REVERSE ENGINEERING OF MOBILE PHONE CASING AND ANALYSIS OF WELD-LINE DEFECT

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Dedicated to my beloved parents

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ABSTRACT

In recent decades, reverse engineering (RE) has gradually become important when it comes to the situation that a component must be reproduced but its original engineering data are no longer or not accessible. Sophisticated technologies are introduced for the purpose of reverse engineering. The state-of-the-art technology in latest days is the use of 3D laser scanning with aid of reverse-engineering software to create the 3D geometry model of the existing component. The most appropriate way to duplicate the component is by plastic injection moulding. However, defect such as weld lines always occur during injection moulding process which makes the component aesthetically and structurally unacceptable. Therefore, injection moulding simulation on the component is necessary to investigate the variables that affect the formation of weld lines. Simulations are repetitively done to determine the most optimal variables that remove or reduce weld lines to minimum before the component is ready for reproduction.

ABSTRAK

‘Reverse engineering’ (R.E) kian memainkan peranan penting dalam zaman sekarang kerana selalu berlakunya bahawa sesuatu produk yang telah wujud perlu dihasilkan semula, tetapi tanpa data asal rekabentuknya. Beberapa teknologi yang canggih telah diperkenalkan untuk tujuan RE. Salah satu teknologi yang terkini ialah cara ‘3D laser scanning’ yang digunakan untuk menghasilkan model geometri 3D produk yang bakal dihasilkan semula. Model geometri 3D amat penting untuk tujuan simulasi pengacuan suntikan. Melalui simulasi tersebut, kecacatan yang terhasil seperti ‘weld lines’ dapat diperlihatkan. Kewujudan ‘weld lines’ sedemikian bukan sahaja menjadikan permukaan produk menjadi kurang menarik, tetapi juga menyebabkan ketahanan dan kelasakan pada bahagian ‘weld lines’. Maka, simulasi pengacuan suntikan adalah sangat penting untuk menentukan factor-faktor yang mengakibatkan pembentukan kecacatan tersebut. Simulasi dijalankan berulang-ulang kali sehingga pembentukan ‘weld lines’ telah dihilangkan atau dikurangkan kepada jumlah yang paling minimum.

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LIST OF SYMBOLS

D	Diameter of runner
Ø	Diameter of runner
W	Weight of mobile phone casing
L	Length of runner
°C	Degree Celsius (Temperature)
MPa	Mega Pascal (Pressure)
g	Gram (Mass)

LIST OF ABBREVIATIONS

ABS	Acrylonitrile butadiene styrene
AMA 2010	Autodesk® Moldflow® Adviser 2010
CAD	Computer-aided design
CAM	Computer-aided Manufacturing
CCD	Charge coupled device
CMM	Coordinate measurement machine
LED	Light-emitting diode
RE	Reverse engineering
NC	Numerical control
3D	Three dimensional
USSR	Union of Soviet Socialist Republics

CHAPTER 1

INTRODUCTION

1.1 Introduction

Engineering is the process of designing, manufacturing, assembling, and maintaining products or systems. However, there are two types of engineering, forward engineering and reverse engineering. Reverse engineering differs from forward engineering in such a way that the basic concept of duplicating an existing part based on an original or physical model without the use of an engineering drawings or documentations. Thus, reverse engineering can be known as re-engineering an existing product as well. In such an intensely competitive global market nowadays, product enterprises are constantly seeking novel ways to shorten lead times for new product developments that cater for all consumer expectations. Generally, product enterprise has invested tremendously in computer-aided design and manufacturing (CADCAM) and a wide range of new technologies that provide business benefits. Reverse engineering (RE) is now considered as one of the state-of-the-art technologies that is advantageous in significantly shortening the product development cycle. (Raja et al., 2008).

Reverse engineering of mobile phone casing involves disassembly of an existing mobile phone casing to figure out how it was built and how does it work. The mobile phone casing is undergoing a physical-to-digital process, in which its geometry computer-aided design (CAD) model (digital) is created by scanning the existing object (Lai et al., 1998). Three-dimensional scanners are employed to scan the part geometry capturing information that describes all geometric features such as steps, slots, pockets and holes. The fabricate of the mobile phone casing, injection moulding is the most ideal way as it is a versatile process capable of producing complex shapes with good dimensional accuracy. During the injection moulding, structural defects such as weld lines can occur. These defects can develop in manufacturing processes depending on factors such as materials, part design, and processing techniques. These factors are crucial considerations to be taken in terms of defect elimination.

In recent decades, much progress has been made in the analysis of material flow in injection moulding, Modelling techniques and simulation software has been developed for studying optimum gating systems, mould filling, mould cooling, and part distortion. Software programs expedite the design process for moulding parts with good dimensions and characteristics. The programs take into account such significant factors as injection pressure and temperature (Schmid et al., 2006). The reverse engineering of mobile phone casing project is completed with the simulation of a defect-free injection moulding process.

1.2 Problem Statement

Reverse engineering has been rather common and essential especially when it comes to a situation that the original product design documentation has been obsolete or never existed, some bad features of a product need to be eliminated, analysing the good and bad features of competitors' products, exploring new avenues to improve product performance and features and so forth (Raja et al., 2008). Defect such as weld lines always occur during injection moulding which affect the appearance also has adverse effects on the structural integrity of the products. Thus, this defect has to be removed.

1.3 Objectives

The objectives of "Reverse Engineering of Mobile Phone Casing and Analysis of weld Line Defect" project are to:

i) Create a CAD model of mobile phone casing by using reverse-engineering hardware and software

ii) Investigate weld lines based on injection moulding simulation

1.4 Scope of Study

The scope of study for this project includes the disassembly of a mobile phone casing and creation of its geometry CAD model by employing 3D laser scanner with the aid of *PolyWorks* software which reconstructs the scanned data into a 3D geometry CAD model. The CAD model is imported into *Autodesk*® *Moldflow*® *Adviser 2010* software to simulate the material flowing process and to test the manufacturability of the object. Factors of causing weld-line defect are analysed to find out ways such as necessary alterations on the parameter settings in order to remove the weld-line defects.

CHAPTER 2

LITERATURE REVIEW

2.1 Reverse Engineering

2.1.1 Introduction

In common usage in industry, RE often involves taking something apart and analyzing its workings in detail, usually with the intention to construct a new device or program that does the same thing without actually copying anything from the original. But it is important to realise that it is possible to reverse engineer almost any system, even living systems or self-organizing systems that were not “engineered” in the first place, such as a mechanical device, an electronic component, a software program, a living cell or organism, or even a geologic structure. In this sense, reverse engineering is essentially science, using the scientific method as well as measurement, analysis and other tools to gain an understanding of the inner workings and overall function of a system or structure. Thus, sciences such as biology and physics can be seen as reverse engineering of living biological systems' and the physical world respectively (Vinesh et al., 2008).

In the United States and many other countries, even if an artifact or process is protected by trade secrets, reverse-engineering the artifact or process is often perfectly legal as long as it is obtained legitimately. Patents, on the other hand, require a public disclosure of an invention, and therefore patented items don't necessarily have to be reverse engineered to be studied. One common motivation of reverse engineers is to determine whether a competitor's product contains patent infringements or copyright infringements.

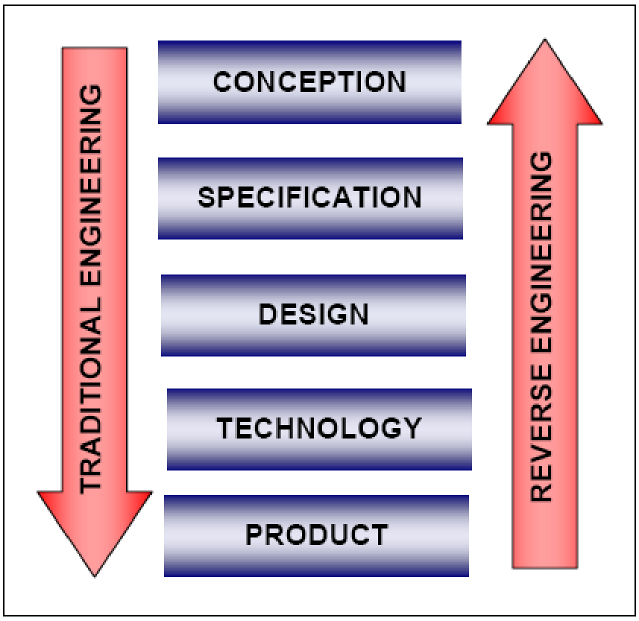


Figure 2.1: Difference between reverse engineering and traditional engineering

Source: Vinesh et al. (2008)

2.1.2 Applications of Reverse Engineering

Reverse engineering can be used in various kinds of fields range from automotive to architecture and medical to software applications. Below are some examples of applications of reverse engineering in different kinds of fields.

In military field, reverse engineering is often used in order to copy technology devices or parts of other nations, which, have been obtained by regular troops in the fields or by intelligence operations. It had been widely used during the Second World War and the Cold War. One of the well-known examples from World War II was "Tupolev Tu-4". A number of American B-29 bombers on missions over Japan were forced to land in the Union of Soviet Socialist Republics (USSR). The Soviets who did not have a similar strategic bomber decided to duplicate the B-29 Superfortress. Within a few years they had developed the Tu-4, a nearly identical duplication. Figure 2.2 and Figure 2.3 show the original U.S. B-29 Superfortress and its reverse-engineered copy, Tupolev-Tu-4 by the Soviet Union.

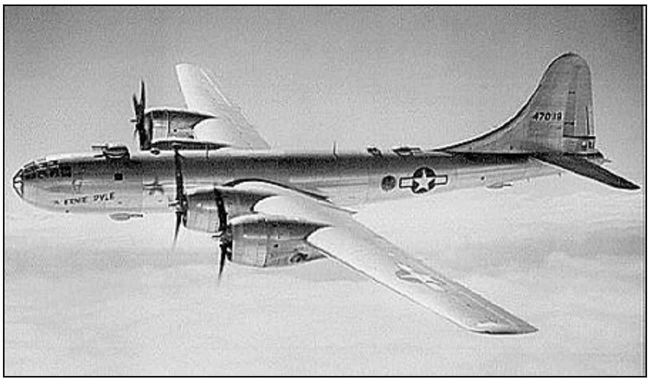


Figure 2.2: Four-engine propeller-driven heavy bomber “The Boeing B-29 Superfortress” flown by the United States Military in World War II

Source: http://www.britannica.com (20 February 2009)

Figure 2.3: Reverse-engineered copy of U.S.-made “The Boeing B-29 Superfortress” by the Soviet Union

Source: http://www.britannica.com (20 February 2009)

In mechanical field, reverse engineering recreates drawings for old parts. For instance, a blade on the impeller of an air compressor breaks off after years of service. But the compressor manufacturer asked for eight months to make a new one. Plant engineers decide to reverse-engineer a new one from the original existing model. The new impeller is milled from an aluminum blank with the toughness and corrosion resistance at least equal to the original. The entire process only consumes three weeks.

In medical field, reverse engineering has been employed in generating data to create dental or surgical prosthetics (artificial body parts which replace missing part), tissue engineered body parts, or for surgical planning. A virtually perfectly custom-fit prosthetic can be duplicated to replace the missing part such as knee joint, femur bones and teeth lost by injury (traumatic) or missing from birth (congenital) or to supplement defective body parts. Figure 2.4 shows how reverse engineering is applied in medical field to produce a prosthetic finger.

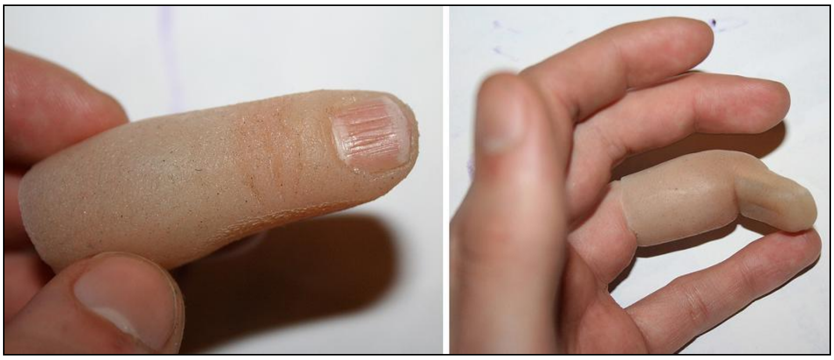


Figure 2.4: Prosthetic finger duplicated by reverse engineering

Source: http://www.prostheticinnovations.com (12 March 2009)

2.1.3 Importance of Reverse Engineering

There are many reasons that reverse engineering has been widely used in numerous applications. When the original manufacturer of a product no longer exists, but a customer needs the product, for instance, aircraft space required typically after an aircraft has been in service for several years. Thus, reverse engineering play a crucial role to create data which has been lost, obsolete or never existed to refurbish or manufacture the desired product. Furthermore, reverse engineering helps in strengthening the good features of a product based on long-term usage by exploring new avenues to enhance product performance and eliminating some bad features of a product. However, there are many more reasons for using reverse engineering than mentioned above (Vinesh et al., 2008).

