PROCESS OPTIMIZATION IN RUBBER INJECTION MOULDING MANUFACTURING

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PROCESS OPTIMIZATION IN RUBBER INJECTION MOULDING MANUFACTURING

ABSTRACT

Rubber injection moulding is a process of moulding the rubber to produce an applicable product in the manufacturing industry today.

Rubber injection moulding which is, a compound strips of rubber fed into the screw barrel of the injection machine, then the material is injected into the mould cavity, with controllable parameters: speed, pressure and temperature.

The objective of this research is to optimize the process which are: faster in cycle time, saving material and maintaining products quality. Process optimization is a method to help manufacturers on process improvement in production efficiency and products accuracy.

Taguchi method is a technique to define control factors in the process optimization. Taguchi orthogonal array is used to select a combinations of multiple factors at multiple levels. Signal-to-noise ratio (S/N ratio) is used to compares the highest and lowest level of desired, in the control factors of process optimization. The one-way analysis of variance (ANOVA analysis) is used to define statistically significant differences between means of three or more groups' data.

The results of the experiment showed process optimization in rubber injection moulding that can reduce cycle time and material, and also sustaining products quality.

Key words: Rubber, injection moulding, cycle time, hardness.

PENGOPTIMUMAN PROSES PEMBUATAN DI PENGACUAN SUNTIKAN GETAH

ABSTRAK

Pengacuan suntikan getah adalah proses mengacu getah untuk membuat produk di industri pengeluran getah pada hari ini.

Pengecuan suntikan getah adalah getah kompaun berpotong jalur dimasukkan ke dalam bekas suntikan mesin, kemudian getah disuntik ke dalam acuan, dengan dikawal parameter: kelajuan, tekanan, dan suhu.

Objektif penyelidikan ini adalah untuk optimum proses dengan: memantaskan masa kitaran, jimatkan penggunaan bahan, dan mengekalkan kualiti produck. Pengoptimuman proses adalah kaedah untuk membantu pengilang atas peningkatan proses dalam kecekapan pengeluaran dan ketepatan produk.

Kaedah Taguchi adalah teknik untuk menakrifkan faktor kawalan di pengoptimuman proses. Taguchi orthogonal array digunakan untuk memilih kombinasi pelbagai factor di pelbagai peringkat. Nisbah Signal-to-noise (nisbah S/N) digunakan untuk membanding tahap tertinggi dan terendah yang dikehendaki, dalam faktor kawalan di pengoptimuman proses. Analysis of variance sehala (analisis ANOVA) digunakan untuk, membezakan statistik yang signifikan dengan purata antara tiga atau lebih kumpulan.

Keputusan eksperimen menunjukkan pengoptimuman proses di pengacuan suntikan getah bahawa boleh mengurangkan masa kitaran, menjimatkan penggunaan bahan dan juga mengekalkan kualiti produk.

Perkataan utama: Getah, pengacuan suntikan, masa kitaran, kekerasan.

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CHAPTER 1: INTRODUCTION

1.1 Rubber Injection Moulding

In the year 1940, rubber injection moulding was developed (M. A. Wheelans, 1974). The rubber injection moulding machine is the common machine found in today. It has more advantages compare to rubber compression machine and rubber transfer moulding machine. The injection machine can produce high volume production, reduce cost effectively, and create high quality products.

Typical rubber moulded include automotive parts (such as rubber bushes, grommets), electronic goods (such as Liquid Crystal Display gaskets, case seals), and household articles (such as components of chair and table).

Rubber injection moulding has two major types of runner: cold runner injection moulding and hot runner injection moulding. For cold runner injection moulding, the pre-heated rubber injected into the cold runner plate, which is the rubbers runner keep in the uncured temperature and waiting for next cycle injection. The aim of the cold runner injection moulding is to eliminate the runner waste. In the hot runner injection moulding, which is without runner plate, the soften rubber injected through mould runner and directly into mould cavity. The rubbers runner and formed product were cured together inside the mould during vulcanization process.

The rubber injection moulding process, which is a process to feed in the rubber strip into the screw barrel, then the rubber is pre-heating and become soft inside the barrel. The soften rubber which is under high pressure, and was injected efficiently into mould cavity, to become rubber product when it cools and hardens.

1.2 Problem Statement

This research is to study on three key problems are: longer cycle time, material wastage, and with maintaining the products quality. The filling time, which is time required to inject rubber into the mould cavity, with controls the flow of rubber during the cycle time. The material wastes such as defect waste (is known as rejected product) and product flashes. The most important of rubber product quality is hardness, which is to resist product deformation and wear resistance.

