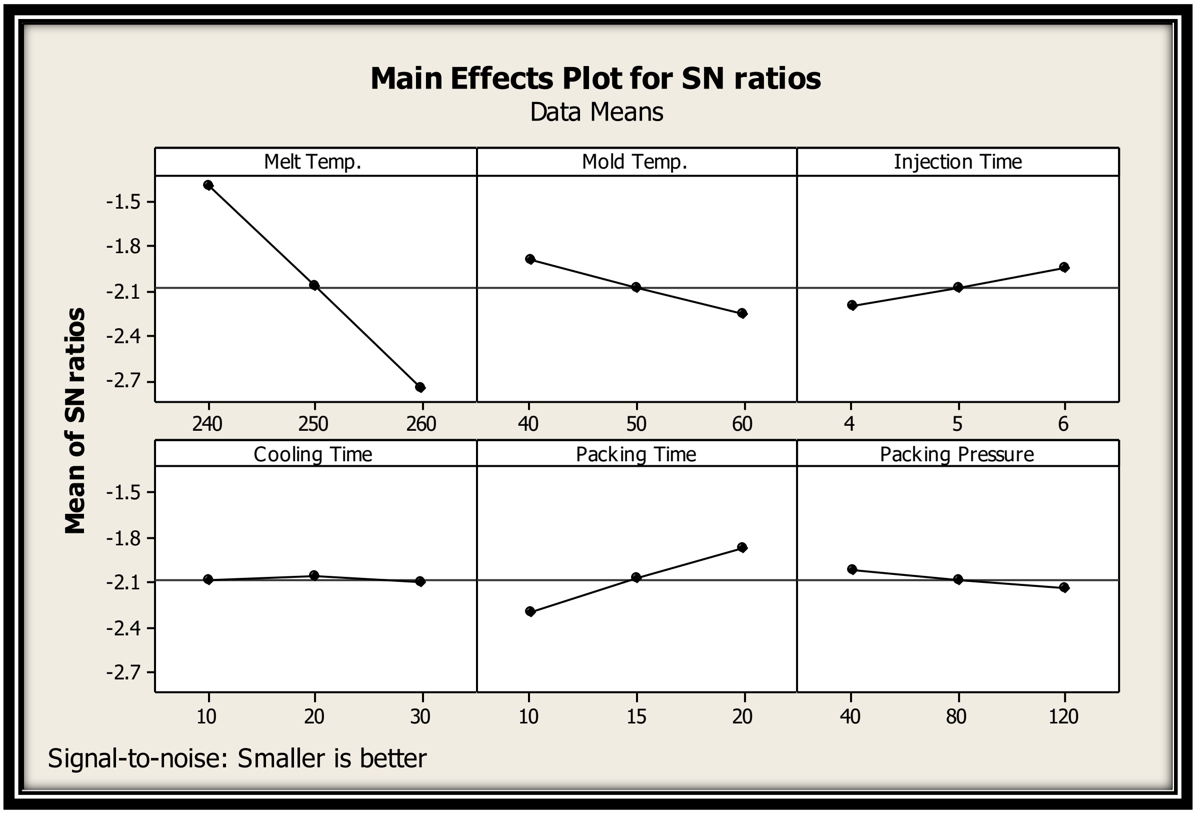


Figure 4.2: S/N ratio graph of ABS for sink marks

4.1.2 S/N ratio graph for PP

Table 4.3: Response table-S/N ratio of PP for shrinkage

Level	Melt Temp. (A)	Mold Temp. (B)	Injection Time (C)	Cooling Time (D)	Packing Time (E)	Packing Pressure (F)
1	-24.28	-24.39	-24.49	-24.46	-24.50	-24.54
2	-24.46	-24.48	-24.45	-24.46	-24.43	-24.46
3	-24.64	-24.50	-24.44	-24.44	-24.45	-24.38
Delta Δ	0.37	0.11	0.05	0.02	0.08	0.16
Rank	1	3	5	6	4	2

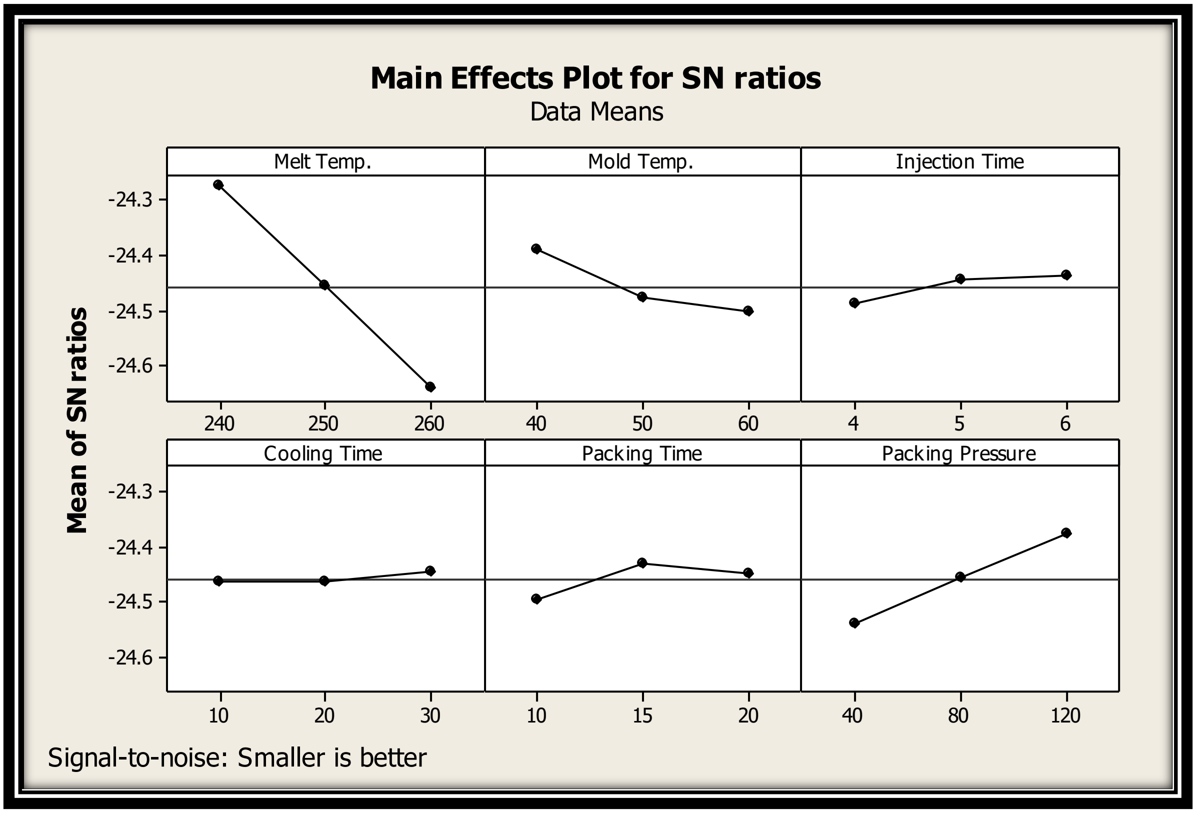


Figure 4.3: S/N ratio graph of PP for shrinkage

Table 4.4: Response table-S/N ratio of PP for sink marks

Level	Melt Temp. (A)	Mold Temp. (B)	Injection Time (C)	Cooling Time (D)	Packing Time (E)	Packing Pressure (F)
1	-7.870	-8.050	-8.150	-8.142	-8.420	-8.061
2	-8.118	-8.148	-8.149	-8.133	-8.061	-8.130
3	-8.408	-8.198	-8.097	-8.121	-7.915	-8.205
Delta Δ	0.538	0.149	0.053	0.022	0.505	0.144
Rank	1	3	5	6	2	4