2.2 Reverse Engineering – The Generic Process

Typically, there are four steps in the reverse engineering process to create a CAD model from an existing real-world object as shown in Figure 2.5.

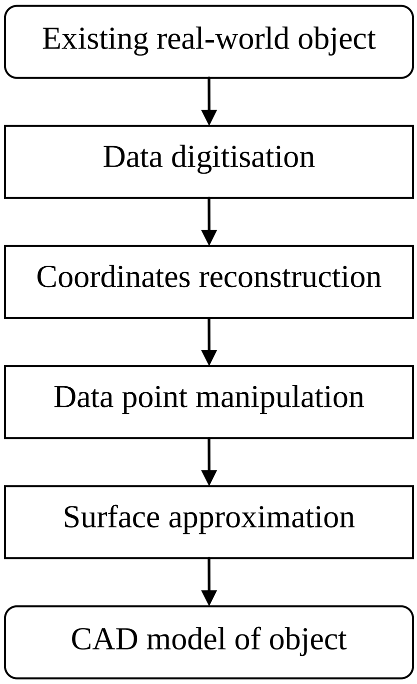


Figure 2.5: Block diagram of reverse-engineering generic process based on the scanning strategy.

Source: Milroy et al. (1996)

2.2.1 Data Digitisation

This phase is involved with the scanning strategy – selecting the correct scanning technique, preparing the part to be scanned, and performing the actual scanning to capture information that describes all geometric features of the part such as steps, slots, pockets, and holes (Raja et al., 2008). Three-dimensional scanners are employed to scan the part geometry, producing clouds of points, which define the surface geometry. There are two distinct types of scanners, contact and non-contact.

The typical 3D CMM is a contact type. In the 3D CMM, the probe slightly touches the surface of the measured part during the scanning process. The 3D profile data in X-, Y-, and Z-directions of the parts are captured as long as the contact pressure is high enough to trigger the sensor to capture signals. Via the computing process, the 3D digitized data of the parts are then recorded for later. This is also known as a “point-to-point" 3D CMM system. The 3D CMM system is able to provide accurate measurements, but is time consuming and labor intensive (Yao, 2005).

Conversely, a non-contact 3D CMM captures 3D data of parts by band scanning of laser or LED photo sources and CCD camera. The most commonly used computing principle is the triangle measuring method. It has a fast scanning speed and is suitable for fragile parts (Yao, 2005). Figure 2.6 shows a contact scanner and a non-contact scanner.

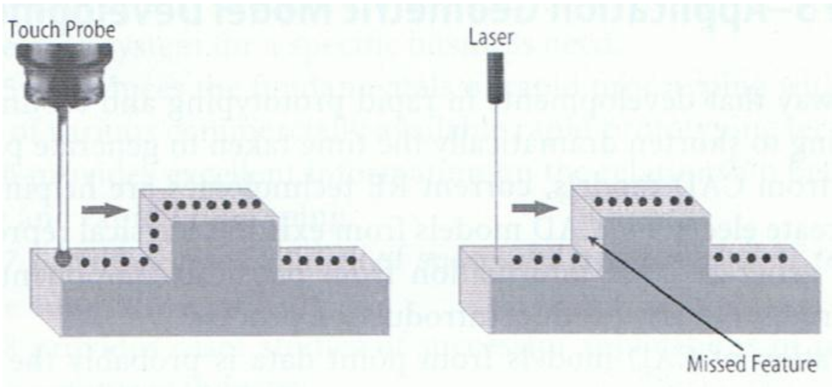


Figure 2.6: Contact scanner with touch probe and non-contact scanner with laser beam

Source: Ryal et al. (2001)

2.2.2 Coordinate Reconstruction

After the data parts have been digitized, these parts are processed into a model rebuild process. The first step is the reconstruction of the coordinates. Generally, the component needs to scan several regions in the scanning process. For each scan, each data file has its own coordinate system. During the stitching process, two files of data have to compute and transfer, to synthesize into a single coordinate system. The process of coordinate reconstruction is also a time consuming task, when doing data transformations by computer (Yao, 2005).

2.2.3 Data Point Manipulation

The pre-processing of measured data should include data point manipulation and characteristic line definition. Data point manipulation contains data point sorting, rearrangement, segmentation, reduction, smoothing, and exaction. This process can eliminate the noise of data measuring (Yao, 2005).

2.2.4 Surface Approximation

Once the noise of digitized data has been removed, the next step is to derive the surface approximation. The surface approximation uses the digitized data as inputs, to derive the surface model using the reverse engineering software such as *PolyWorks*. Once the surfaces have been formed, they are processed into solid models, which are needed to export the NC (numerical control) file or the STL file for RP (Yao, 2005). Figure 2.7 shows the CAD model generated by 3D scanning strategy.

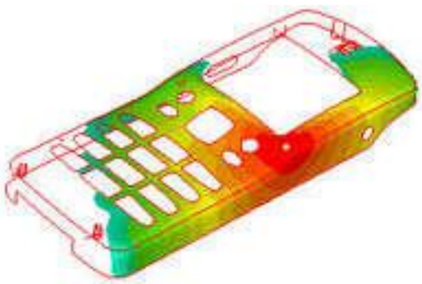


Figure 2.7: CAD model of a mobile phone casing generated by 3D scanning strategy

Source: Herbert (2002)

2.3 Injection Moulding

Injection moulding is a cyclic process of forming plastic into a desired shape by forcing material under pressure into a cavity. It is one of the most common and versatile operations for mass production of complex plastics parts with excellent dimensional tolerance (Shelesh et al., 1997). It requires minimal or no finishing or assembly operations. By weight, approximately 32% of all plastics processed go through injection-moulding machines. An injection-moulding machine consists essentially of four distinct elements as shown in Figure 2.8, which are injection system, hydraulic system, mould system, clamping system and control system (Schmid, 2006). The invention of various new alternative processes, such as the reciprocating screw machine, and the application of computer simulation to the design and manufacture of plastics parts are the major milestones of injection moulding. There are several kinds of injection-moulding machines, however, the invention of reciprocating screw machine has revolutionised the versatility and productivity of the thermoplastic injection-moulding process.

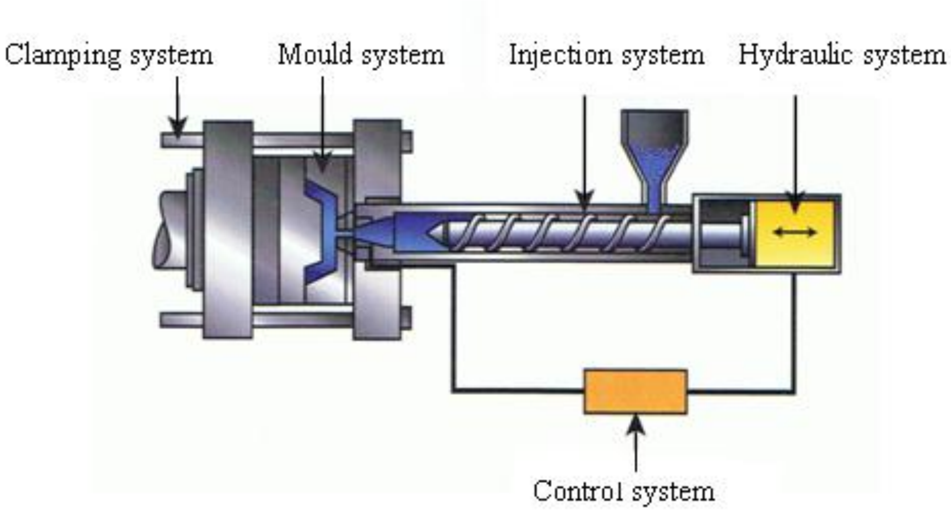


Figure 2.8: The reciprocating-screw injection-moulding machine

Source: Jay (2006)

2.3.1 Processing Conditions

The quality of the moulded part is greatly influenced by the conditions under which it is processed. Therefore, an ideal conditions setting is very important before an injection-moulding process is run. Factors which affect the injection moulding are as follows:

2.3.1.1 Melt Temperature

If the melt temperature is too low, the resin (binder) might not be completely melted or it might be too sticky to flow. However, if the melt temperature is too high, the resin could degrade. Hence, an optimum melt temperature is crucial for a smooth flow of molten material. Suggested melt temperatures for specific materials are available from the resin suppliers (Malguarnera et al., 1981)

2.3.1.2 Injection Pressure

The injection pressure is the pressure of the melt in front of the screw. The injection pressure should be as low as possible to reduce part internal stress. On the machine, set the injection pressure to nearly the machine maximum to completely exploit the injection velocity of the machine, so that the pressure setting valve does not limit the velocity. Because the switch-over to packing pressure occurs before the mould is completely filled, no damage will be done to the mould (Malguarnera et al., 1981). Based on the statement above, the hot plastic is pushed by the injection pressure and flows between the relatively cold walls of the cavity and the core to fill the cavity space. Generally, the filling speed is proportional to the injection speed. Injection pressure is important to ensure the cavity is filled before the plastic freezes in the narrow passages between the cooled mould walls.

2.3.1.3 Injection Speed

With the highest possible injection speed within shear rate limits can reduce flow resistance, and allow longer flow length as well as improved strength in weld lines (Malguarnera et al., 1981). However, slower injection at the beginning of the injection may be necessary to avoid turbulent flow and jetting, as the material passes through the restrictive areas (e.g. gates). A reduced speed is necessary as well in the end of the injection to avoid flashing at the end of stroke, and to enhance the formation of homogenous weld lines after a divided flow.

2.3.1.4 Packing Time

The ideal packing time setting is the gate freezing (sealing) time or the part freezing time, whichever is shorter. The gate and part freezing times can be calculated or estimated. The calculated values of the packing time are based on packing analysis results when the frozen layer fraction is 1.0 for the gate. Without packing analysis results, the packing time is estimated to be 10 times the filling time (Alfredo, 2006).

Based on the statement above, packing time is also known as post-filling time. After the mould is filled with polymer melt, the injection machine maintains a high melt pressure to force additional polymer melt into the mould cavity to compensate for the volumetric shrinkage as the melt in the cavity cools.

2.3.1.5 Cooling Time

Cooling time can be calculated or estimated. The cooling time is after packing time. During cooling the part continues to solidify so it can be ejected, and material for the next shot is prepared. The calculated value of cooling time is from a cooling or packing analysis. Without simulation results, the cooling time can be 10 times the filling time. For instance, if the predicted filling time is 0.85 seconds, the initial cooling time would be 8.5 seconds (Alfredo, 2006). The combination of packing time (if estimated would be 8.5 seconds) and the cooling time should be a high estimate to ensure the part and runner system will be sufficiently solid for ejection.

2.4 Product Design

Producing quality thermoplastic parts requires converting the functional requirement of the application into a design. The product design's geometrical configurations should not only satisfy functionally, but it has also has to meet the condition required by mould design and construction and operation of the mould in order to produce quality parts and guarantee efficient moulding process (Jay, 2006).

2.4.1 Uniform Wall Thickness

Abrupt changes in the wall thickness make it difficult to maintain a uniform temperature throughout the mould cavities during the moulding cycle. After the thermoplastic melt has been injected, variations in part wall thickness do not allow the walls to cool at consistent rates. Thick walls will shrink more than thin walls, causing part warpage (bending or twisting), voids on thicker wall cross sections, poor dimensional control, long cycle times, poor surface finish, and structural defects (Herbert, 2002). Plastics are poor heat conductors. A thicker plastic will take a longer time for the heat to travel from the hot plastic to the cold cavity walls. Briefly, thicker walls require longer cooling time.

2.4.2 Balance Geometrical Configuration

The positioning of the cavity should be balanced on both sides of the mould parting line. Both halves of the cavity should be subjected to the same volume of polymer melt for uniform cooling in the mould cavity (Herbert, 2002). If one side of the cavity is injected with more melt than the other side, this side will become hotter. The hotter side of the cavity will have the tendency to stick on the deep hot spots, causing warpage, poor surface finish of the moulded part, and long cycle times.