The problems can causes by control parameters are:-

- For fastest speed: Product consists air trapped (Matt Proske, 2017), burn mark and excess flash.
- For highest pressure: Injection gates of the product contains back-grinding (M. A. Wheelans, 1974).
- For highest temperature: product distortion after remove rubber from the mould, product contains scorch (John Sommer, 2013), flow lines, short mould, and burn mark.

1.3 Objective of Research

The objective of this research is to optimize the process of rubber injection moulding by control the machine parameters:

- Speed including feeding speed, injection speed and bumping speed.
- Pressure with feeding pressure, injection pressure, bumping pressure and curing pressure.
- Temperature containing feeding temperature, injection temperature and curing temperature.

The aims of this process optimizing are reduce cycle time by 5 %, material saving by 3 %, and retain products quality.

1.4 Scope of Research

The scope of this research is to optimize process in rubber injection moulding by using Taguchi method and ANOVA analysis.

Taguchi method is used for evaluating results to determine the best levels of control factors. ANOVA analysis is used for comparing multiple groups, and provides equality means from the variance among the groups.

1.5 Outline of Research

The outline of this research report as below:-

Chapter 1: Introduction

This chapter introduce the rubber injection moulding process, the objectives to optimize the process, the scope of the process, and the outline of the research report on individual chapter.

Chapter 2: Literature Review

This chapter reviews the process optimization in rubber injection moulding. It providing information on rubber injection moulding machine, rubber injection mould, rubber material, and rubber injection moulding process, which are used in this research.

Chapter 3: Methodology

This chapter defines and conducts the research methodology used in the report. The sub-topics for this chapter include methodology flow, research design, research analysis, control factors selection, and data collection.

Chapter 4: Results and Discussion

In this chapter, the results are presented to discuss for process optimization in rubber injection moulding.

Chapter 5: Conclusion

This chapter summarizes the process optimization in rubber injection moulding and suggest to implement the process for future work.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter describes the process in rubber injection moulding for optimization. Process optimization is to minimize cost and maximize output.

The effective approach to reduce cost is by improve process quality. This is for decreasing mistakes and unnecessary deviation process in rubber injection moulding. One of the easiest way to increase output in rubber injection moulding is by increase products quantity because by reducing setup time, which is indirectly to increase output time for manufacturing more numbers of products.

Rubber injection moulding is a process that produces a rubber product by injecting a rubber into mould cavity. Injection moulding with faster cycle time, compare to compression and transfer moulding. Injection moulding able to fill-up cavity faster and automatically.

Rubber injection moulding make a product with material saving and less flashes. Injection moulding can set-up process parameter to reduce material effectively.

Injection moulding capable to make a product in reliable quality which that, hardness and dimension are maintainability to meet customer requirements. The operator is loading the pre-forms rubber of blank into mould cavity, is eliminated and ultimately to prevent human error, for wrong placing the blank into the cavity.

2.2 Rubber Injection Moulding Machine

Rubber injection moulding machine with three components combination, such as an extruder, a reservoir (which is a tank) and mould. The machine works follow sequence and automatically by feeding, heating and plasticisation, high pressure screw barrel injecting soften rubber, flow speedily through the nozzle into closed mould cavity, then subsequent to cure rubber into product's shape (which is called as vulcanization process). This process is rotating by fresh rubber prepared for next cycle.

Rubber injection moulding machine has three major types of injection unit: the ram type of the machine, the in-line reciprocating screw type of the machine, and the out-of-line non-reciprocating screw type of the machine, as shown in Figure 2.1, Figure 2.2 and Figure 2.3. The in-line reciprocating screw type of the machine is generally used by screw friction for uniformity of feeding, mixing and heating (A.I. Isayev 1989).