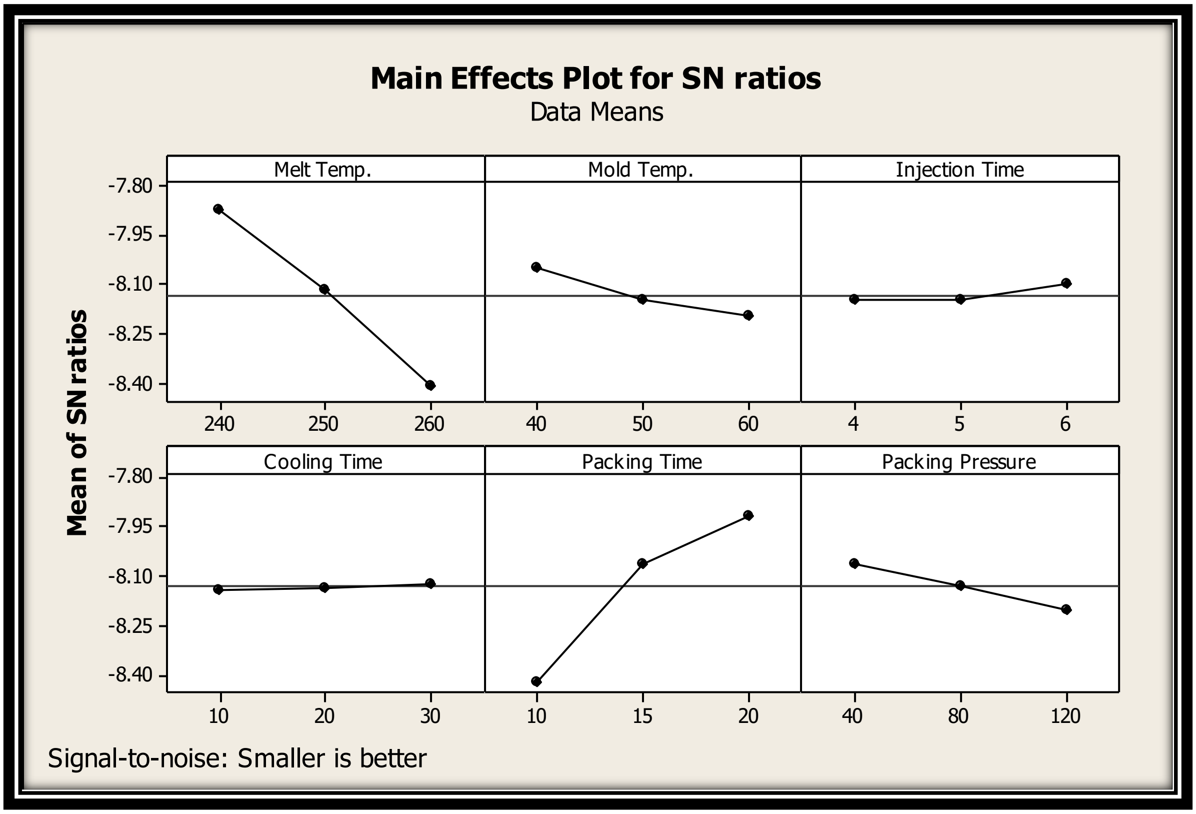


Figure 4.4: S/N ratio graph of PP for sink marks

4.1.3 S/N ratio graph for PBT

Table 4.5: Response table-S/N ratio of PBT for shrinkage

Level	Melt Temp. (A)	Mold Temp. (B)	Injection Time (C)	Cooling Time (D)	Packing Time (E)	Packing Pressure (F)
1	-23.05	-23.45	-23.60	-23.54	-23.59	-23.78
2	-23.52	-23.49	-23.44	-23.46	-23.49	-23.36
3	-23.89	-23.51	-23.41	-23.46	-23.38	-23.31
Delta Δ	0.84	0.06	0.19	0.08	0.21	0.47
Rank	1	6	4	5	3	2

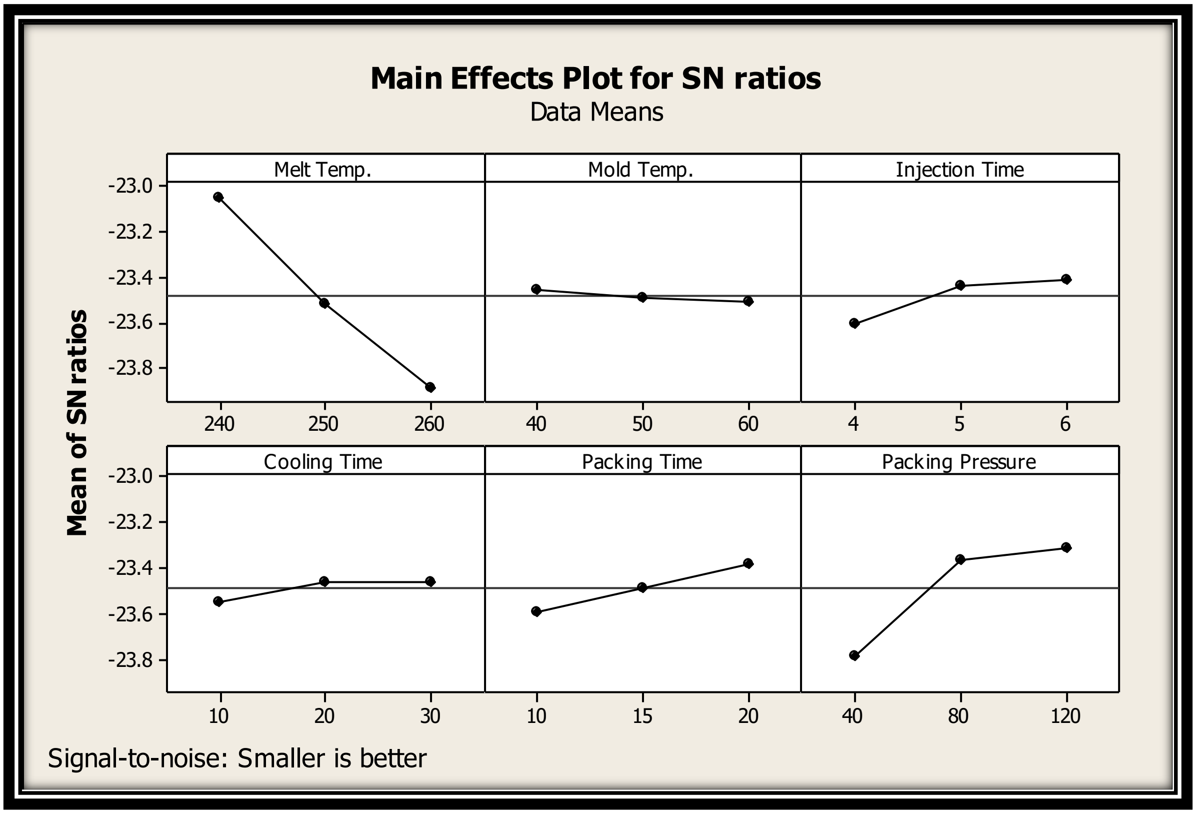


Figure 4.5: S/N ratio graph of PBT for shrinkage

Table 4.6: Response table-S/N ratio of PBT for sink marks

Level	Melt Temp. (A)	Mold Temp. (B)	Injection Time (C)	Cooling Time (D)	Packing Time (E)	Packing Pressure (F)
1	-3.800	-4.527	-4.909	-4.713	-4.981	-4.562
2	-4.745	-4.701	-4.726	-4.712	-4.734	-4.762
3	-5.601	-4.918	-4.511	-4.721	-4.431	-4.822
Delta Δ	1.801	0.391	0.398	0.009	0.549	0.264
Rank	1	4	3	6	2	5

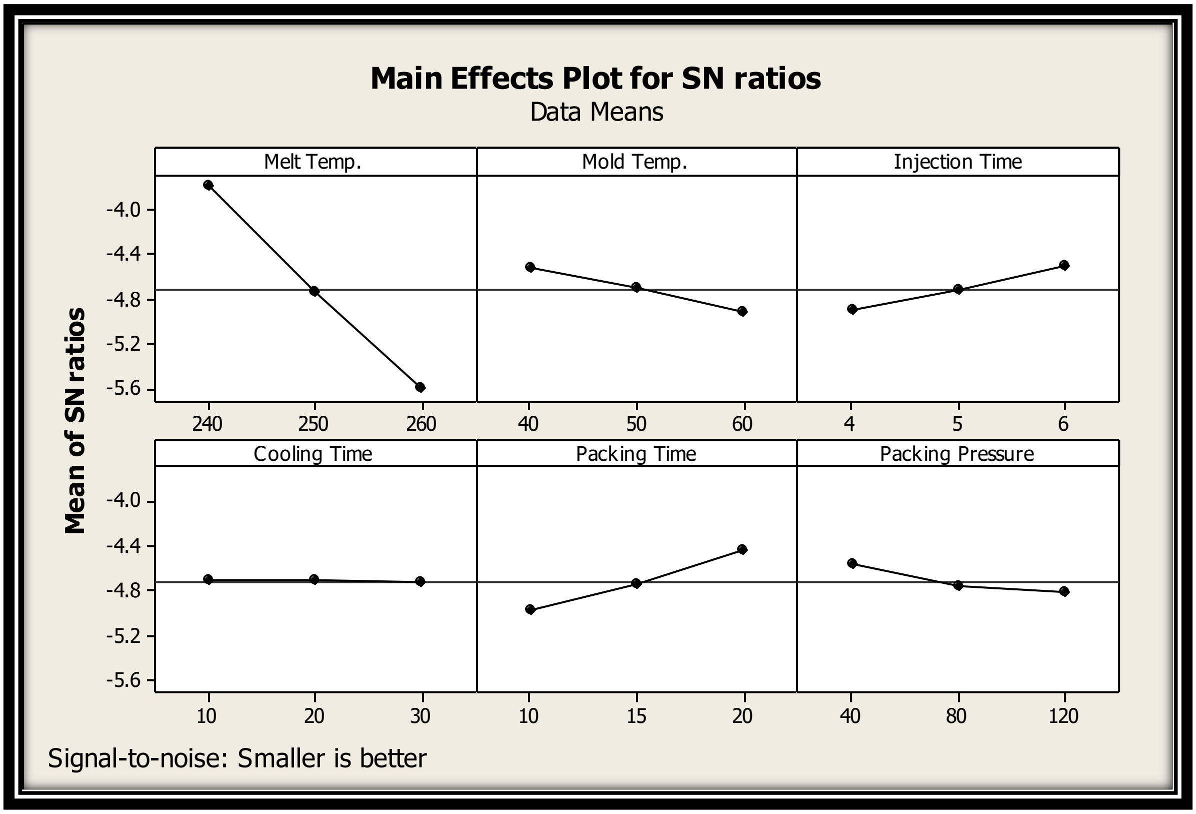


Figure 4.6: S/N ratio graph of PBT for sink marks

4.1.4 S/N ratio graph for ABS/PC

Table 4.7: Response table-S/N ratio of ABS/PC for shrinkage

Level	Melt Temp. (A)	Mold Temp. (B)	Injection Time (C)	Cooling Time (D)	Packing Time (E)	Packing Pressure (F)
1	-17.76	-18.23	-18.28	-18.19	-18.42	-18.39
2	-18.27	-18.14	-18.25	-18.14	-18.15	-18.11
3	-18.62	-18.28	-18.12	-18.32	-18.08	-18.16
Delta Δ	0.85	0.13	0.15	0.18	0.33	0.28
Rank	1	6	5	4	2	3