2.4.3 Smooth Internal Sharp Corners

Sharp corners create high stress concentrations on the thermoplastic part. They are also stress concentrators within the mould cavity. These sharp corner areas fail under high loads. Internal radii of at least 0.031 inch should replace sharp corners in thermoplastic part design wherever possible (Alfredo, 2006). If a sharp corner is unavoidable, reduce the radii and polish this surface area. In addition, these mould cavity areas should be designed with removable inserts to facilitate ease of repair.

2.4.4 Draft Walls

Thermoplastic parts should be designed with positive draft walls. Minimum positive draft is required on all walls in the direction of mould opening or core pulling. Without draft, thermoplastic moulded parts adhere to the mould cavity surface, causing drag marks and surface finishing defects. In many cases, the part will not be fully ejected so that the mould may close on it and cause damage. Lack of positive draft also increases cycle time and moulding costs (Alfredo, 2006).

2.4.5 Feather Edges

Avoid the use of feather-shaped edges that require thin and fragile steel. Within the mould cavity, feather edges tend to break and chip, resulting in mould maintenance and downtime. Undetected broken and chipped feather edges will cause flashing problems as the thermoplastic melt fills into the mould vents. Feather edges become extremely hot and take longer to cool because cooling water channels cannot be brought to the feather edge, thus increasing cycle time (Schmid, 2006).

2.4.6 Proportional Boss Geometries

Avoid the use of narrow cores. The height of the unsupported core should not exceed four times the core base thickness. During the moulding process, the injection pressure will deflect long narrow cores, because they act as cantilever beams, causing parting line openings and possible early failure of the mould core insert. In critical cases, a structural analysis of the mould can be made based on expected forces and allowable deflection. Cores of greater height must be fully supported using core inserts to decrease the chance of failure and to ease repair (Herbert, 2002).

2.4.7 Gate Type and Location

The location of gate determines the mould shrinkage, the melt flow, part dimension, warpage, and weld line strength. The gate functions as a thermo-valve between the runner and the cavity. The temperature is increased around the gate area by melt injection speed, pressure, and temperature. The hot gate allows the melt to enter the cavity without shearing off the polymer. The gate cools off when the melt stops moving, closing the gate while the melt inside the cavity cools off under packing pressure (Schmid, 2006).

2.4.8 Runner Sizing

The size and dimension of runners can affect the filling time of the melt and hence the formation of weld lines. Runner size can be determined or estimated by using the formula as stated in Eq (2.1) below (Alfredo, 2006).

$$D = \frac{W^{\frac{1}{2}} L^{\frac{1}{4}}}{3.7} \tag{2.1}$$

Where,

D = Diameter of runner

W = Weight of mobile phone casing

L = Length of designed runner

2.5 Simulation of Injection Moulding

Advanced manufacturing, now relies heavily on the use of simulation codes to optimise part and mould design. Flow simulation software allows a component manufacturer to predict and eliminate potential manufacturing problems as well as optimize part design, mould design, and the injection moulding process (Jay, 2006). The use of these cost effective technologies is becoming popular as it allows a product manufacturer to remain competitive in the global market. To avoid the high costs and time delays associated with problems discovered in the manufacturing environment, it is necessary to consider the combined effects of part geometry, material selection, mould design, and processing conditions on the manufacturability of a part. Using predictive analysis tools to simulate the moulding process, companies can optimize these variables in the part and mould design phases of a project, where the cost of change is minimal and the impact of change is greatest.

2.5.1 Finite Elements Used by Simulation Software

In order to run a simulation analysis, the part must have an appropriate finite element mesh created on it. Often, the finite element mesh is referred to simply as a *mesh*. Elements divide the geometry (domain) of the part or other tool component into a number of small domains. These small domains or elements are defined by nodes (coordinates in space) and are used for the calculations inside simulation. There are three main categories namely beam, triangle and tetrahedron as shown in Figure 2.9.

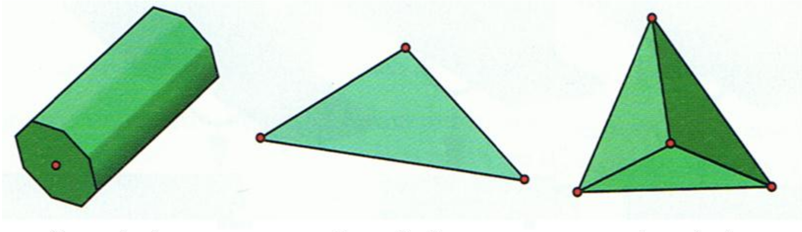


Figure 2.9: Element types

Source: Jay (2006)

Simulation software uses three mesh types for analysis which are Midplane, Fusion and 3-D. The mesh types use a combination of the element types of 2-noded beam element, 3-noded triangular element and 4-noded tetrahedral element (Jay, 2006).

2.5.2 Mesh Requirements and Weld-Line Prediction

The mesh density is an important consideration in addition to properly representing the geometry of the part. Generally, it is easy to achieve a mesh density that can provide good pressure predictions. It does not take a fine mesh to accurately predict pressures. Filling effects, however, can only be accurately predicted if the mesh is detailed enough to capture relevant details of the model. One of the important considerations is weld lines which represent common mesh density-related problems (Jay, 2006). If the mesh is not fine enough, the analysis will not pick up the problems as weld-line prediction is extremely sensitive to mesh density issues. Therefore, when weld-line information is required, a fine mesh is essential because a coarse mesh does not always indicate the presence of weld lines.

2.6 Weld lines

Various defects can develop in manufacturing processes depending on the factors such as materials, part design, and processing techniques. While some defects affect only the appearance of the parts made, others can have major adverse effects on the structural integrity of the parts. One of the examples of defect is weld line (also known as weld mark or a knit line). A weld line is formed when separate melt fronts travelling in opposite direction meet as the mould cavity is filled (Jay, 2006) as shown in Figure 2.10.

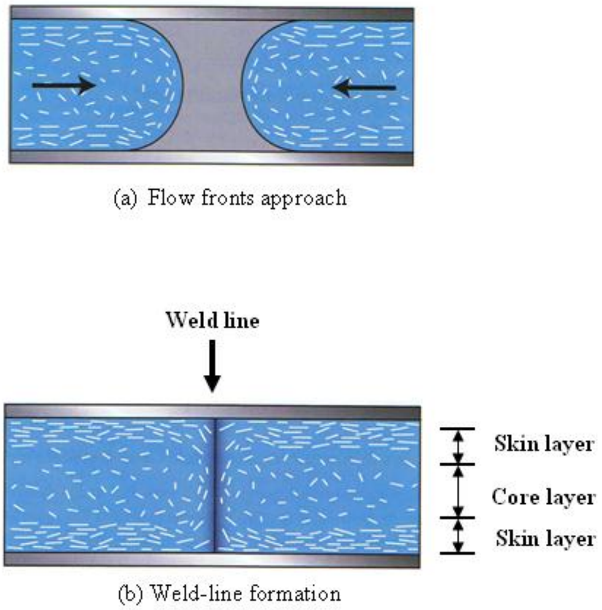


Figure 2.10: Formation of weld lines when two melt fronts meet

Source: Alfredo (2006)

Weld lines are generally undesirable when part strength and surface appearance are major concerns. It creates an unsightly line or even voids on the surface of the product (Schmid, 2006). Weld lines create a weakness and change material strength characteristics where cold melt fronts reunite. The extent of the property change depends on the ability of the two melt fronts to knit together homogeneously. The following conditions affect weld line integrity: base resin type, part thickness, mould design, resin impact modifiers, resin mould released additives, reinforcements, moulding process conditions (such as temperature and viscosity of the molten thermoplastic when they come together), and lubricants sprayed on the mould cavity surfaces. Different resins will exhibit different characteristics of tensile strength retention at the weld line (Fellahi et al., 1995).

Strong weld lines are critical, because the properties in the weld line region decline significantly compared to those in the rest of the part. These lines become likely points of part failure. Weld lines can also cause irregularities in the surface appearance of the moulded part, making it more prone to wear. Therefore, weld lines should be located in less critical areas if possible. Weld lines can be reduced or removed by altering the following variables as follows (Malloy, 2004):

i) Alter gate positions.
ii) Reduce the number of gates
iii) Change the part thickness
iv) Increase the melt temperature, injection speed, or packing pressure. This will allow the flow fronts to weld to each other better.
v) Increase the diameters of gates and runners, to make it easier to pack the part.
vi) Move injection locations to make weld lines form closer to the gates, so the weld line is created with a higher flow front temperature and is packed with more pressure.
vii) Move injection locations to make flow front meet more obliquely, turning the weld line into a meld line.
viii) Optimize runner system design.
ix) Reduce runner dimensions and maintain the same flow rate to use shear heating to increase the melt temperature at the flow front.

CHAPTER 3

METHODOLOGY

3.1 Introduction

Methodology can properly refer to the theoretical analysis of the methods appropriate to conduct a project or study which is of utmost importance to ensure a smooth development of the study.

In this project, an existing model of mobile phone casing is disassembled and being scanned by a 3-D laser scanner for data acquisition. The data collected are processed by *Polywork* software for mesh reconstruction to create a geometry CAD (*AMA 2010*) model. The CAD model is being imported into *Autodesk*® *Moldflow*® *Adviser 2010* software to simulate an injection moulding process. This simulation helps in detecting injection-moulding defects. Factors of causing weld-line defect are exclusively analysed for the purpose of eliminating weld lines. Figure 3.1 illustrates the flow chart of project.

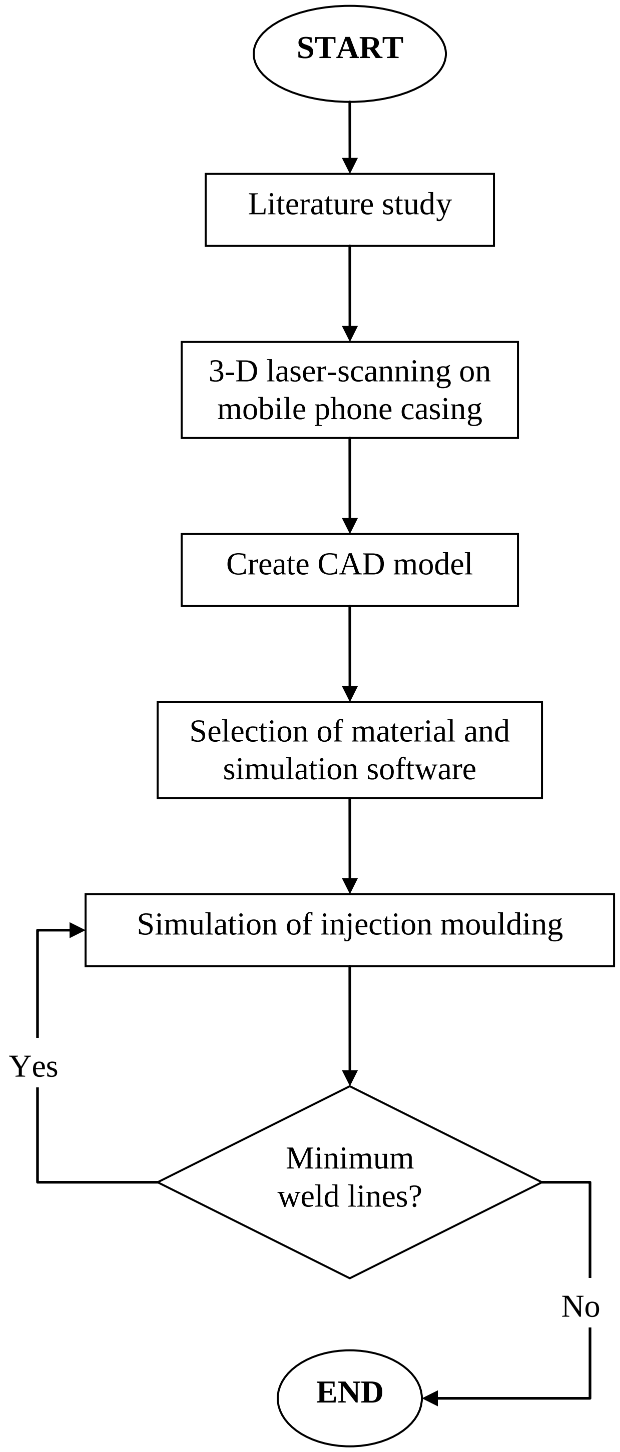


Figure 3.1: Flow chart of methodology

3.2 Three-Dimensional Laser Scanning

The product to be reverse-engineered is the upper mobile phone casing of model Nokia 9500 as shown in Figure 3.2. Before scanning, the mobile phone casing must firstly be disassembled to identify its components. 3-D laser scanner as shown in Figure 3.3 performs a non-contact scanning to capture point data that describes all geometric features of the part such as steps, slots, pockets and holes (Raja et al., 2008).