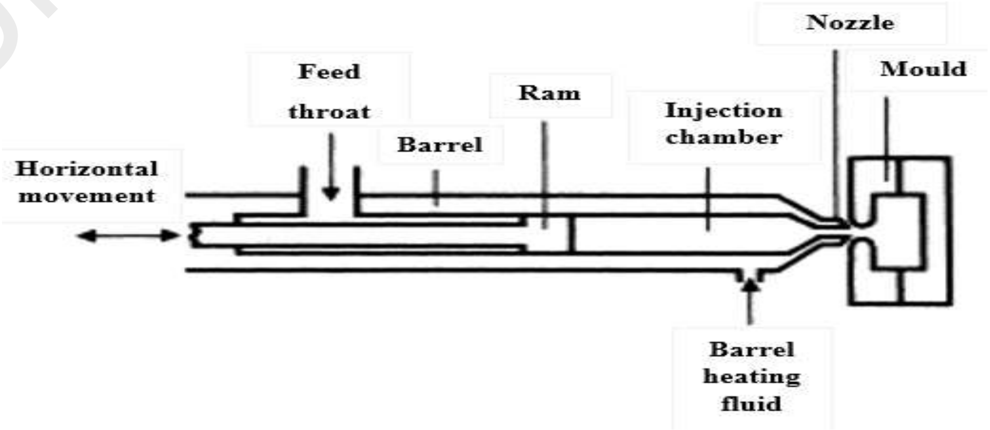


Figure 2.1: The ram type of rubber injection moulding machine. Schematic diagram from A.I. Isayev (1989).

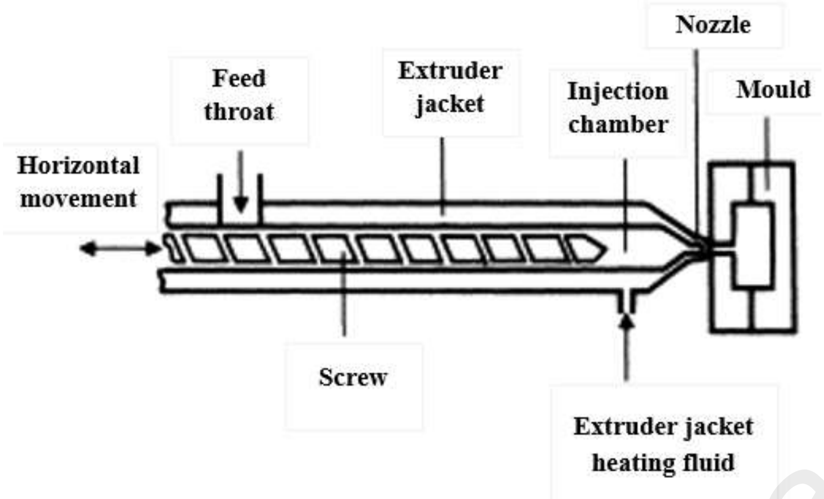


Figure 2.2: The in-line reciprocating screw type of rubber injection moulding machine. Schematic diagram from A.I. Isayev (1989).

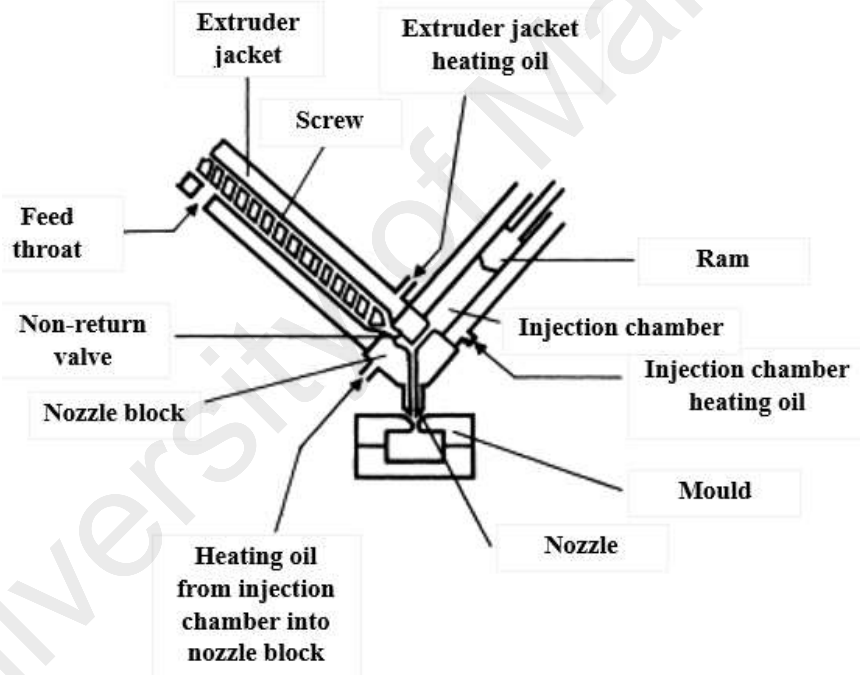


Figure 2.3: The out-of-line non-reciprocating screw type of rubber injection moulding machine. Schematic diagram from A.I. Isayev (1989).

There are two main types of feature for rubber injection moulding machine: vertical type of rubber injection moulding machine and horizontal type of rubber injection moulding machine, as shown in Figure 2.4 and Figure 2.5.