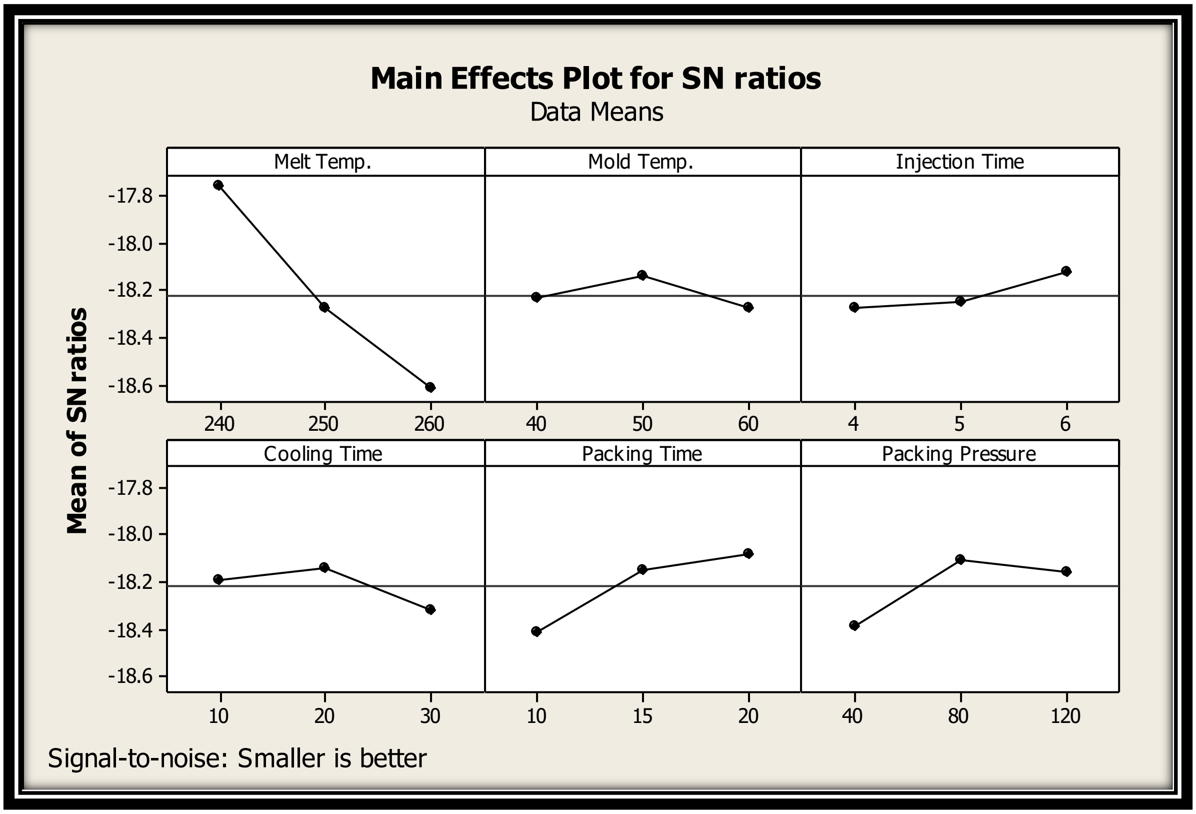


Figure 4.7: S/N ratio graph of ABS/PC for shrinkage

Table 4.8: Response table-S/N ratio of ABS/PC for sink marks

Level	Melt Temp. (A)	Mold Temp. (B)	Injection Time (C)	Cooling Time (D)	Packing Time (E)	Packing Pressure (F)
1	2.3788	1.7956	1.3447	1.5825	1.2605	1.6741
2	1.5490	1.5680	1.5905	1.5603	1.5743	1.5630
3	0.7789	1.3431	1.7715	1.5639	1.8719	1.4696
Delta Δ	1.5999	0.4525	0.4269	0.0222	0.6115	0.2045
Rank	1	3	4	6	2	5

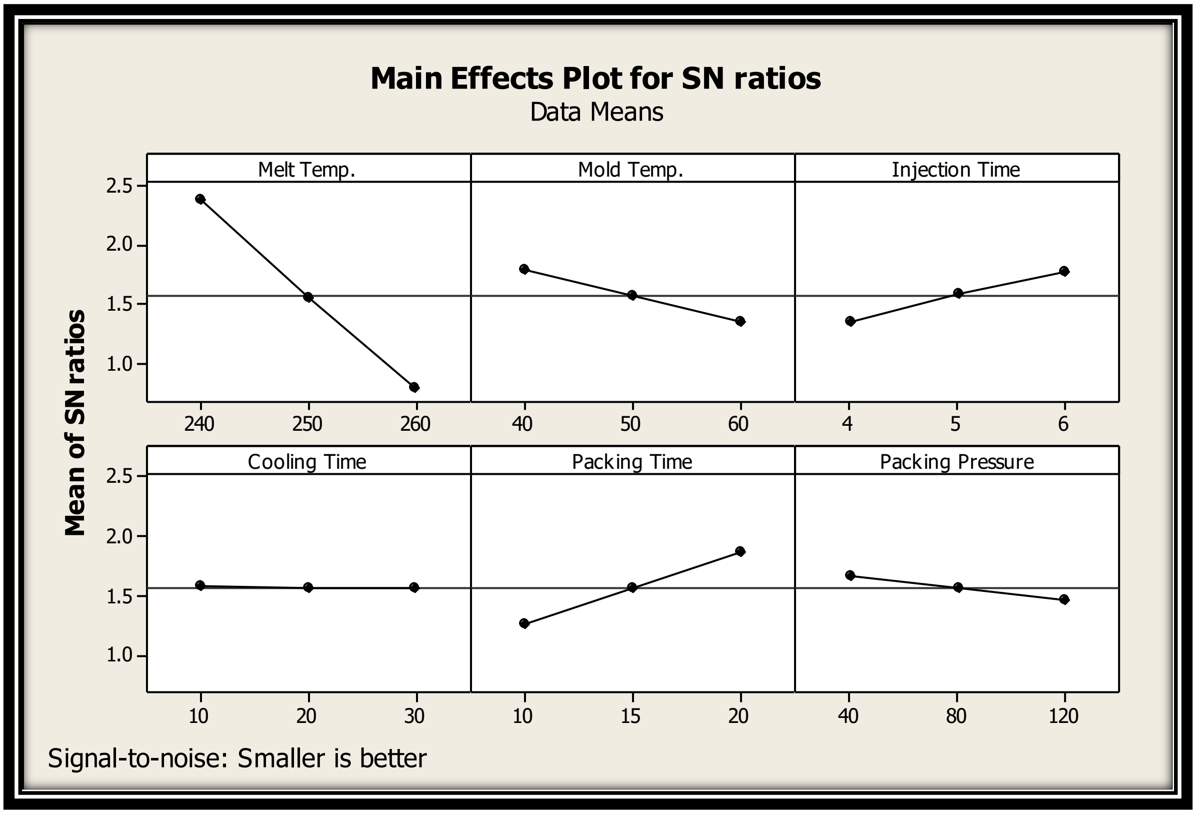


Figure 4.8: S/N ratio graph of ABS/PC for sink marks

As for ABS, PP and PBT, first and second rank are of melt temperature and packing pressure shown in Table 4.1,Table 4.3Table 4.5, but for ABS/PC, packing time is on 2nd rank shown in S/N ratio graph for ABS/PC

Table 4.7, it means these two ranks have the highest effect on volumetric shrinkage respectively. Table 4.2,Table 4.4Table 4.6Table 4.8 show that melt temperatsure and packing time are the two top ranked parameters and have the maximum effect on sink marks for all materials. Hence, Influence order of process parameters on all materials for volumetric shrinkage are as follows:

ABS:	A>F>E>D>B>C
PP:	A>F>B>E>C>D
PBT:	A>F>E>C>D>B
ABS/PC:	A>E>F>D>C>B

While for sink marks, Influence order of process parameters are:

ABS:	A>E>B>C>F>D
PP:	A>E>B>F>C>D
PBT:	A>E>B>C>F>D

ABS/PC	A>E>C>B>F>D

Optimum process parameters for volumetric shrinkage and sink marks are same except the packing pressure. Study shows that volumetric shrinkage decreases by increasing packing pressure, while sink marks has almost the opposite trend as shown in Figure 4.1-Figure 4.8

4.2 Analysis of variance

It is used to determine the effect and significance of each parameter during simulation (Mirigul 2010, Barghash and Alkaabneh 2014). General linear model (GLM) is used for ANOVA calculation in Minitab V.16. GLM calculates:

I. (DF) Degree of freedom
II. (SS) sequential sums of squares
III. (Adj MS) adjusted mean square
IV. (Adj SS) adjusted sum of squares
V. F-value and p-value

Percentage contribution of variance (P %) can be calculated by

$P\ \% = SS/SS_T \times 100$

Where SS_T is the total sum of SS and error.