(a) (b) (c)

Figure 3.2: Top view (b) and bottom view (c) of upper part of mobile phone casing of Nokia 9500 (a) selected for reverse-engineering

Source: http://www.nokia.com (18 April 2009)

Figure 3.3: Three-dimensional laser scanner

Source: http://www.scantech.dk (18 April 2009)

3.3 3-D Geometry CAD Model

RE software (*Polyworks*) is employed to transform the RE data produced by RE hardware (3-D laser scanner) into 3-D geometric models. The point data collected from 3-D laser scanning are being processed by *PolyWorks* software to produce a clean, merged, point cloud data set in the most convenient format. The final outputs of the RE data process are usually reconstructed mesh model in the STL format which is commonly used for simulation purpose or CAD applications (Raja et al., 2008).

3.4 Selection of Material

Toyolac 100 Acrylonitrile Butadiene Styrene (ABS) manufactured by Toray Industry Incorporated is chosen as the plastic material of injection moulding for duplicating the mobile phone casing. It is a copolymer made by polymerizing styrene and acrylonitrile in the presence of polybutadiene. Acrylonitrile butadiene styrene (ABS) (chemical formula $(C_8H_8\cdot C_4H_6\cdot C_3H_3N)_n$) is a common thermoplastic used to make light, rigid, molded products such as piping (for example Plastic Pressure Pipe Systems), musical instruments (most notably recorders and plastic clarinets), golf club heads (used for its good shock absorbance), automotive body parts, wheel covers, enclosures, protective head gear and toys (Schmid et al., 2006). The most important mechanical properties of ABS are impact resistance and toughness. A variety of modifications can be made to improve impact resistance, toughness, and heat resistance. Generally ABS would have useful characteristics within a temperature range from -40 to 100 °C.

3.5 Selection of Simulation Software

Autodesk® Moldflow® Adviser 2010 (AMA 2010) software represents the most comprehensive suite of definitive tools for simulating, analyzing, optimizing, and validating plastics part and mould designs. *AMA 2010* reinforces once again its lead in 3D simulation innovation with more efficient meshing tools for faster and more accurate analysis results as well as numerous enhancements to the 3-D simulation capabilities. *AMA 2010* provides the tools to quickly optimize part designs and check the impact of critical design decisions on the manufacturability and quality of the product early in the design process (Jay, 2006). *AMA 2010* software is selected for the simulation of this project as it saves the need to:

i) Compromise the esthetics of your design concept for manufacturability
ii) Go through a lengthy trial and error process to find the best suitable material to produce the part with the highest possible quality and the lowest possible cost
iii) Find out during trial runs that the produced part has visual blemishes, such as sink marks, weld lines, meld lines, or burn marks
iv) Go through a lengthy trial and error process to find the best gate locations or cooling circuit layout
v) Run up job costs or decrease profits due to mould rework or delivery delays

3.6 Simulation on Injection Moulding

The simulation on mould flow of the designed injection mould using *Autodesk® Moldflow® Adviser 2010 (AMA 2010)* software as shown in Figure 3.4 is to test whether the part produced is free from defects. If defect does exist, alteration on parameters setting such as injection temperatures and pressures should be done in order to eliminate the defects (Jay, 2006).

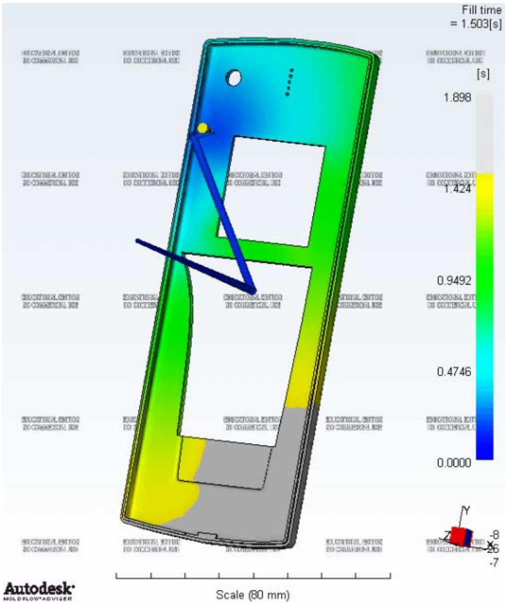


Figure 3.4: Testing of injection mould design by simulating mould flow process

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter shows the results generated by the simulation of *Autodesk® Moldflow® Advisor 2010* software. The simulations performed have generated results overview on the injection moulding process. The purpose of this chapter is to emphasise the analyses of weld-line defects. Comparisons are made among the simulation results of weld-line defect to determine which gate location can minimise the occurrence of weld lines. Based on the result, this chapter also discuss the factors leading to weld-line defect and approaches to strengthen the weld lines if they are unavoidable.

4.2 Computer-Aided Design (CAD) Model

Figure 4.1 and Figure 4.2 show the reverse-engineered CAD model of the mobile phone casing (upper part) of the model Nokia 9500. The CAD model has the dimension entirely identical to the existing model which was generated by the 3D laser scanner.

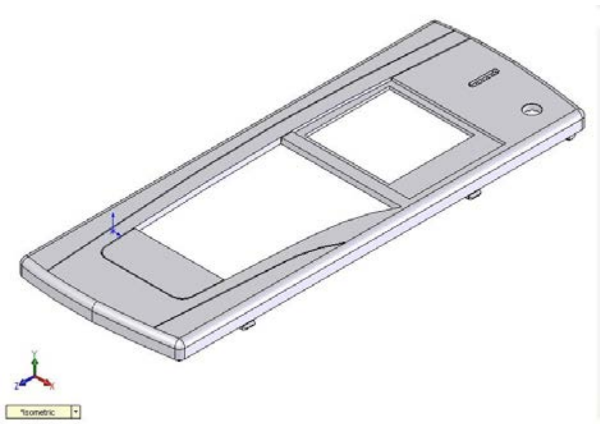
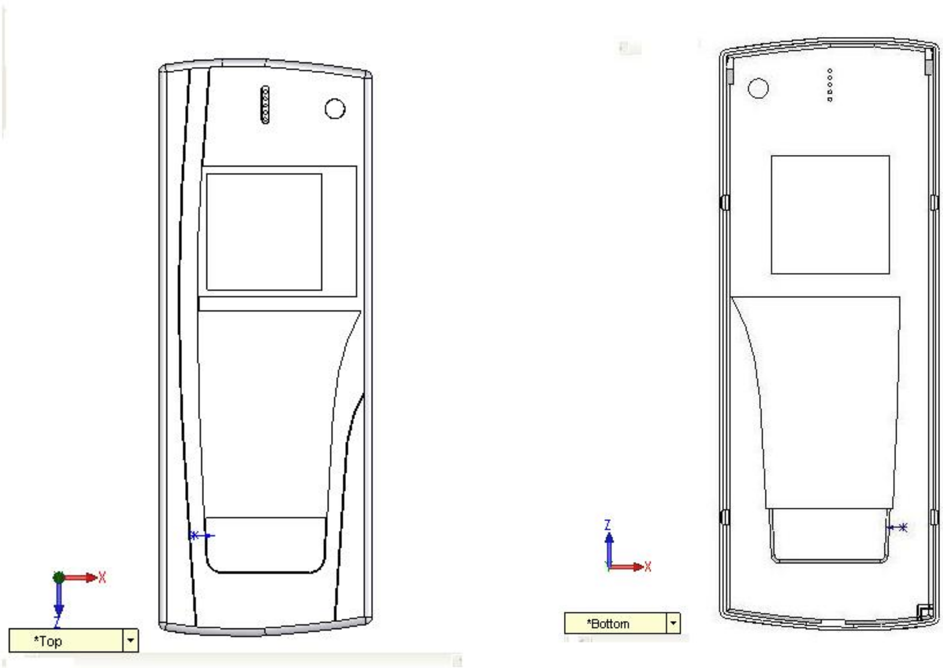


Figure 4.1: CAD model of Nokia 9500 mobile phone casing (isometric view)



(a) (b)

Figure 4.2: Top view (a) and bottom view (b) CAD model of Nokia 9500 mobile phone casing

4.3 The Advanced Gate Locator Algorithm

The Advanced Gate Locator Algorithm locates the optimal injection location based on minimising the flow resistance. However, the locations of the gate positions can relocated to investigate the how it affects the weld-line occurrence. The top surface of the mobile phone casing was being selected as prohibited injection gate location to disallow the Advanced Gate Locator Algorithm positioning any gate on the prohibited surface. This is to keep the top surface as smooth and flawless as possible. Figure 4.3 shows the prohibited surface in red colour.

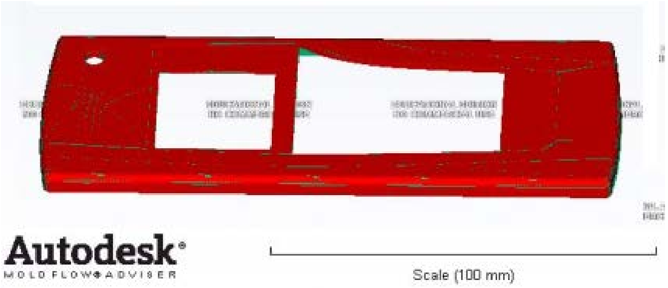


Figure 4.3: Prohibited surface for injection gate location is highlighted in red colour

4.4 Factors of Weld-Line Formation

Factors or variables which significantly affect the occurrence of weld lines on mobile phone casing are taken in consideration when performing simulation of injection moulding. The factors are as follows:

i) Number and location of injection gates
ii) Wall thickness of mobile phone casing
iii) Runner sizing
iv) Injection pressure
v) Melt temperature

For each simulation for (i), (ii) and (iii), the parameter settings such as mould temperature, melt temperature and injection pressure are being fixed as a constant variables so as to accurately investigate the effects of the changeable variables. Figure 4.4 shows the magnitude of the constant variables.

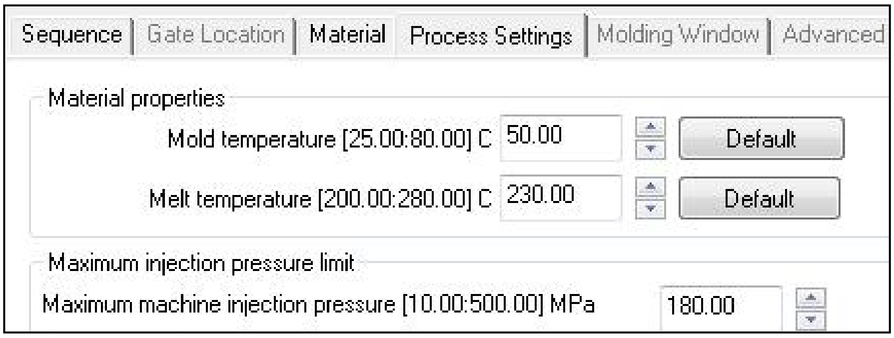


Figure 4.4: Constant variables (parameter settings of injection moulding simulations)

4.4.1 Number and Location of Injection Gates

Simulations were done to observe how the different number of injection gates and their locations affect the occurrence of weld lines. The simulation was started with three gates. Figure 4.5 shows the weld lines produced when 3 gates were located.

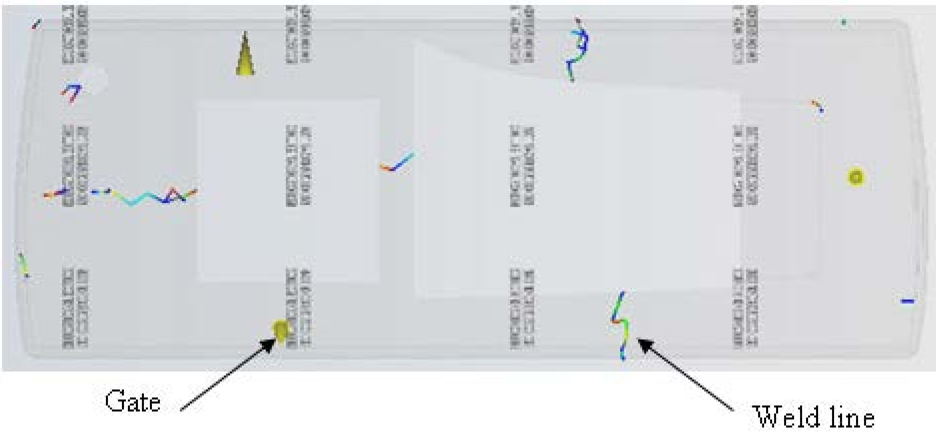


Figure 4.5: Weld lines produced by 3 injection gates

When the gates are reduced to two, the weld lines produced are as follows. Figure 4.6 shows the simulation results on weld lines produced by different locations of two gates. Refer the rest of the results for weld lines produced by two injection gates at different gate locations in Appendix A.