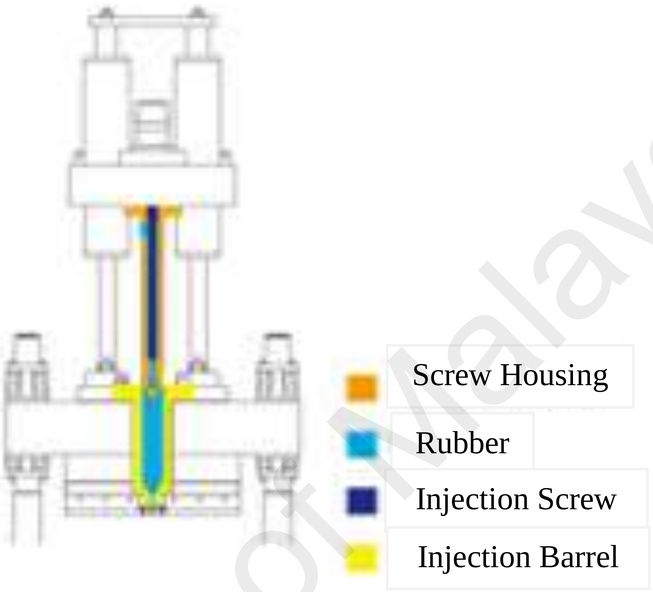


Figure 2.4: Vertical type of rubber injection moulding machine. Schematic diagram from Pan Stone Hydraulic Indus. Co. Ltd.

The vertical type of rubber injection moulding machine is used to avoid rubber scorch inside the barrel, change all varieties of rubber compound straightforwardly, and without rubber wastage.

Figure 2.5: Horizontal type of rubber injection moulding machine. Photo from Pan Stone Hydraulic Indus. Co. Ltd.

The horizontal type of rubber injection moulding machine is used for automated production: quick mould change system (as shown in Figure 2.6), semi-automated feeding system (as shown in Figure 2.7), and automated removal products system (as shown in Figure 2.8).

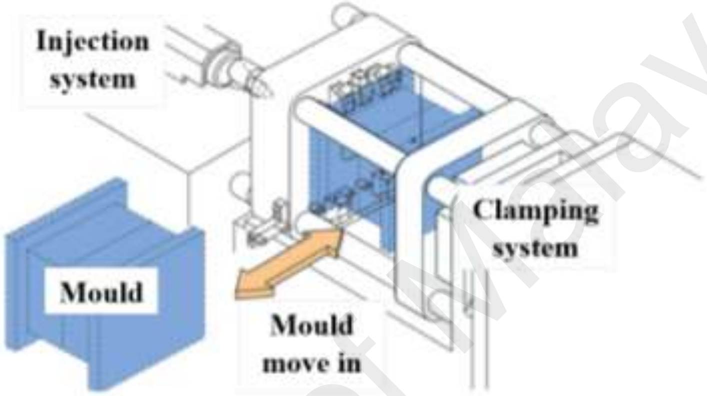


Figure 2.6: Quick mould change system. Schematic diagram from Forwell Precision Machinery Co. Ltd.

Figure 2.7: Semi-automated rubber feeding system. Photo from DESMA USA, Inc.

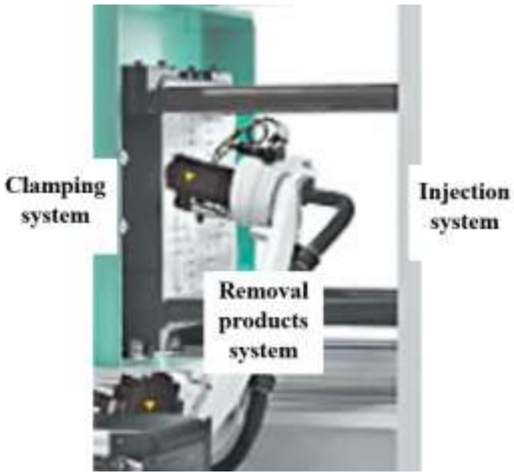


Figure 2.8: Automated removal products system. Photo from ARBUG Company.

Injection moulding capable to reduce labour costs and process is cheaply. The material directly feed into injection barrel, skipping material preparation by manpower from blanking process.

Injection moulding can shorter cycle times. The material injected automatically into mould, escaping manning to load “blank” into mould cavity. The material is pre-heated inside injection barrel, curing time can be faster. This process can manufacturing hundreds of products rapidly in a cycle time.