ANOVA results for each parameter are shown in the ANOVA results for ABS:

Table 4.9-Table 4.16. If we consider ABS material, the minimum and maximum values for volumetric shrinkage are 8.822% and 10.52%, and for sink marks are 1.146mm and 1.448mm respectively. Factors which have the significant effect on the process can be identified by p-value test (Barghash and Alkaabneh 2014). If the p-value is equal to or lower than 0.05, it means the parameter is significant. ANOVA results for ABS:

Table 4.9 shows that packing pressure and melt temperature are the most significant parameters have an extensive effect on volumetric shrinkage due to the highest percentage contribution of 75.2% and 14.29% respectively. Table 4.10 shows that sink marks are mainly affected by melt temperature which has 81.94% contribution and packing time which has a percentage contribution of 8.8%, while all other parameters have less effect on it. This is the same effect on all other materials shown in below tables.

4.2.1 ANOVA results for ABS:

Table 4.9: ANOVA results for volumetric shrinkage [ABS]

Source	DF	SS	Adj SS	Adj MS	F	P	Percentage Contribution
Melt temp.	2	4.26438	4.26438	2.13219	106.67	**0.000**	**75.2**
Mold temp.	2	0.05055	0.05055	0.02527	1.26	0.313	0.90
Injection time	2	0.04327	0.04327	0.02164	1.08	0.365	0.76
Cooling time	2	0.07010	0.07010	0.03505	1.75	0.209	1.24
Packing time	2	0.15059	0.15059	0.07530	3.77	**0.049**	2.65
Packing pressure	2	0.80997	0.80997	0.40499	20.26	**0.000**	**14.29**
Error	14	0.27983	0.27983	0.01999			4.96
Total	26	5.66870					100

Table 4.10: ANOVA results for sink marks [ABS]

Source	DF	SS	Adj SS	Adj MS	F	P	Percentage Contribution
Melt temp.	2	0.177117	0.177117	0.088558	22679.57	0.000	**81.94**
Mold temp.	2	0.013070	0.013070	0.006535	1673.54	0.000	5.97
Injection time	2	0.007404	0.007404	0.003702	948.02	0.000	3.38
Cooling time	2	0.000174	0.000174	0.000087	22.31	0.000	0.08
Packing time	2	0.019262	0.019262	0.009631	2466.48	0.000	**8.80**
Packing pressure	2	0.001742	0.001742	0.000871	223.06	0.000	0.80
Error	14	0.000055	0.000055	0.000004			0.97
Total	26	0.218823					100

4.2.2 ANOVA results for PP:

Table 4.11: ANOVA results for volumetric shrinkage [PP]

Source	DF	SS	Adj SS	Adj MS	F	P	Percentage Contribution
Melt temp.	2	2.21939	2.21939	1.10969	139.17	0.000	**71.02**
Mold temp.	2	0.23525	0.23525	0.11763	14.75	0.000	7.52
Injection time	2	0.04501	0.04501	0.02250	2.82	0.093	1.44
Cooling time	2	0.00859	0.00859	0.00429	0.54	0.595	0.27
Packing time	2	0.07254	0.07254	0.03627	4.55	0.030	2.32
Packing pressure	2	0.43250	0.43250	0.21625	27.12	0.000	**13.84**
Error	14	0.11163	0.11163	0.00797			3.59
Total	26	3.12490					100

Table 4.12: ANOVA results for sink marks [PP]

Source	DF	SS	Adj SS	Adj MS	F	P	Percentage Contribution
Melt temp.	2	0.114102	0.114102	0.057051	230.80	0.000	**46.61**
Mold temp.	2	0.009006	0.009006	0.004503	18.22	0.000	3.68
Injection time	2	0.001569	0.001569	0.000784	3.17	0.073	0.64
Cooling time	2	0.000222	0.000222	0.000111	0.45	0.647	0.09
Packing time	2	0.107269	0.107269	0.053634	216.98	0.000	**43.82**
Packing pressure	2	0.009133	0.009133	0.004566	18.47	0.000	3.73
Error	14	0.003461	0.003461	0.000247			1.43
Total	26	0.244761					100

4.2.3 ANOVA results for PBT:

Table 4.13: ANOVA results for volumetric shrinkage [PBT]

Source	DF	SS	Adj SS	Adj MS	F	P	Percentage Contribution
Melt temp.	2	9.4278	9.4278	4.7139	68.93	**0.000**	**61.61**
Mold temp.	2	0.0485	0.0485	0.0242	0.35	0.708	0.31
Injection time	2	0.5805	0.5805	0.2902	4.24	0.036	3.80
Cooling time	2	0.1186	0.1186	0.0593	0.87	0.442	0.76
Packing time	2	0.5348	0.5348	0.2674	3.91	0.045	3.50
Packing pressure	2	3.6346	3.6346	1.8173	26.57	**0.000**	**23.75**
Error	14	0.9575	0.9575	0.0684			6.27
Total	26	15.3022					100

Table 4.14: ANOVA results for sink marks [PBT]

Source	DF	SS	Adj SS	Adj MS	F	P	Percentage Contribution
Melt temp.	2	0.578175	0.578175	0.289087	6807.56	0.000	**81.39**
Mold temp.	2	0.030144	0.030144	0.015072	354.93	0.000	4.24
Injection time	2	0.031147	0.031147	0.015574	366.73	0.000	4.38
Cooling time	2	0.000105	0.000105	0.000053	1.24	0.319	0.015
Packing time	2	0.054833	0.054833	0.027416	645.61	0.000	**7.71**
Packing pressure	2	0.015304	0.015304	0.007652	180.20	0.000	2.15
Error	14	0.000595	0.000595	0.000042			0.115
Total	26	0.710303					100

4.2.4 ANOVA results for PC/ABS:

Table 4.15: ANOVA results for volumetric shrinkage [PC/ABS]

Source	DF	SS	Adj SS	Adj MS	F	P	Percentage Contribution
Melt temp.	2	2.87768	2.87768	1.43884	33.77	**0.000**	**62.34**
Mold temp.	2	0.06719	0.06719	0.03359	0.79	0.474	1.45
Injection time	2	0.11545	0.11545	0.05773	1.35	0.290	2.50
Cooling time	2	0.14181	0.14181	0.07090	1.66	0.225	3.07
Packing time	2	0.47349	0.47349	0.23675	5.56	0.017	10.25
Packing pressure	2	0.34373	0.34373	0.17187	4.03	0.041	**7.45**
Error	14	0.59655	0.59655	0.04261			12.94
Total	26	4.61590					100

Table 4.16: ANOVA results for sink marks [PC/ABS]

Source	DF	SS	Adj SS	Adj MS	F	P	Percentage Contribution
Melt temp.	2	0.107741	0.107741	0.053870	9989.23	0.000	**74.88**
Mold temp.	2	0.009208	0.009208	0.004604	853.72	0.000	6.4
Injection time	2	0.008453	0.008453	0.004226	783.71	0.000	5.9
Cooling time	2	0.000015	0.000015	0.000007	1.39	0.282	0.04
Packing time	2	0.016129	0.016129	0.008065	1495.42	0.000	**11.2**
Packing pressure	2	0.002253	0.002253	0.001126	208.87	0.000	1.56
Error	14	0.000075	0.000075	0.000005			0.02
Total	26	0.143874					100

4.3 Optimum process parameters

To find out the optimum process parameters for whole injection molding process, it is best to combine the optimum process parameters of each material. Table 4.17 shows the optimum process parameters for each material and the final optimum value for whole injection molding (IM) process. Final optimum values are considered by taking the mean of all optimum values.

Table 4.17: Optimum values for IM process

Process Parameters	Optimum Values								Optimum values for IM process (Mean values)
	ABS		PP		PBT		ABS/PC		
	Shrinkage	Sink marks	Shrinkage	Sink marks	Shrinkage	Sink marks	Shrinkage	Sink marks	
Melt temperature (°C)	240	240	240	240	240	240	240	240	240
Mold temperature (°C)	40	40	40	40	40	40	50	40	40
Injection pressure (MPa)	6	6	6	6	6	6	6	6	6
Cooling time (s)	10	20	30	30	30	10	20	10	20
Packing time (s)	20	20	15	20	20	20	20	20	20
Packing pressure (% at the end of fill)	80	40	120	40	120	40	80	40	80

4.4 Simulation for Verification of optimum parameters

After selecting the optimum process parameters, Simulations were done on ASM advisor 2014 for each material for the verification shown in Figure 4.9-Figure 4.12. Simulation using these optimum process parameters combination A1B1C3D2E3F2 give the minimum volumetric shrinkage and sink marks value for all material as shown in Table 4.18Table 4.21.