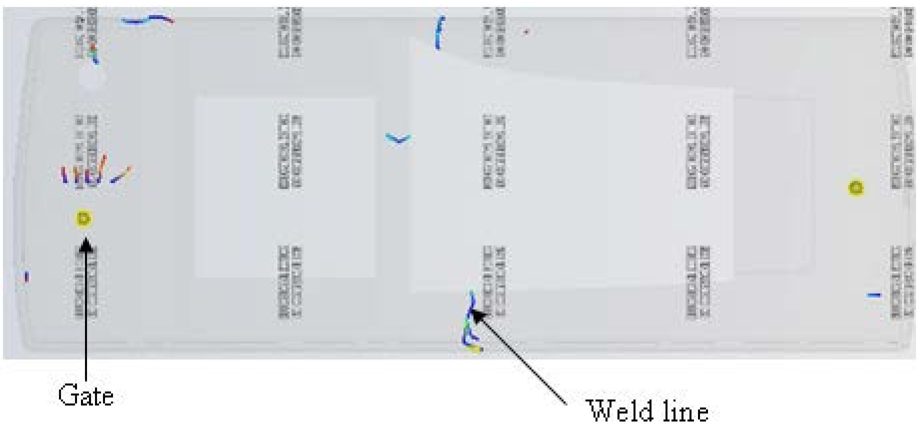


Figure 4.6: Weld lines produced by two injection gates at location A

From observation, it is shown that the simulation of Figure A(1) had the fewest weld lines produced at location B. The number of injection gates was reduced further to become only one. Figure 4.7 shows the weld lines produced by one injection gate at different gate locations. Refer the rest of the results for weld lines produced by one injection gate at different gate locations in Appendix B.

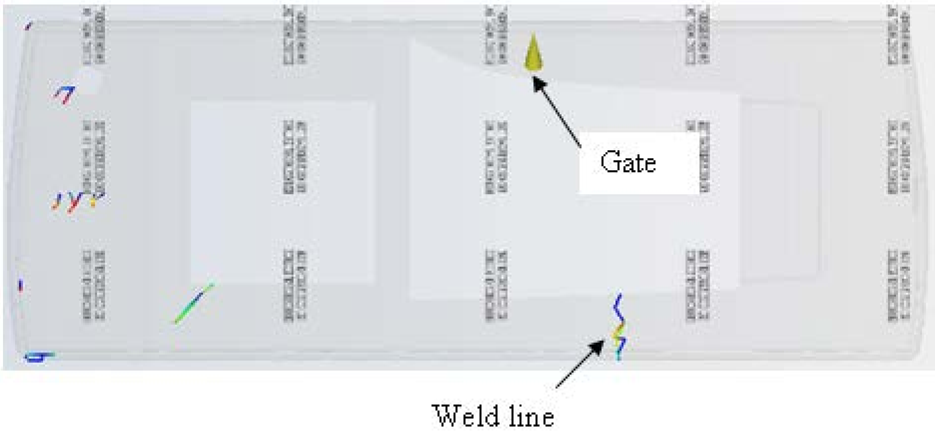


Figure 4.7: Weld lines produced by one injection gate at location A

From observation, it was obviously shown that Figure B(1) had the least weld lines produced at the location B. Figure 4.5, Figure A(1) and Figure B(1) which represent the least weld lines sample produced by three, two and one injection gate(s) respectively were being sorted out and compared among them. Out of the three samples, the one as shown in Figure B(1) in Appendix B of one injection gate at location B was the simulation sample that had least weld-line defect. This sample was being chosen for the following simulations which alter the variable of mobile phone casing's thickness.

4.4.2 Wall Thickness of Mobile Phone Casing

Using the same number and location of injection gate as in Figure B(1), the simulations were performed on the CAD models of mobile phone casings with different wall thickness of 1.5mm, 1.8mm, 2.0mm, 2.5mm, 2.8mm and 3.0mm as shown in Figure 4.8.

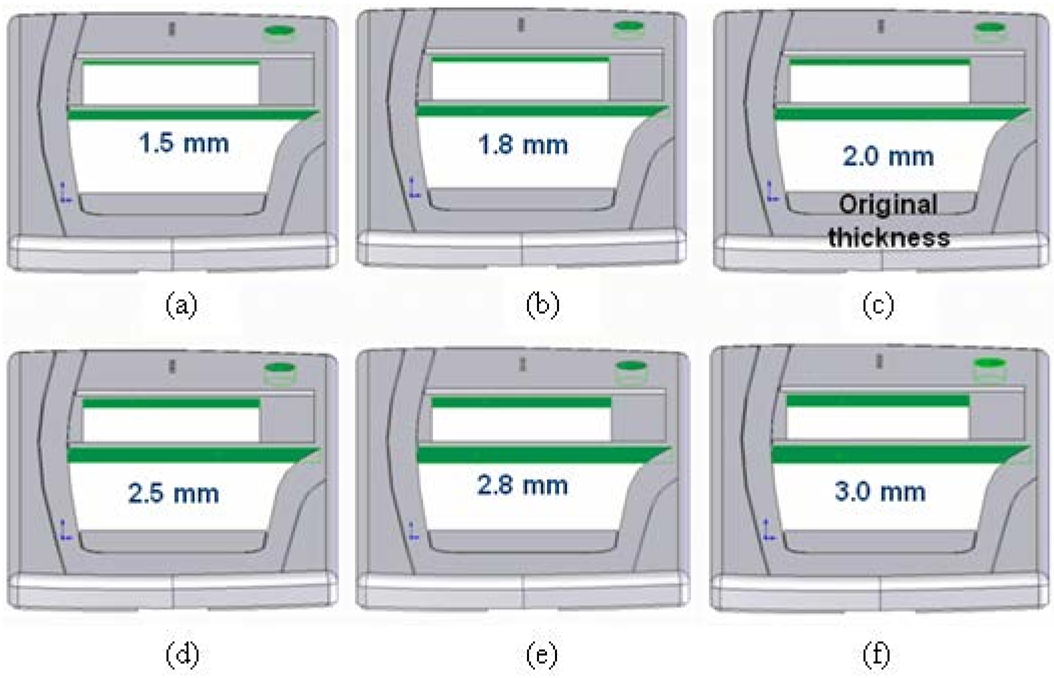


Figure 4.8: CAD Models of mobile phone casings at different wall thickness

Figure 4.9 shows the weld lines produced at different wall thickness. Refer the rest of the results for weld lines produced at different wall thickness in Appendix C. In comparisons, it can be shown that the wall thickness at 2.0mm produced the least weld lines as shown in Figure C(2) in Appendix C.

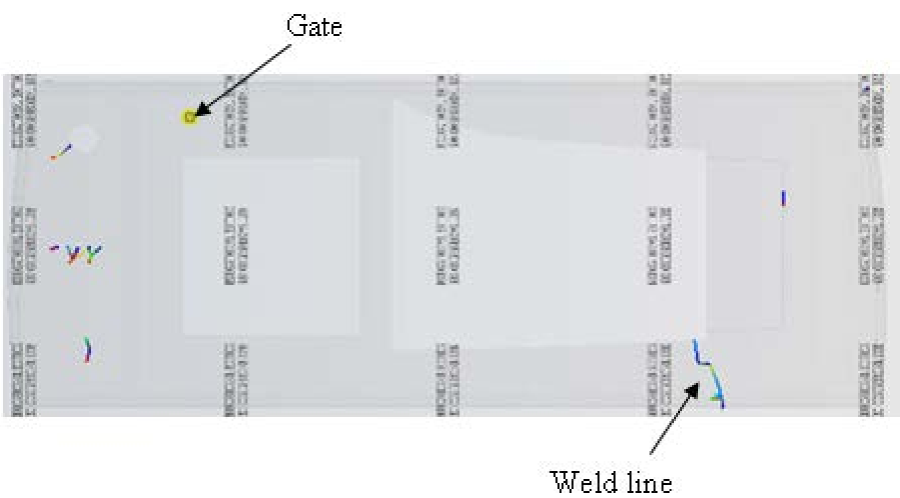


Figure 4.9: Weld lines produced at wall thickness of 1.5mm

The wall thickness of 2.0mm was the most ideal thickness and was chosen for the following simulations in which the runner sizes were varied whilst wall thickness of 2.0mm was fixed as constant variable.

4.4.3 Runner Sizing

Runner size had influence on weld lines density as well. Eq. (2.1) as stated below was used to calculate the approximate runner diameter to be designed for the mobile phone casing.

$$D = \frac{W^{\frac{1}{2}} L^{\frac{1}{4}}}{3.7} \tag{2.1}$$

In the previous simulations, the total weight of mobile phone casing was estimated to be 12.509g whilst the runner length was designed to be 50mm. Thus, the recommended diameter of runner can be calculated as following:

Diameter of runner, $D = \frac{12.509^{\frac{1}{2}} \times 50^{\frac{1}{4}}}{3.7} = 2.542mm$

Therefore, cylindrical runner of diameter 2.542mm was designed for the mobile phone casing. However, the runner sizes were varied at several diameters to investigate the weld lines changes with respect to the varied runner's diameters. Weld lines produced by different runner sizes were shown in Figure 4.10. Refer the rest of the results for weld lines produced at different runner sizes in Appendix D. Tapered submarine gate of 0.8mm was used to connect the runner with the mobile phone casing cavity based on the table as shown in Topic 4.6.5 in discussion part.

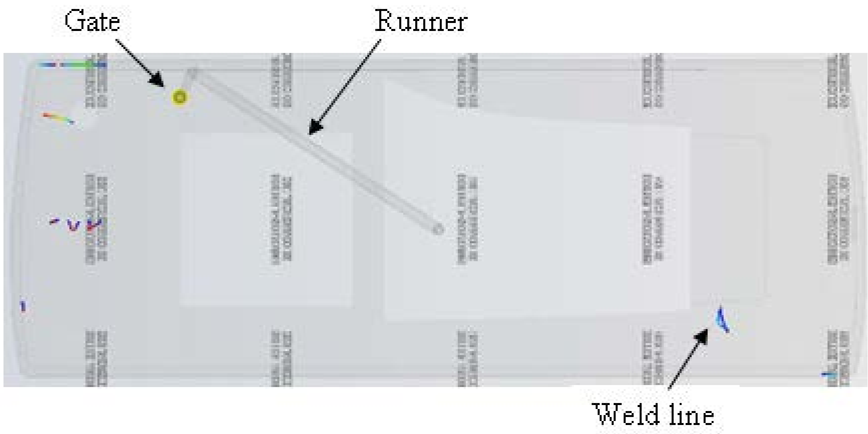


Figure 4.10: Weld lines produced by runner diameter of 2.042mm

In comparisons, the weld lines as shown in Figure 4.10 of runner diameter 2.042mm was the fewest. This indicated runner at diameter 2.042mm was the ideal size for reducing weld lines. Thus, this diameter size was chosen as the fixed variable for the further simulations in which the injection pressure would be altered.

4.4.4 Injection Pressure

In the simulations with respect to varied injection pressures, the melt temperature was fixed at constant magnitude of 230°C. Table below shows the parameter settings of the simulations.

Table 4.1: Parameter settings of injection moulding simulation to investigate the effect of varied injection pressures on weld-line occurrence

Parameter Settings	Melt Temperature (°C)	Injection Pressure (MPa)
Parameter Setting (default)	230	180
Parameter Setting 1	230	200
Parameter Setting 2	230	220
Parameter Setting 3	230	240

Figure 4.11 shows the weld lines produced by each processing conditions of different injection pressure. Refer the rest of the results for weld lines produced at different injection pressures in Appendix E.