Injection moulding able to control products dimension. The dimension is to control products performance, reliability and durability. Manufacturers may use the lowest cost materials for their products. Customer trust a reliable products, so it indicate for products promotion. Customer also demands on products durability, therefore products functionality is increasing.

Injection moulding to make a products with consistent properties like as hardness. Hardness is a resistance for material to deform, indentation (or dent, cut) and penetration (or spreading).

2.2.1 Injection Unit

Injection unit of rubber injection moulding machine has four basics components: feed throat, injection barrel, injection screw, and injection nozzle as shown in Figure 2.9.

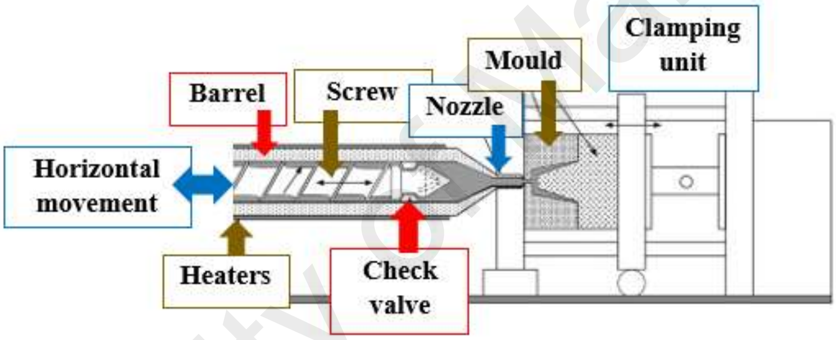


Figure 2.9: Injection unit of rubber injection moulding machine. Schematic diagram from Lorraine F. Francis (2016).

The Feed throat is at the tail end of the injection unit that allow the correct predetermined volume of fresh rubber compound to feed into the heating barrel (Jerry Weddell, 2017), same as shown in Figure 2.7.

The Injection barrel contains the injection screw and check valve assembly. The screw inside the barrel, is to help soften the rubber by injection pressure when the heat generated (Hitoshi Nishizawa, 2015). The check valve allows rubber injected to flow in one direction and automatically prevents back flow when the screw backward in reverses direction (Steven C. Williams, 2015). The barrel need to be cleaned before start production by purging procedure because rubber products can contaminated (William G. Frizelle, 2011).

The injection nozzle is used to connect the rubber injection moulding machine with the rubber injection mould. The nozzle diameter increasing, the injection pressure drop, the injection speed which is injection time is shorter, and the injection temperature decrease. Rises the nozzle diameter for rubber injected to flow faster (Oliver Knack, 2015). If the flow rate (which is injection speed) of the rubber is lower, the injection pressure needed to fill up the mould cavity increases (Jerry M. Fischer, 2003). When the higher pressure wanted to inject rubber into the cavity for fill up completely, the injection temperature rises (Dr. Hans-Joachim Graf, 2014), because the higher energy friction generated to create greater heat during the rubber is shearing inside the injection screw (Hitoshi Nishizawa, 2015).

2.3 Process Parameters

The important control parameters in rubber injection moulding machine are temperature, speed, pressure and time. (Dr. Hans-Joachim Graf, 2015). The process parameters is to achieve the products quality and products dimension, efficient in cost saving and time reducing.

2.3.1 Speed of Control Parameter

Types of speed control for process parameter in rubber injection moulding machine are feeding speed, injection speed and bumping speed.

Figure 2.10 shows the feeding speed is to charge-in rubber quickly into the injection barrel, then the rubber is shear by screw rotation in a non-plasticised state. The high feeding speed to give friction on the rubber in the screw feed zone. (Hitoshi Nishizawa, 2015).