4.4.1 For ABS:

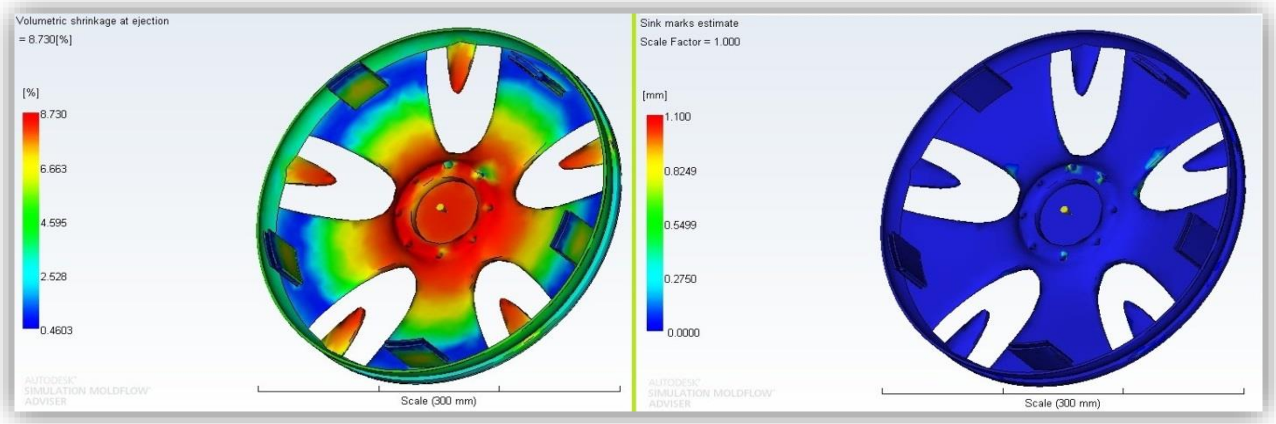


Figure 4.9: Simulation using optimum process parameters [ABS]

Table 4.18: Optimum process parameters effect [ABS]

No.	Melt Temp. °C (A)	Mold Temp. °C (B)	Injection Time(s) (C)	Cooling Time(s) (D)	Packing Time(s) (E)	Packing Pressure (%) (F)	**Volumetric Shrinkage**	**Sink marks**
1	240	40	6	20	20	80	**8.730**	**1.100**

4.4.2 For PP:

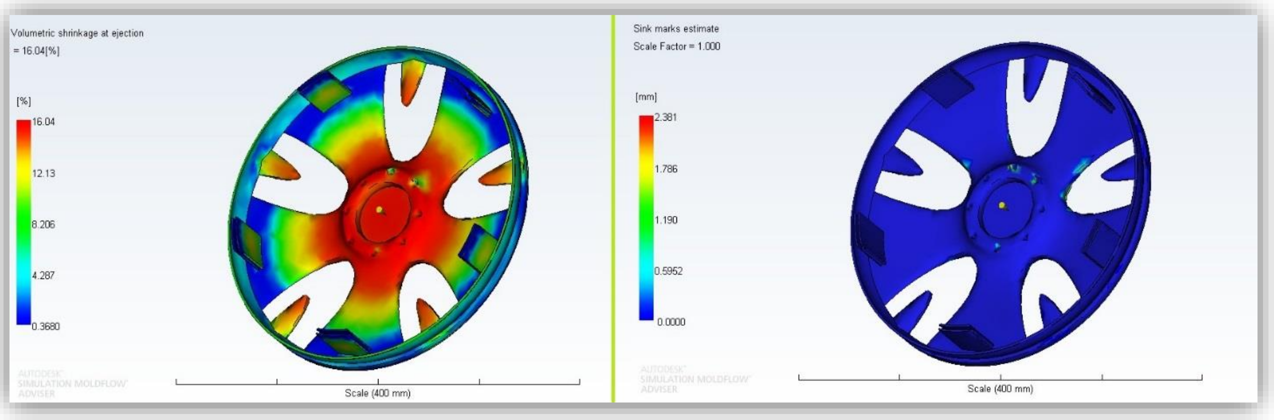


Figure 4.10: Simulation using optimum process parameters [PP]

Table 4.19: Optimum process parameters effect [PP]

No.	Melt Temp. °C (A)	Mold Temp. °C (B)	Injection Time(s) (C)	Cooling Time(s) (D)	Packing Time(s) (E)	Packing Pressure (%) (F)	**Volumetric Shrinkage**	**Sink marks**
1	240	40	6	20	20	80	**16.04**	**2.381**

4.4.3 For PBT:

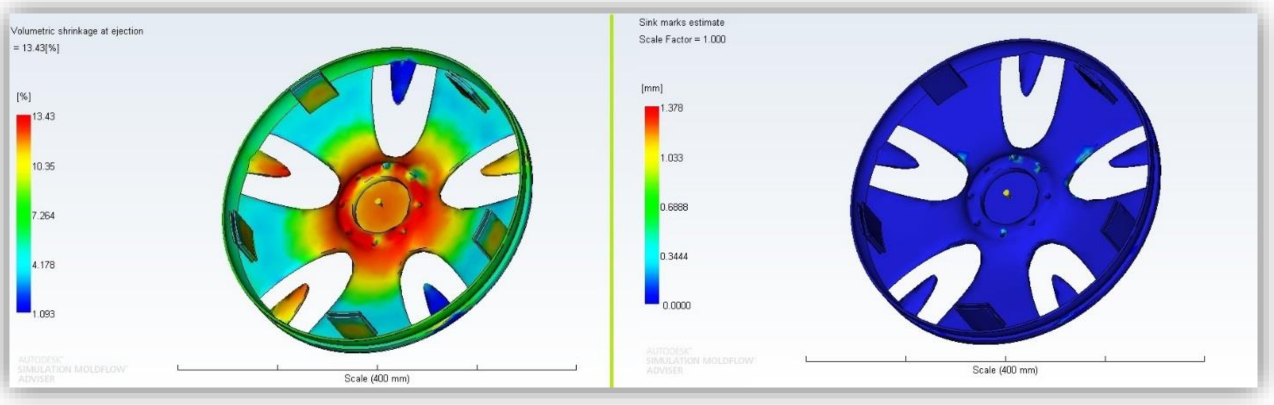


Figure 4.11: Simulation using optimum process parameters [PBT]

Table 4.20: Optimum process parameters effect [PBT]

No.	Melt Temp. °C (A)	Mold Temp. °C (B)	Injection Time(s) (C)	Cooling Time(s) (D)	Packing Time(s) (E)	Packing Pressure (%) (F)	**Volumetric Shrinkage**	**Sink marks**
1	240	40	6	20	20	80	**13.43**	**1.378**

4.4.4 For PC/ABS:

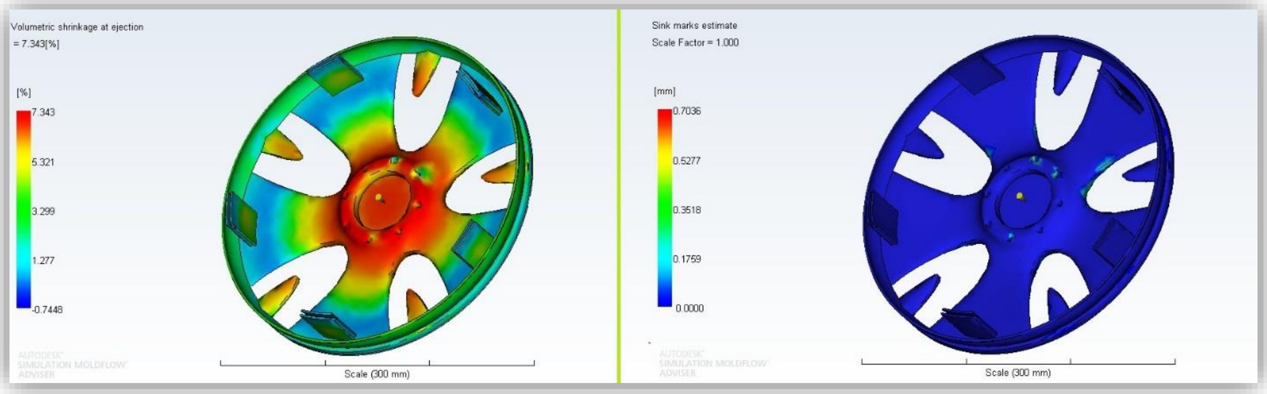
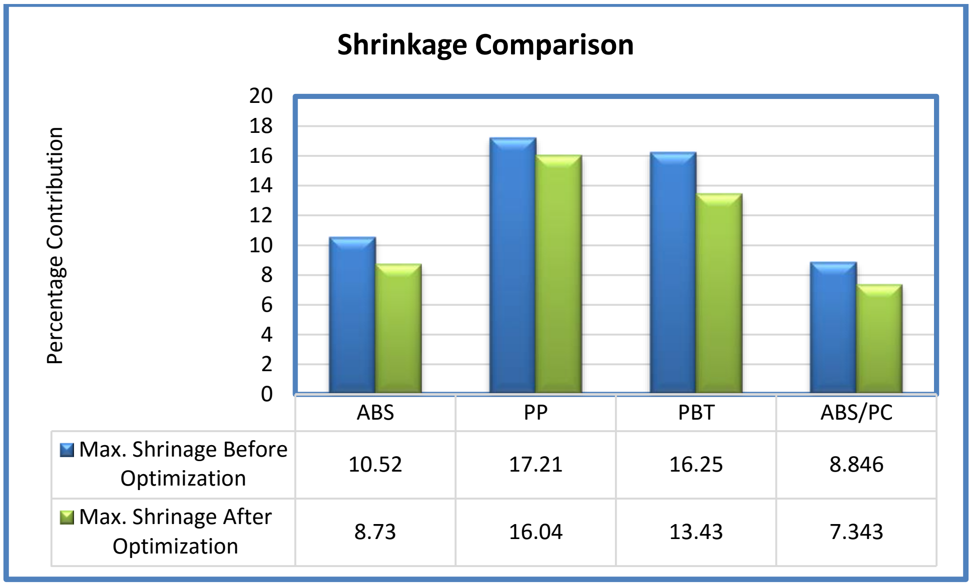