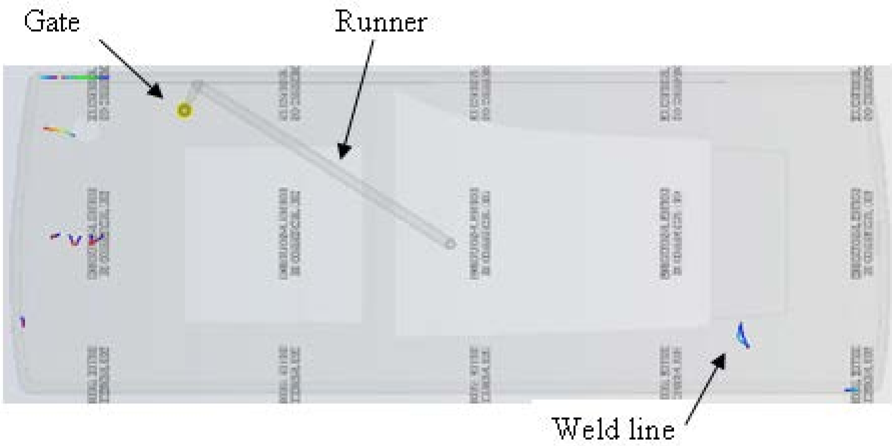


Figure 4.11: Weld lines produced at the injection pressure of 180 MPa

After being compared to each other, the weld lines as shown in the Figure E(2) in Appendix E were the fewest. Apparently, injection pressure of 220MPa was the most suitable processing condition to produce the fewest weld lines. Hence, this magnitude of injection pressure was fixed as the constant variable for the further simulations.

4.4.5 Melt Temperature

Using the 220MPa as constant variable for processing conditions of simulations, the melt temperatures were varied in order to investigate the effect of melt temperature with respect to the occurrence of weld lines. Table below shows the processing conditions of simulations in which the melt temperatures were varied in increasing order.

Table 4.2: Parameter settings of injection moulding simulation to investigate the effect of varied melt temperatures on weld-line occurrence

Parameter Settings	Melt Temperature (°C)	Injection Pressure (MPa)
Parameter Setting (default)	210	220
Parameter Setting 1	230	220
Parameter Setting 2	250	220
Parameter Setting 3	270	220

Figures 4.12 shows the weld lines produced by simulations at different melt temperatures. Refer the rest of the results for weld lines produced at different melt temperatures in Appendix F.

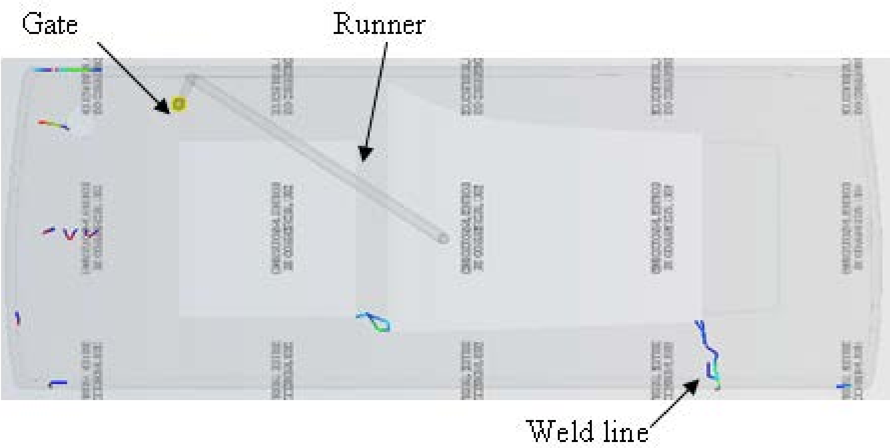


Figure 4.12: Weld lines produced at the melt temperature of 210°C

In comparison, weld lines as shown in the Figure F(2) in Appendix F were the fewest among all. This indicated that the melt temperature at 230°C was optimum to reduce weld lines to the least.

4.5 Summary of Simulation of Fewest Weld Lines

After a series of simulations had been performed by altering the significant variables that affected weld-line occurrence, a summary of the magnitudes of variables that were optimum to reduce weld lines to the fewest can be listed out. The summary is shown in Table as follows:

Table 4.3: Summary of variables properties that produce minimum weld lines

Variables affecting weld-line occurrence	Magnitudes
Number of gate(s)	One
Wall thickness of mobile phone casing	2.0mm
Diameter of runner	2.042mm
Melt temperature	230°C
Injection pressure	220MPa

4.6 Discussions

In this topic, discussions on reverse-engineering methods as well as how did the factors as shown above affect the occurrence of weld lines were done for theoretical or practical justifications.

4.6.1 Method of Reverse Engineering

There are two types of reverse engineering method which are contact scanning method using Coordinate Measurement Machine (CMM) and non-contact scanning method using 3D laser scanning machine with aid of RE software. This project used non-contact scanning method by using 3D laser scanner with aid of *Polyworks* software which are known as reverse-engineering hardware and software respectively. Contact scanning method using CMM was not used for this project because it requires a highly skilled operator to carry out NC programming to plan tool path for contact-scanning process to generate the 3D CAD model of the mobile phone casing (Milroy, 1996). Besides, 3D laser scanner provided more accurate measurement on the dimensions and geometry of mobile phone casing. Since it does not have contact with the scanned object, thus, it is adequate for fragile or soft objects.

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4.6.2 Effect of Number of Gates on Weld-Line Formation

Formation of weld lines is directly proportional to the number of gates. Based on the above result, the number of weld lines apparently appeared lesser as the number of gates was reduced. This is due to the reason that reducing the injection gates will reduce the melt flow fronts moving in the cavity (Young, 1994). However, obstructions such as cores and holes also attribute to weld-line formations. Melt flow fronts divide as they meet the obstructions and recombine at another end of the obstructions. The recombination interfaces are the planes where the weld lines are formed (Chan, 2001). When lesser injection gates are used, the lesser separation and recombination of melt flow front will take place as they flow through the obstructions. Hence, fewer weld lines are formed.

4.6.3 Effect of Locations of Gates on Weld-Line Formation

Although the Advanced Gate Locator Algorithm in *Autodesk*® *Moldflow*® *Advisor 2010* software can suggest the best gate location for injection moulding, the gate position can be relocated within the appropriate region to investigate if the relocation of gate will result in lesser weld-line formations. The locations of gate are determined through repetitive attempts of simulations in order to find out which region to locate the gate can make the recombination of flow fronts take place narrower region. The weld lines formed at narrower region will naturally become less in terms of visibility and number compared to the weld lines formed at broader region.

4.6.4 Effect of Wall Thickness on the Weld-Line Formation

Altering wall thicknesses can set up a different fill time. With a different fill time, flow fronts may meet at a different location and therefore the weld lines will move from a more critical region to a less critical region or from a broader region to a narrower region (Lam, 2001). The moving of weld lines can help in reducing the visibility and number of weld lines formed. The wall thickness was changed at 0.2mm difference because the weld lines appearance did not display significance change if the change of wall thickness was less than 0.2mm.

4.6.5 Effect of Runner Sizing on the Weld-Line Formation

As stated earlier in Eq. (4.1), the formula is useful to give a rough approximation of what diameter of runner for the mobile phone casing should be used. Cylindrical runner was chosen because cylindrical-shaped runner consumes less material than that of quadrilateral shape. Theoretically, increasing the runner size allows the melt to pack the cavity easier and faster. However it reaches a threshold limit that if keep increasing the runner size larger than 2.042mm, the formation of weld lines will not be reduced but increased instead. This is because the runner sizes larger than 2.042mm are too large to be complimentary to the injection pressure and melt temperature. In other words, runner diameter larger than 2.042mm (threshold value) will make the injection pressure and melt temperature too low to pack the cavity completely before a thin freezing layer formed at the surface of melt flow fronts. Apart from that, the runner dimension should be reduced as much as possible so that the filling time travelled by the flowing melt in the runner is minimised. A longer time travelled by the flowing melt in the runner cavity will cause a thin layer of solidification takes place at the melt fronts before the cavity is thoroughly packed with the molten plastic (Piccarolo, 1988). The drawback of such condition is the weld lines formed are very weak in terms of strength and integrity because freezing layers at the melt front surfaces prevent an interfusion between two recombining melt fronts.

In injection gate wise, submarine gate was used because it is suitable for two-plate mould. The gate size was determined to be 0.8mm based on the weight of the mobile phone casing according to the Table 4.4 as shown below:

Table 4.4: Customary dimension of injection gates

Mass of Part (g)	Conical beam sprue/ direct spur (Ø mm)	Needle gate/ pinpoint gate/ submarine gate (Ø mm)	Height of firm gate (mm)
1 – 10	2.5 – 3.5	0.8	1
11 – 20	3.5 – 4,5	0.8	1.0 – 1.2
21 – 40	4.0 – 4.5	1.0 – 1.2	1.2 – 1.5
41 – 150	4.5 – 6.0	1.5 – 2.5	1.5 – 2.5
151 – 300	4.5 – 7.5	1.5 – 2.8	2.5 – 3.0
301 – 500	6.0 – 8.0	1.8 – 3.5	–
501 – 1000	8.0 – 10.0	–	–
1001 – 5000	10.0 – 15.0	–	–

Source: Pandelidis (1990)

4.6.6 Effect of Injection Pressure and Melt Temperature on Weld-Line Formation

The strength and appearance of a weld line can be altered to some degree by adjusting processing conditions such as melt temperature and injection pressure. In accordance with the above result, increasing the melt temperature and injection pressure will reduce the formation of weld lines. This is likely to have some positive effect on weld line performance by promoting entanglement across the weld interface. Figure 4.13 shows that increasing the melt temperature and injection pressure will enhance molecular diffusion as well as subsequent molecular entanglement at the recombination interface (Malloy, 2004). Melt temperature at the weld is the most significant process variable due to its influence on molecular mobility (Tan, 1997). Hotter melts and higher injection pressures tend to improve weld strength, but effects due to molecular degradation can occur if the temperature and pressure are excessive.

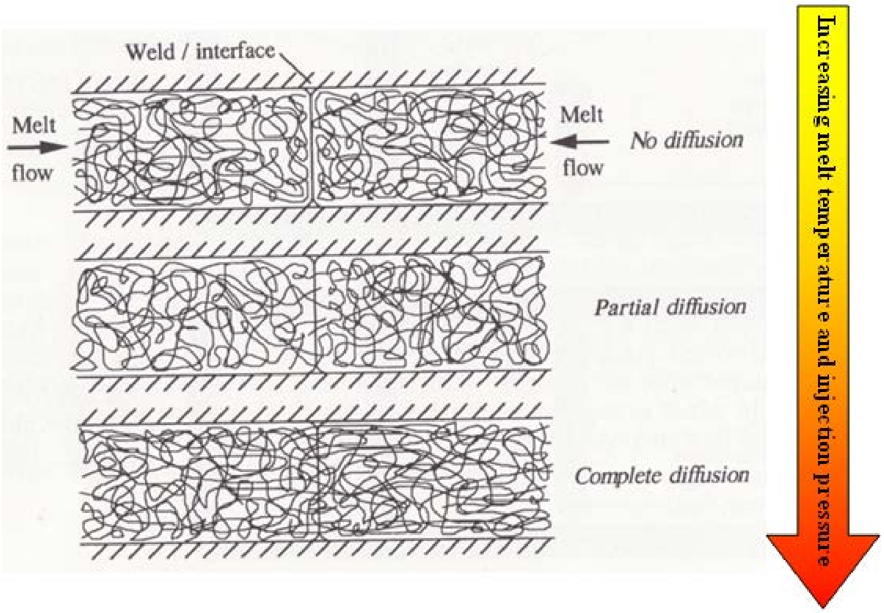

Figure 4.13: Increasing the melt temperature and injection pressure will result in more molecular diffusion and entanglement taking place at weld interface

Source: Malloy (2004)

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The reverse-engineered CAD model generated via 3D laser scanning is entirely identical to the existing model and is much more accurate than the CAD model created by using Solidworks. 3D laser scanning method reduces the parallax errors of measuring the dimensions of mobile phone casing virtually to zero and also overcomes the problems of inaccuracy in sketching curved shape of the casing. Formations of weld lines are significantly affected by the gate location, number of gate, wall thickness of part, injection pressure and melt temperature. From the simulations of this project, it can be postulated that the formation of weld lines can be removed or reduced if only one injection gate is used and is positioned at the upper left corner (8mm from the side edge and 2mm from the top edge of the rectangular hole) on the mobile phone casing's bottom surface. The wall thickness of 2mm, runner's diameter of 2.042mm, melt temperature of 230°C and injection pressure of 220MPa provide the most optimum conditions for the injection moulding process to produce the mobile phone casing with the fewest formations of weld lines.