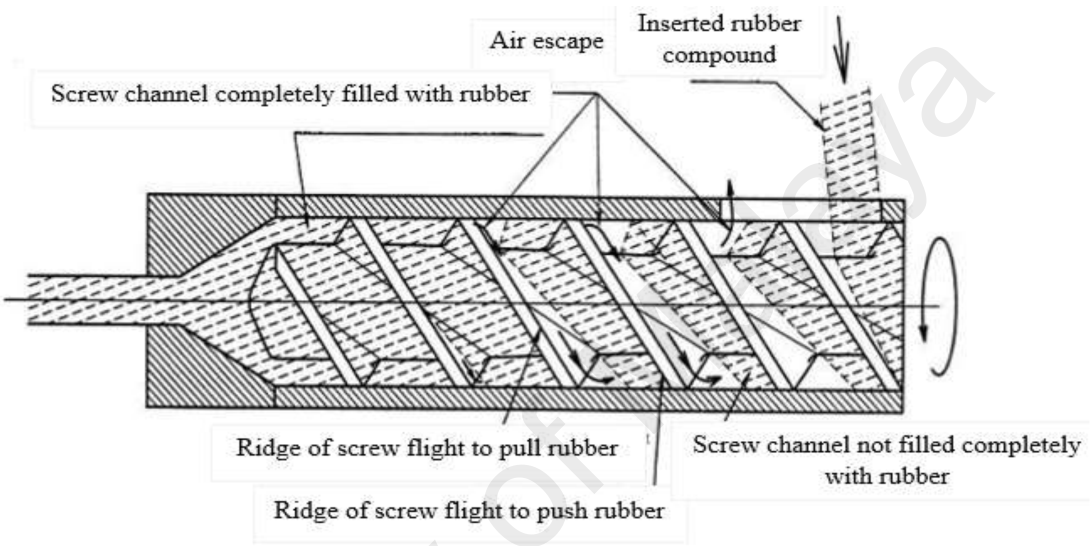


Figure 2.10: Screw feed zone. Schematic diagram by Tsuyoshi Kojima.

Figure 2.11 shows the injection speed is most influencing the “scorch index” at end of rubber filling phase, then influencing “cycle time”, and lastly less influencing “minimum degree of cure”. (M. Fasching, 2014). Injection speed is slowest, scorch time is shortest, this can affect the rubber compound almost fully vulcanized inside the injection barrel, which is before the rubber inject into mould cavity.

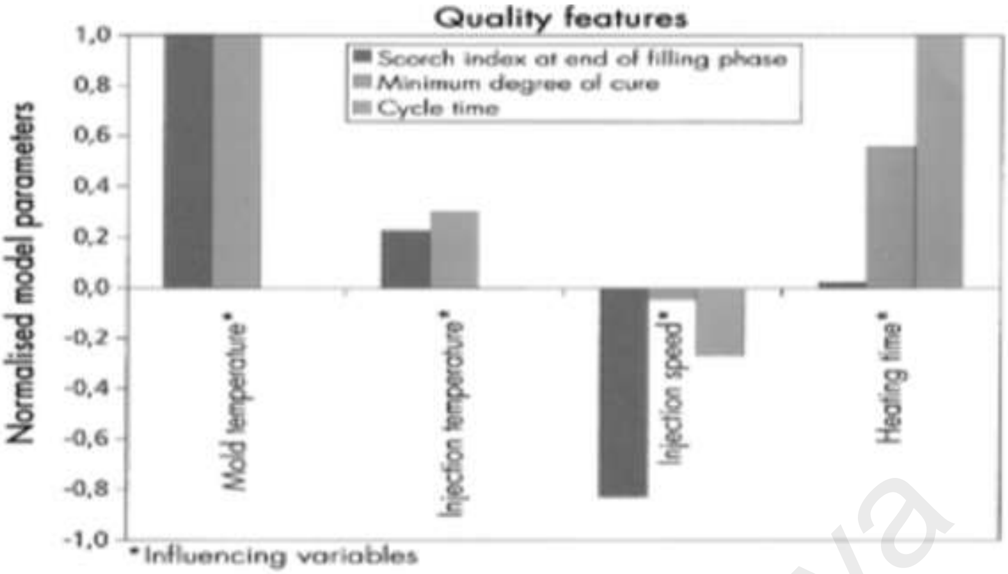


Figure 2.11: Injection speed influencing "scorch index" at end of rubber filling phase. Bar chart from M. Fasching (2014).

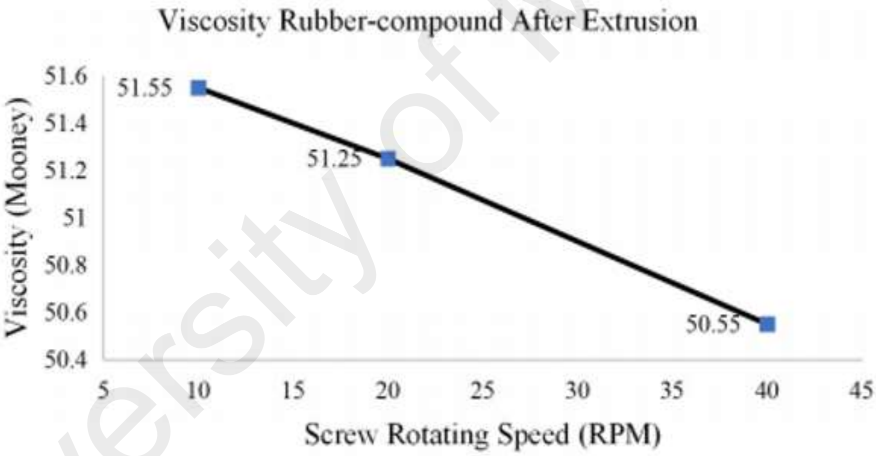


Figure 2.12: Screw speed versus Mooney viscosity. Line chart from A Zohari (2017).