Figure 4.12: Simulation using optimum process parameters [ABS/PC]

Table 4.21: Optimum process parameters effect [ABS/PC]

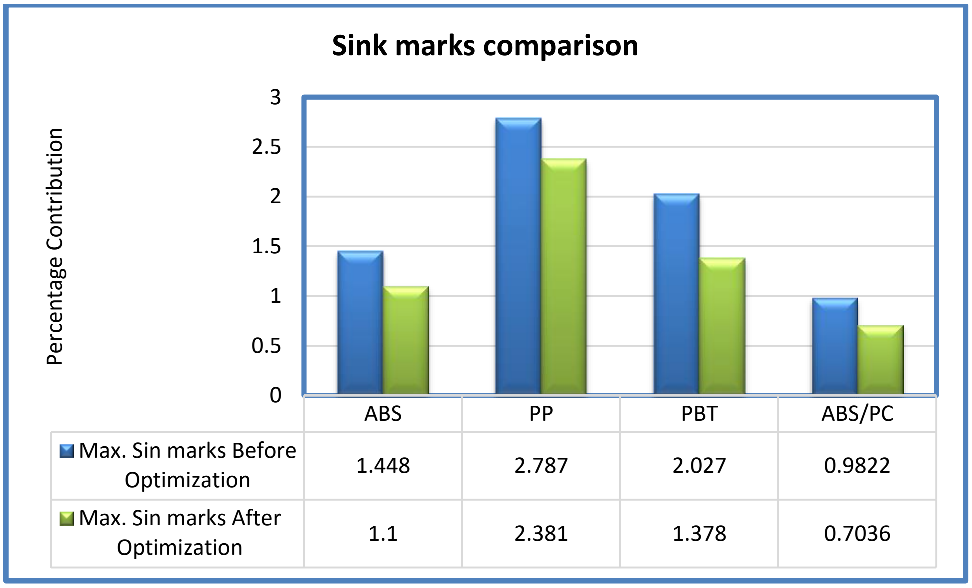
No.	Melt Temp. °C (A)	Mold Temp. °C (B)	Injection Time(s) (C)	Cooling Time(s) (D)	Packing Time(s) (E)	Packing Pressure (%) (F)	**Volumetric Shrinkage**	**Sink marks**
1	240	40	6	20	20	80	**7.343**	**0.7036**

Graph 4.1-4.2 shows the final comparison of shrinkage and sink marks after optimization and before. It clearly shows decrease in both defects percentage contribution.



	ABS	PP	PBT	ABS/PC
🟦 Max. Shrinage Before Optimization	10.52	17.21	16.25	8.846
🟩 Max. Shrinage After Optimization	8.73	16.04	13.43	7.343

Graph 4.1: Shrinkage comparison after optimization



	ABS	PP	PBT	ABS/PC
🟦 Max. Sin marks Before Optimization	1.448	2.787	2.027	0.9822
🟩 Max. Sin marks After Optimization	1.1	2.381	1.378	0.7036

Graph 4.2: Sink marks comparison after optimization

Chapter: 05

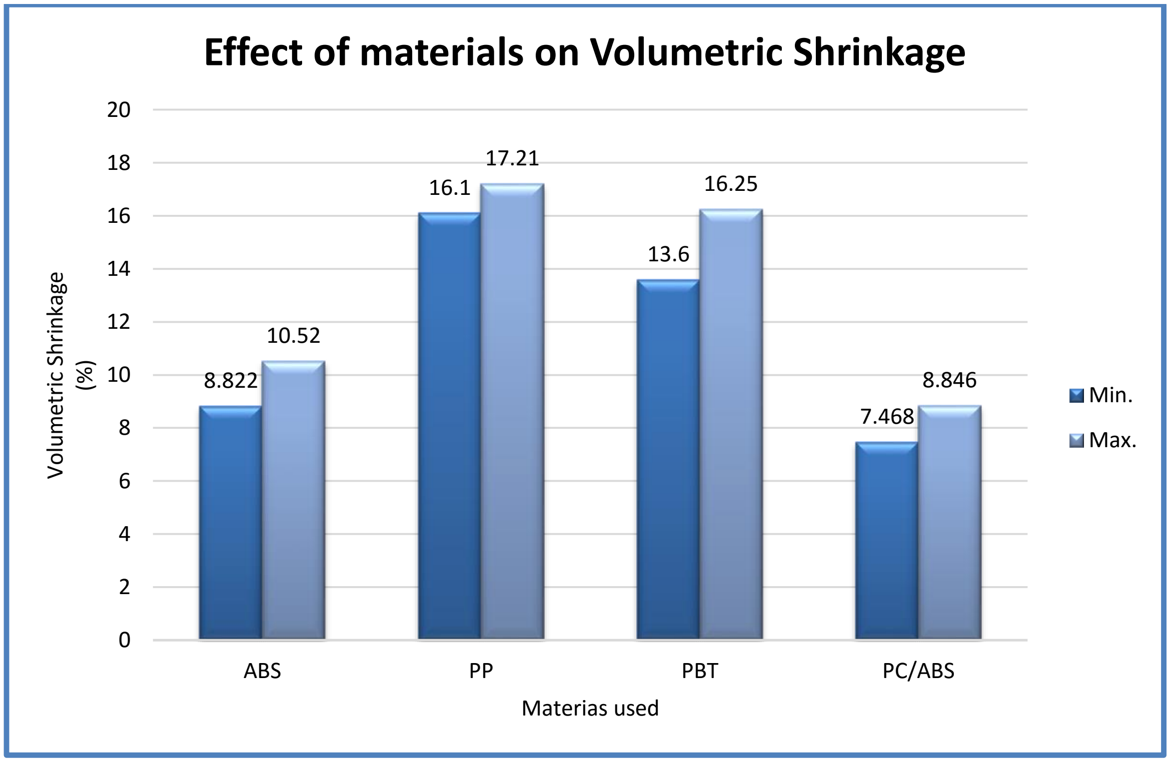
5 Discussions

5.1 Effect on shrinkage and Sink marks

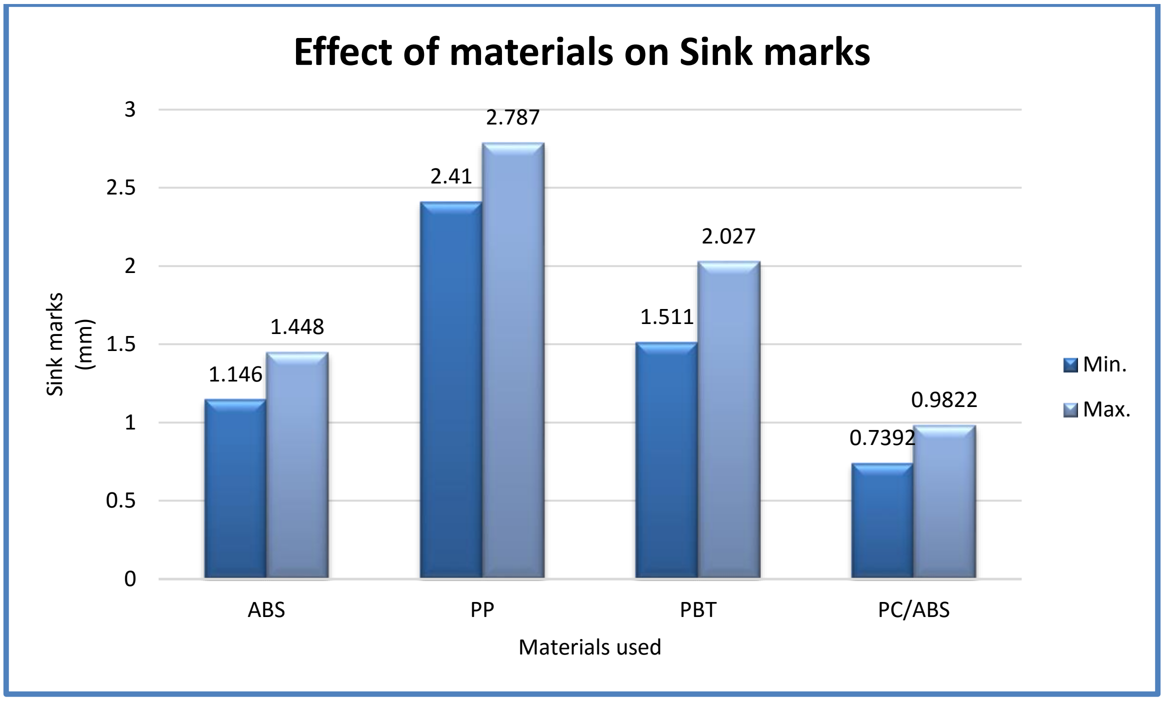
By seeing the results of signal-to-noise ratio and ANOVA analysis, it is clear that process parameters and materials have substantial effect on both shrinkage and sink marks.