5.2 Future Works

The similar method of simulations in this project can be continued for the analyses of other defects such as sink marks, air traps, and warpage. There are still various types of injection-moulding defects which need to be taken in considerations to ensure the mobile phone casing is defect-free as much as possible before it is manufactured. The simulation can also performed on other analyses such as cooling channel and materials of injection moulding.

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APPENDIX A

WELD LINES PRODUCED BY TWO INJECTION GATES AT DIFFERENT GATE LOCATIONS

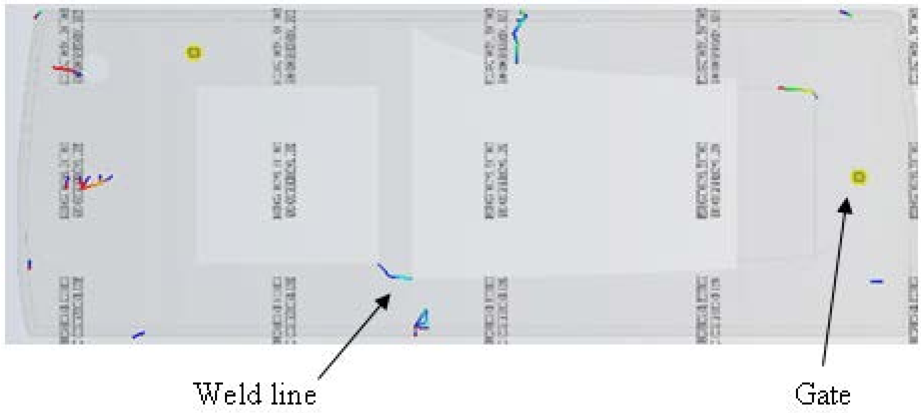

Figure A(1): Weld lines produced by two injection gates at location B

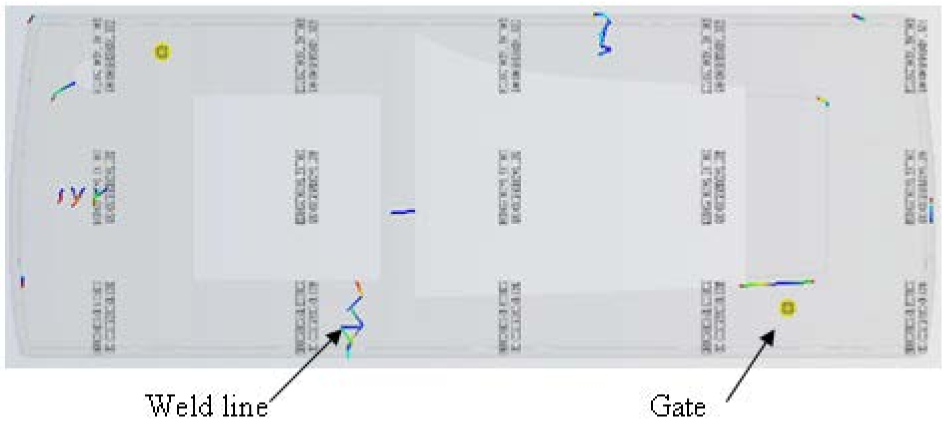

Figure A(2): Weld lines produced by two injection gates at location C

APPENDIX B

WELD LINES PRODUCED BY ONE INJECTION GATE AT DIFFERENT GATE LOCATIONS

Figure B(1): Weld lines produced by one injection gate at location B

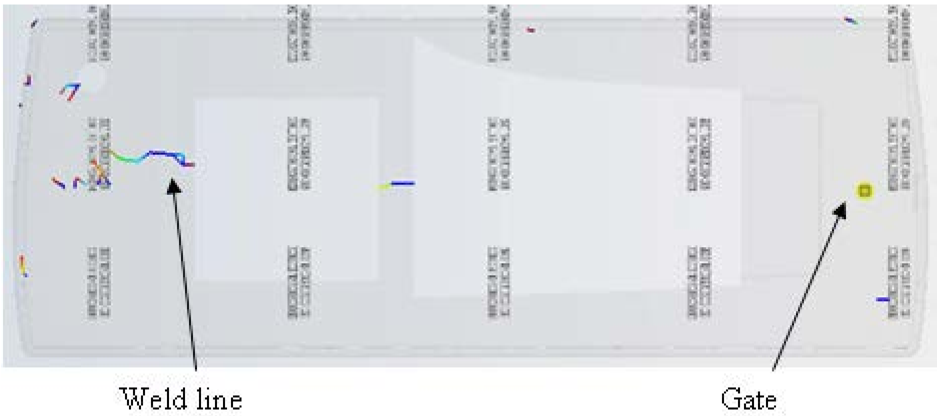

Figure B(2): Weld lines produced by one injection gate a location C

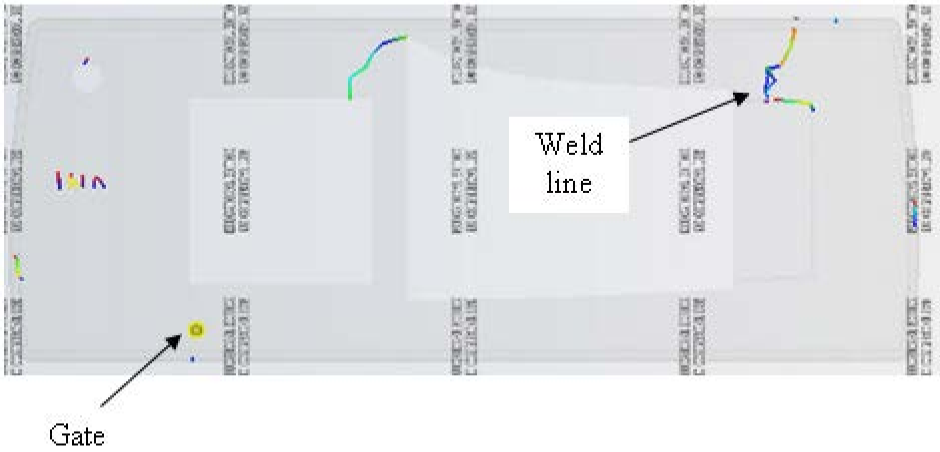

Figure B(3): Weld lines produced by one injection gate at location D

APPENDIX C

WELD LINES PRODUCED AT DIFFERENT WALL THICKNESS

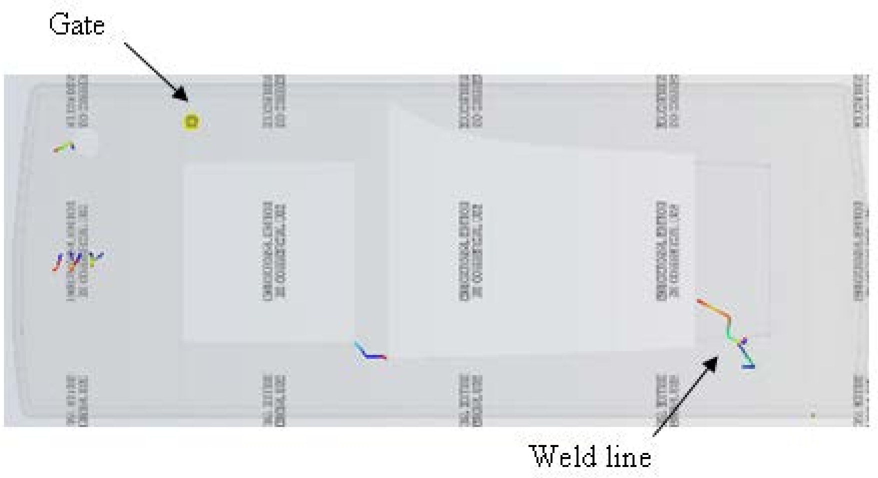

Figure C(1): Weld lines produced at wall thickness of 1.8mm

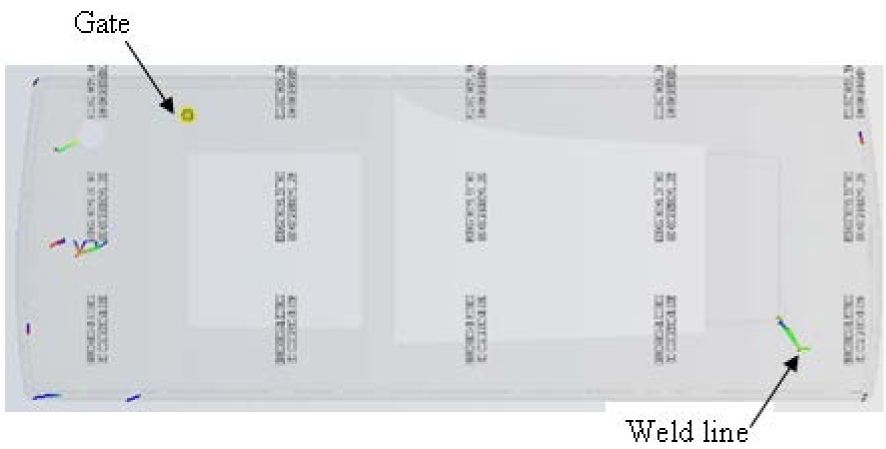

Figure C(2): Weld lines produced at wall thickness of 2.0mm