Figure 2.12 shown the higher extrusion screw speed (which is similar to injection speed), the lower Mooney viscosity. (A Zohari, 2017). Mooney viscosity is low, which is molecules of rubber flows easily and faster, when lesser internal friction between the molecules.

The injection speed is high, rubber products occasioned by joint lines defect unavoidably as shown in Figure 2.13. This defect occurs whereas the rubber is injecting to fill up mould cavity, before the rubber becomes a product.

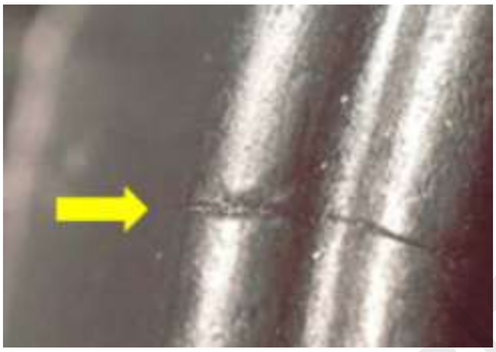


Figure 2.13: Joint lines defect on the rubber product.

It also can happen air trapped at the end of flow path on the products, when the injection speed is too high. (Tatjana Geminger, 2016). The cycle time can be reduced by high screw speed, which is injection speed is indirectly proportional to cycle time. (K. Kyas, 2012 and M. Fasching, 2014).

Bumping techniques (or bumping speed) are compulsory for complex shapes and thick products. The bumping is involved before the rubber become a product. Air trapped on products surface may happen if the bumping is too late or too less implemented (Johnnymat, 2013). Bumping is a clamp pressure relieved in a short duration with multiple times during a pre-curing, it is to vent out air trapped inside the rubber. (Bernie Stritzke, 2010). Rubber product defect with air trapped as shown in Figure 2.14.

Figure 2.14: Air trapped on the rubber products surface.

Flow mark is similarly as wavy line, which the rubber is shearing and stressing inside mould cavity wall in the rubber injection moulding process (Guojun Xu, 2004). The injection speed is too low, rubber has flow mark (as shown in Figure 2.15) on the products surface, and decreases the products strength. (Tatjana Geminger, 2016).

Figure 2.15: Flow mark on the rubber products surface.

2.3.2 Pressure of Control Parameter

Types of pressure control for process parameter in rubber injection moulding machine are feeding pressure, injection pressure, bumping pressure and curing pressure.

Figure 2.16 shown injection flow which is injection speed is higher, the higher injection pressure. Shear stress increase with higher injection pressure to generate higher heat inside injection barrel. So, the rubber become softer to flow and fill-up mould cavity faster. (Zhang Di, 2015).

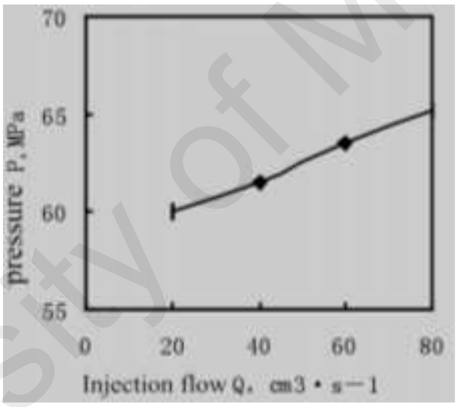


Figure 2.16: Injection flow versus injection pressure. Line chart from Zhang Di (2015).

Figure 2.17 (Dr. Hans-Joachim Graf, 2014) shows when injection pressure increases and temperature increases, rubber product has under fill (which is incomplete fill).

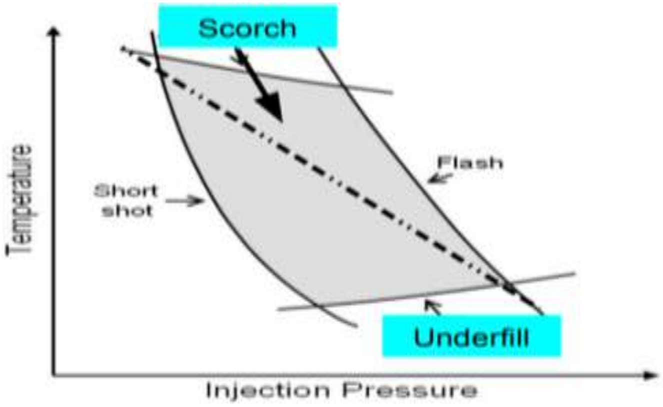


Figure 2.17: Injection pressure versus temperature. Line chart from Dr. Hans-Joachim Graf (2014).