5.1.1 Effect of materials

Every material exhibits different values of shrinkage and sink marks. It is clear from the Graph 5.1Graph 5.2 that polypropylene (PP) gives the highest shrinkage (17.21%) and sink marks (2.787mm) after injection molding (IM) process. Polybutylene Terephthalates (PBT) has slightly lower value of shrinkage (16.25%) and sink marks (2.027mm) than PP. But as compared to PP & PBT, acrylonitrile butadiene styrene (ABS) and ABS blend with polycarbonate (PC/ABS) exhibit much lower shrinkage (10.52% & 8.846%) and sink marks (1.448mm & 0.9822mm) respectively.



Graph 5.1: Effect of materials on volumetric shrinkage

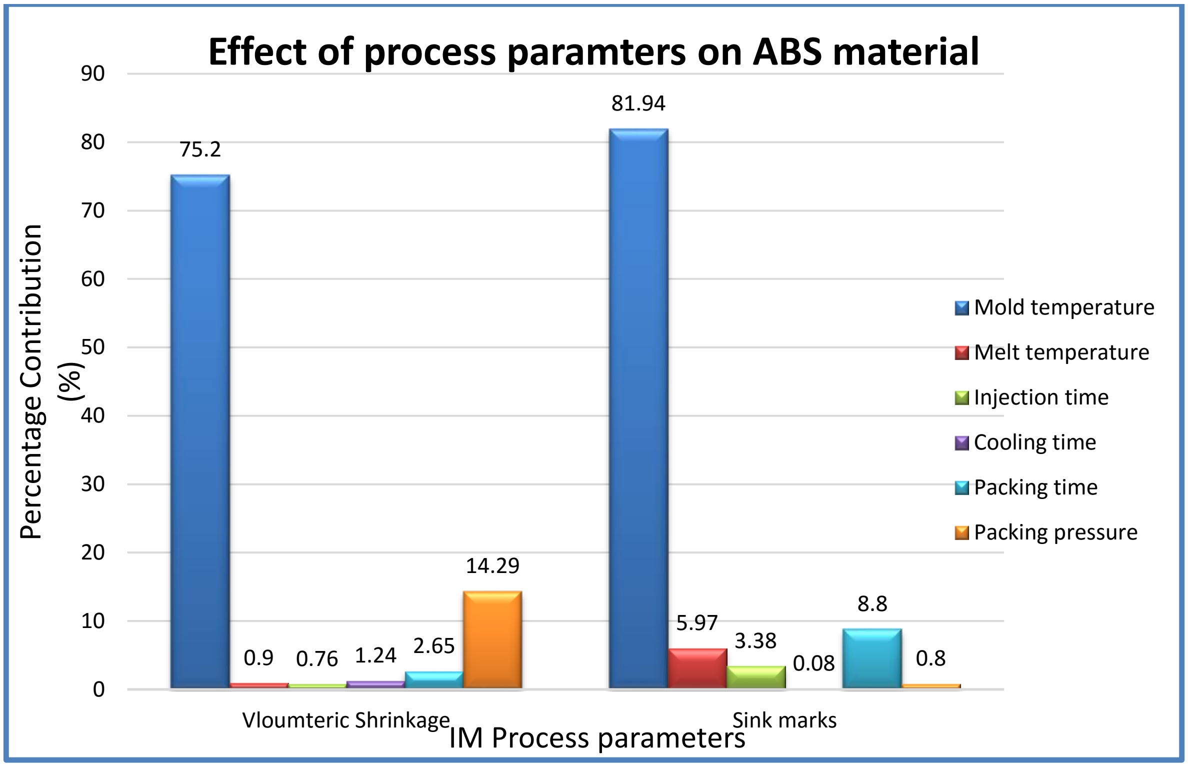


Graph 5.2: Effect of materials on sink marks

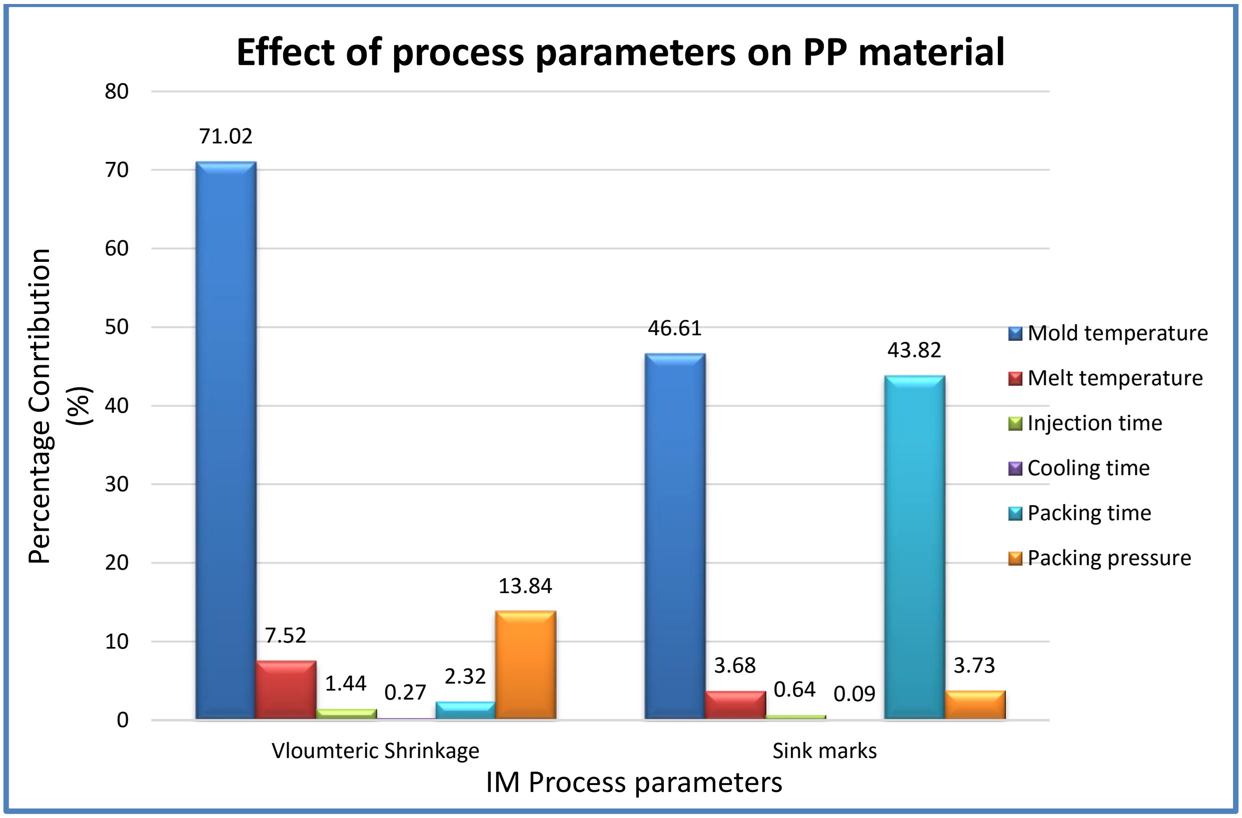
PP and PBT are semi-crystalline polymers while ABS and PC/ABS are amorphous in nature. As molecules in crystalline polymers are aligned so when these polymers cooled below their melting point, the molecules in crystalline part initiates to arrange themselves in orderly way. They exhibits less volume by contraction than if these were in amorphous phase. Amorphous polymers have same shrinkage in both flow direction as well as in transverse to flow direction, while in semi-crystalline materials shrinkage in both directions are different. That’s the reason crystalline polymers have higher shrinkage than amorphous polymers. Sink marks are the result of uneven shrinkages produced during injection molding process, hence it take the same effect of materials as shrinkage.