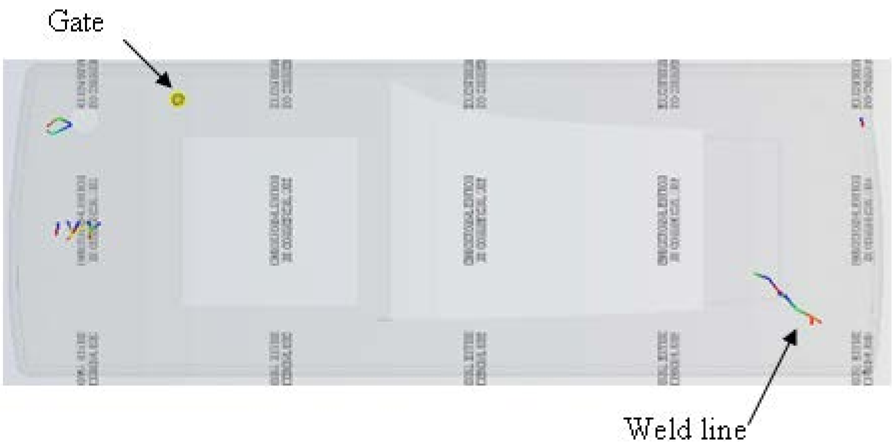

Figure C(3): Weld lines produced at wall thickness of 2.5mm

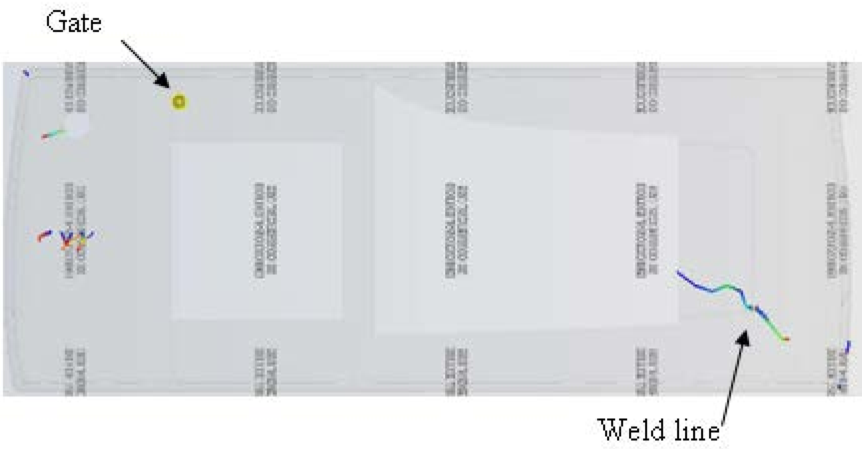

Figure C(4): Weld lines produced at wall thickness of 2.8mm

Figure C(5): Weld lines produced at wall thickness of 3.0mm

APPENDIX D

WELD LINES PRODUCED BY AT DIFFERENT RUNNER SIZES

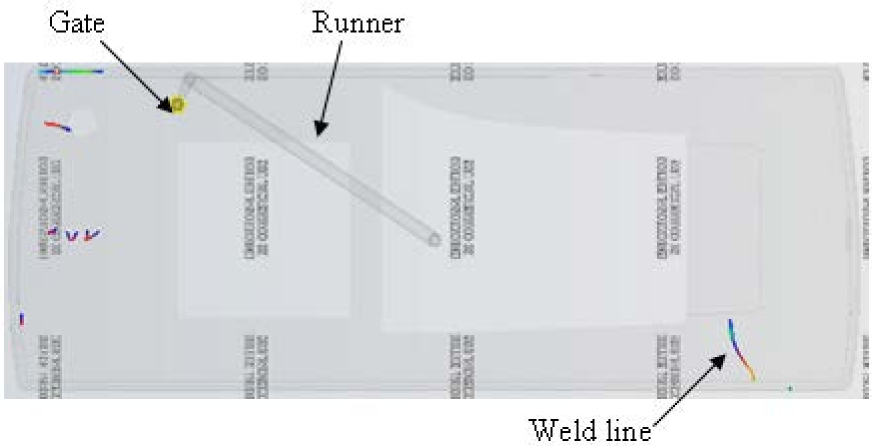

Figure D(1): Weld lines produced by runner diameter of 2.542mm

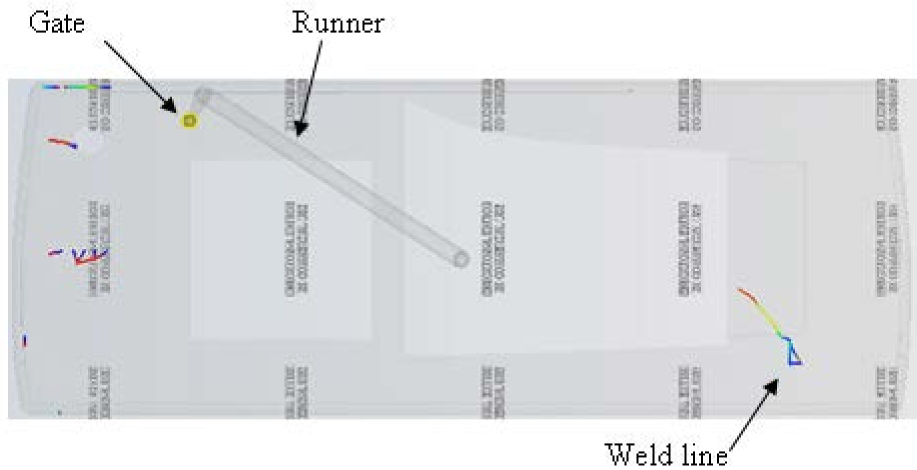

Figure D(2): Weld lines produced by runner diameter of 3.042mm

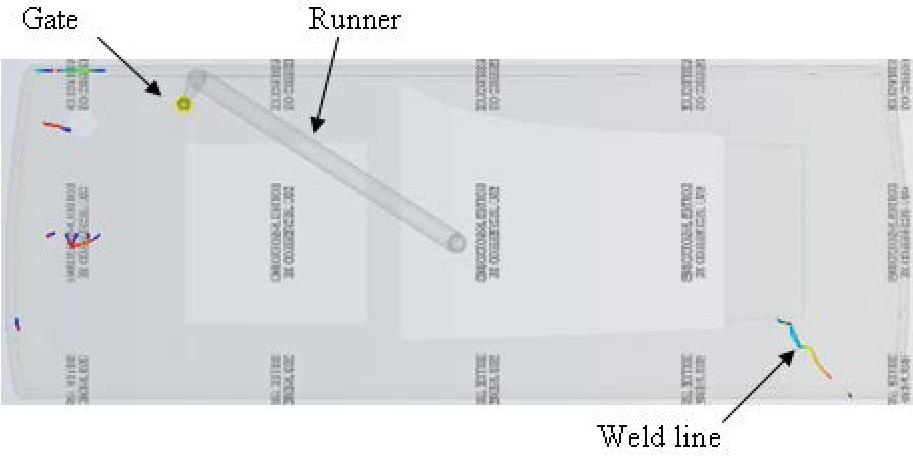

Figure D(3): Weld lines produced by runner diameter of 3.542mm

APPENDIX E

WELD LINES PRODUCED AT DIFFERENT INJECTION PRESSURES

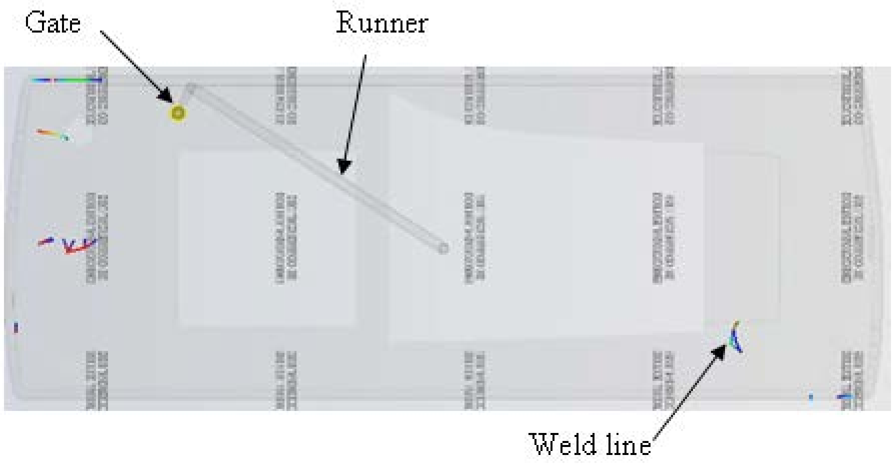

Figure E(1): Weld lines produced at the injection pressure of 200 MPa

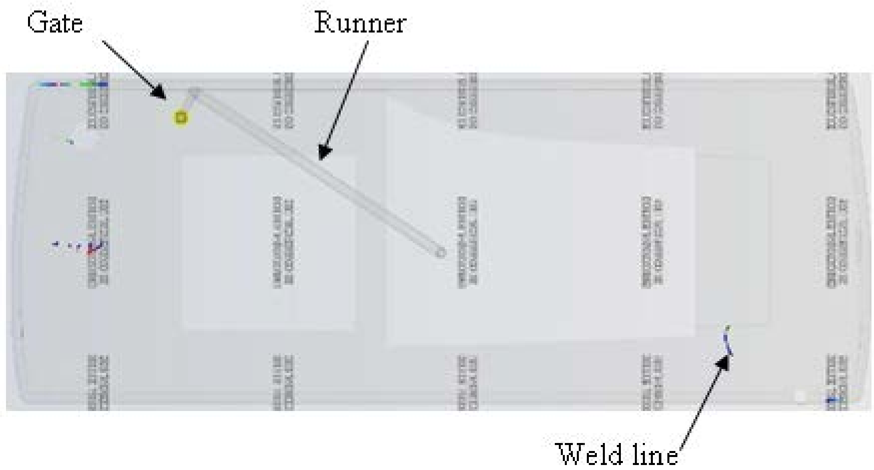

Figure E(2): Weld lines produced at the injection pressure of 220 MPa

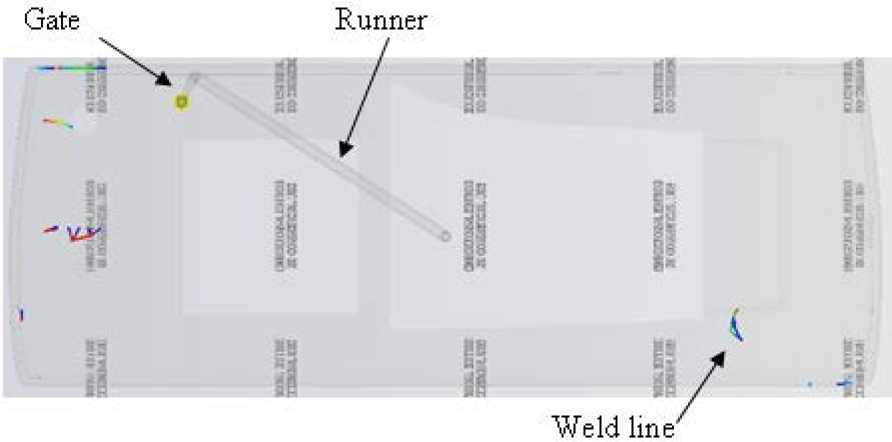

Figure E(3): Weld lines produced at the injection pressure of 240 MPa

APPENDIX F

WELD LINES PRODUCED AT DIFFERENT MELT TEMPERATURES

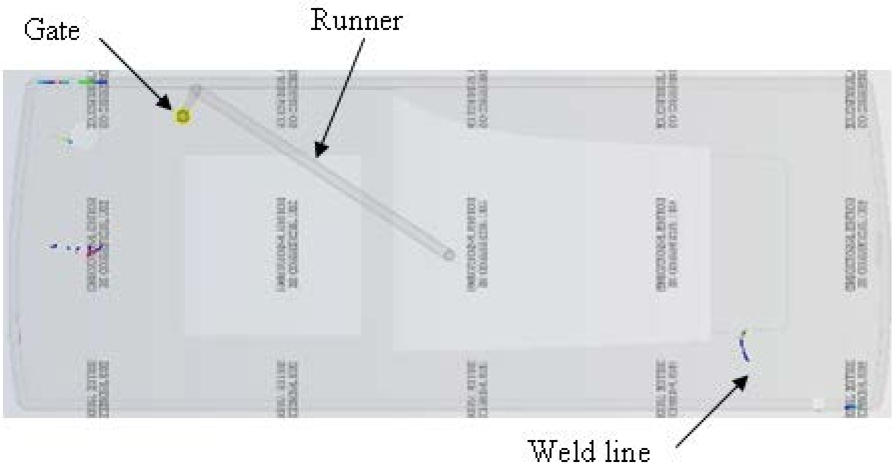

Figure F(1): Weld lines produced at the melt temperature of 230°C

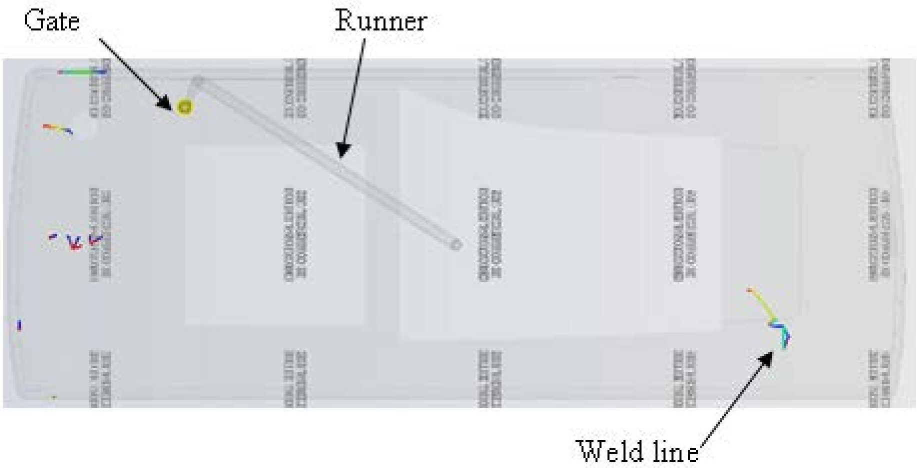

Figure F(2): Weld lines produced at the melt temperature of 250°C

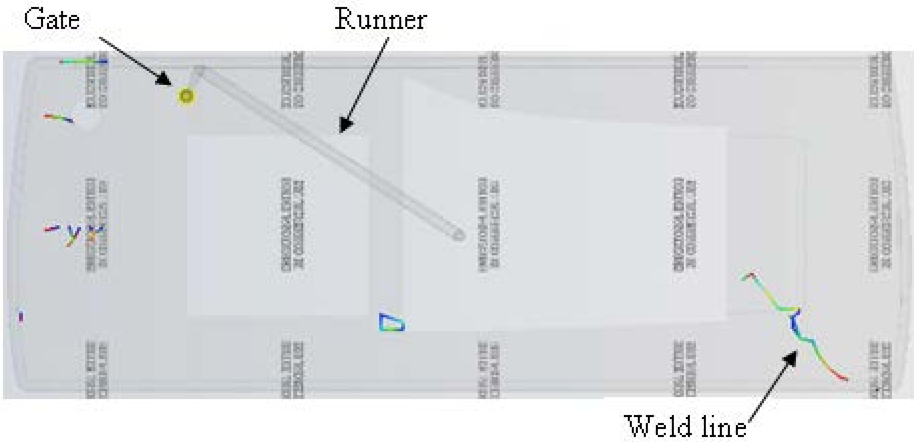

Figure F(3): Weld lines produced at the melt temperature of 270°C