5.1.2 Effect of process parameters

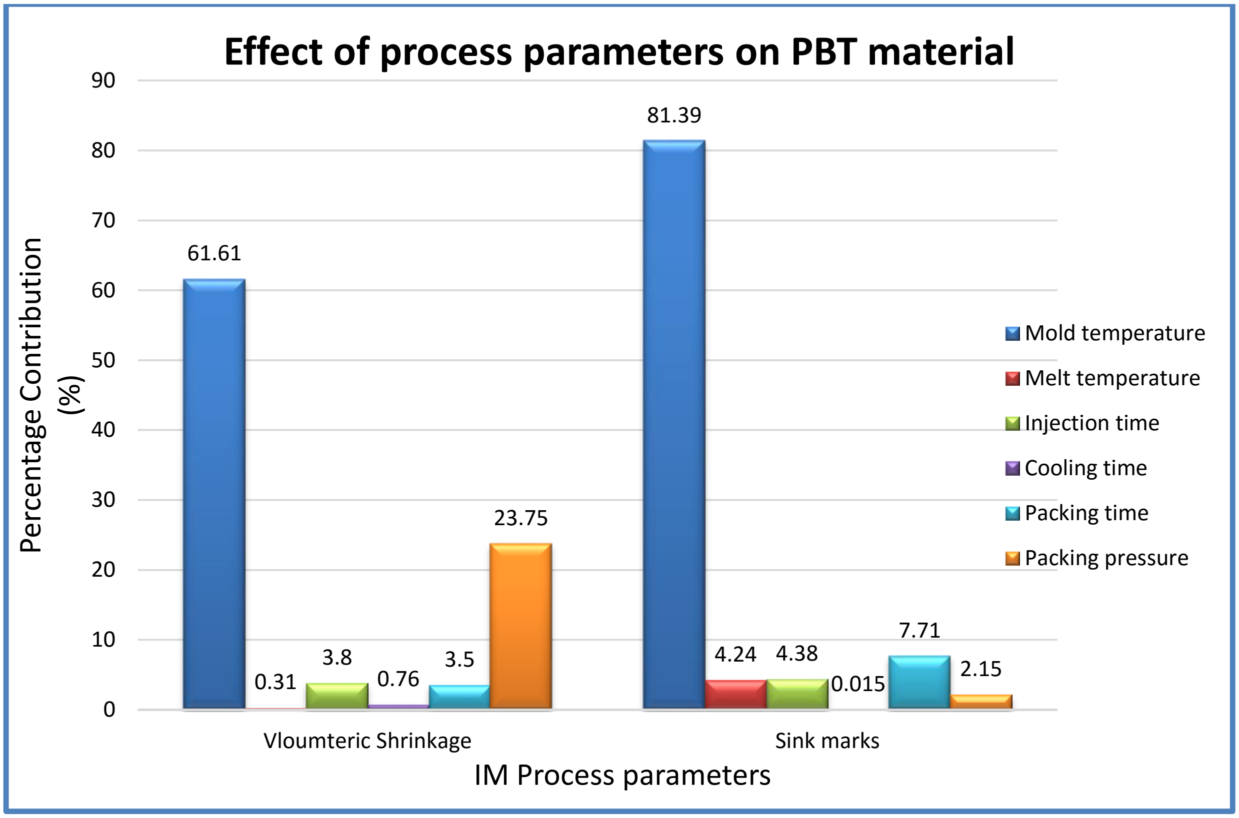
Every process parameter affects shrinkage of each material with almost same effect but with different percentage contributions. Study shows that melt temperature and subsequently packing pressure are the most important parameters affecting shrinkage in material. While, sink marks are significantly influenced by melt temperature and then packing time. Following are the graphical results shown in Graph 5.3Graph 5.6



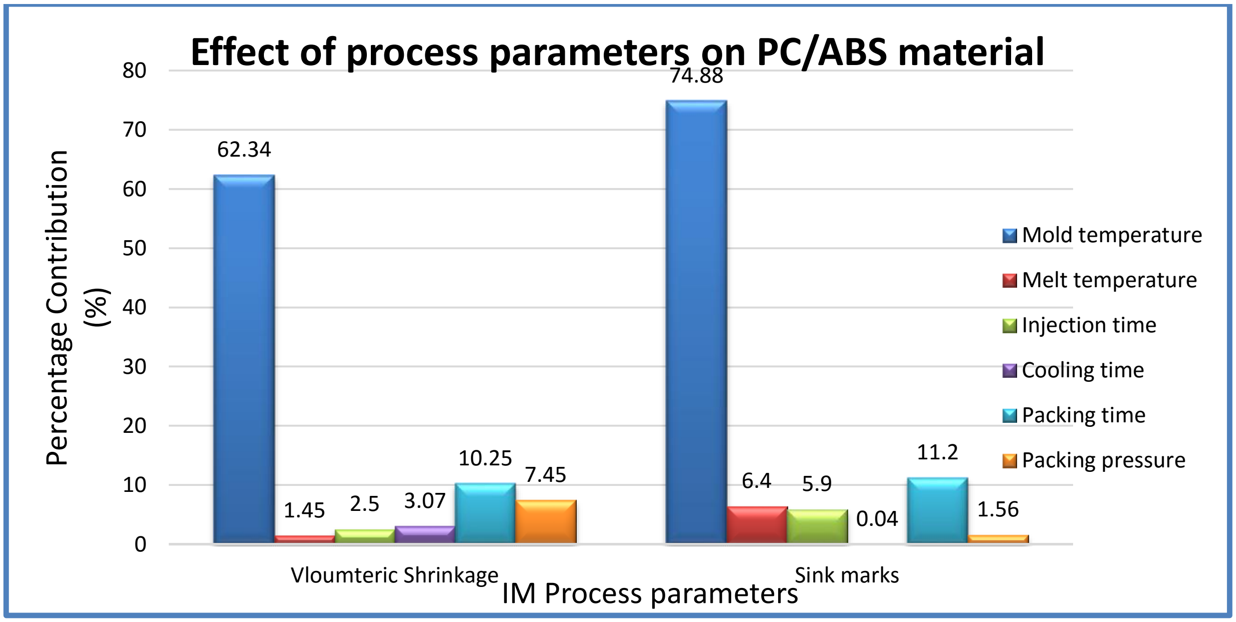
Graph 5.3: Effect of process parameters on ABS



Graph 5.4: Effect of process parameters on PP



Graph 5.5: Effect of process parameters on PBT



Graph 5.6: Effect of process parameters on PC/ABS

5.1.3 Effect of melt and mold temperature

Study shows that melt temperature has the direct relation to volumetric shrinkage and sink marks and is the most influential parameter in IM process which considerably increases both. (Fischer 2003) states that shrinkage will increase at both if the melt temperature is too much low or too much high. When melt temperature is high, packing time may end before the freezing of gate. Hence the central melt remains hot, increase the cooling time and cause shrinkage.

Mold temperature has also affected shrinkage and sink marks in this study with direct relation. As when the mold temperature is high, the part cools down slowly and the cycle time increases. This prolonged slow cooling produce more stress relaxation and shrinkages.

5.1.4 Effect of packing pressure

Packing pressure directly affects the volumetric shrinkage. In this study, packing pressure is the 2nd most influential parameter affecting shrinkage. When the pressure is high, it keeps a constant volume of material in the mold cavity. When this melt cools down, specific volume decreases and extra melt squeezed into the mold before gate freezing. This extra melt which enters just before gate freezing completely fill the mold and results in decreasing of overall shrinkage of the part. Though, excess packing pressure caused over packing which cause difficulty during ejection. This study shows opposite trend of packing pressure on sink marks in every material. By increasing the percentage of pressure at the end of fill somehow increase sink marks. This is due to over packing of the material, (Erzurumlu and Ozcelik 2006) also found in his study that PA66 exhibits more sink marks when the packing pressure exceeds too much.

5.1.5 Effect of packing time

Packing time is the 3rd influential process parameter which affects shrinkage and 2nd most significant parameter which affects sink marks. Though percentage contribution of packing time on shrinkage is not much as compared to melt temperature and packing pressure but by increasing it, shrinkage vastly decrease. If the packing time is small, there is a chance of melt leakage from cavity before solidification, which cause decrease in packing pressure and ultimately shrinkage increases.

Chapter: 06

6 Conclusion

This thesis studies the effect of different materials and process parameters on injection molding process to minimize the volumetric shrinkage and sink marks using a CAD model of wheel cover (used in automobiles) as a mold part. CAD model was designed on SolidWorks® plastics premium 2015 and process simulations were done through Autodesk Simulation Moldflow (ASM) Advisor® 2014. Four type of materials are used for the analysis, two are amorphous: Acrylonitrile butadiene styrene - Polycarbonate blend (ABS/PC) and Acrylonitrile butadiene styrene (ABS), other two are semi-crystalline: Polybutylene Terephthalates (PBT) and Polypropylene (PP). Six parameters (melt temperature, mold temperature, injection time, cooling time, packing time and packing pressure) were selected. An orthogonal array of L_{27} (3**6) was selected for the DOE. After "best gate location analysis", gate location is selected on ASM 2014. Every material showed different volumetric shrinkage and sink marks. PP has the highest volumetric shrinkage percentage and sink marks value while ABS/PC curve shows minimum values of both. S/N ratio and ANOVA analysis results show that melt temperature was the only parameters which enormously influenced both shrinkage and sink marks. Packing pressure and packing time were the next following most influential parameters. However packing pressure profile gives an irregular behavior and has opposite effect on both volumetric shrinkage and sink marks.

Each material had its own but almost same optimum process parameters. To select the best value of parameters for whole injection molding (IM) process, mean of every parameter's optimum value is selected. The optimum process parameters values selected to optimize the volumetric shrinkage and sink marks in IM process are A1B1C3D2E3F2 i.e. A(240°C), B(40°C), C(6s), D(10s), E(20s) and F(80% at the end of fill). To verify these, simulations of optimum process parameters A1B1C3D2E3F2 for every material is being done again and compared its results with the previous maximum values of shrinkage and sink marks for each material. It shows that in each material both volumetric shrinkage and sink marks were decreased.

Hence by considering the order of shrinkage and sink marks PP>PBT>ABS>ABS/PC and strength ABS>ABS/PC, hence it is clear that Acrylonitrile butadiene styrene is the best suitable material for the making of wheel covers through injection molding process using optimum process parameters of A1B1C3D2E3F2.

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