Refer to Figure 2.17: when the temperature rises, the soften rubber with high viscosity and flows slowly into mould cavity (Hitoshi Nishizawa, 2015). This phenomena can affects the product becomes short mould, which is also known as under fill.

Figure 2.18 shows the injection time at different injection pressure, with changing mould temperatures: 170 ^{0}C, 180 ^{0}C and 190 ^{0}C. So, the injection pressure is maximum and resulting the injection time is faster, which is injection flow is shorter (Dr. Hans-Joachim Graf, 2015).

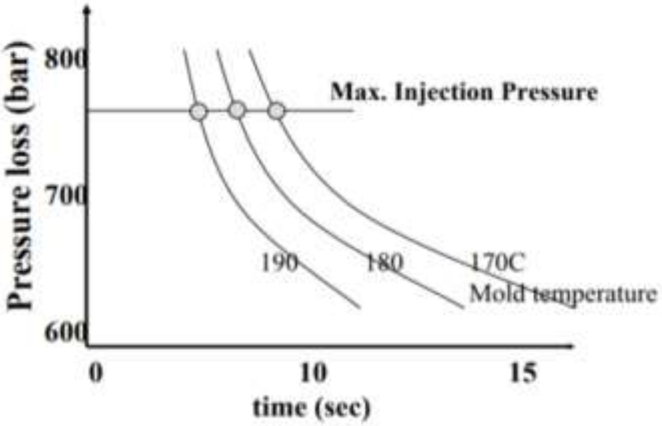


Figure 2.18: Injection time at various injection pressure with different mould temperature. Line chart from Dr. Hans-Joachim Graf (2015).

Rubber product has back grinding defect as shown in Figure 2019, where the rubber starts cure and thermal expansion at the gate or the parting line of mould cavity (DuPont Performance Elastomers, 2008). This can happen at highest injection pressure, which is the highest kinetic energy creates greatest heat by the rubber shears and friction at the parting line (DOW, 2012). So, the parting line of rubber product has shrinks and torn.

Figure 2.19: Rubber product has back grinding defect.

2.3.3 Temperature of Control Parameter

Types of temperature control for process parameter in rubber injection moulding machine are feeding temperature, injection temperature, and curing temperature.

Rubbers temperature is lower than plastics temperature to avoid pre-vulcanisation or scorch, which is before rubber become the final shape of product. Rubber injection temperature is 80 to 120 ^{0}C (Evan Mitsoulis 2017).

Feeding temperature rises inside the screw of barrel because heat created by friction between the rubber and the screw, as shown in Figure 2.20, which is due to shearing in screw rotation (Hitoshi Nishizawa, 2015).

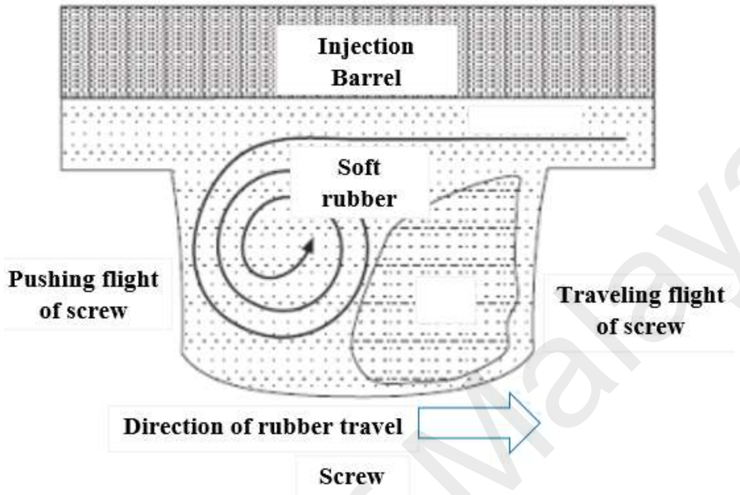


Figure 2.20: Friction between the rubber and the screw of barrel. Schematic diagram from Dynisco.

Figure 2.21 shows vulcanization time, which is curing time is faster when injection temperature increases (Dr. Hans-Joachim Graf, 2014).

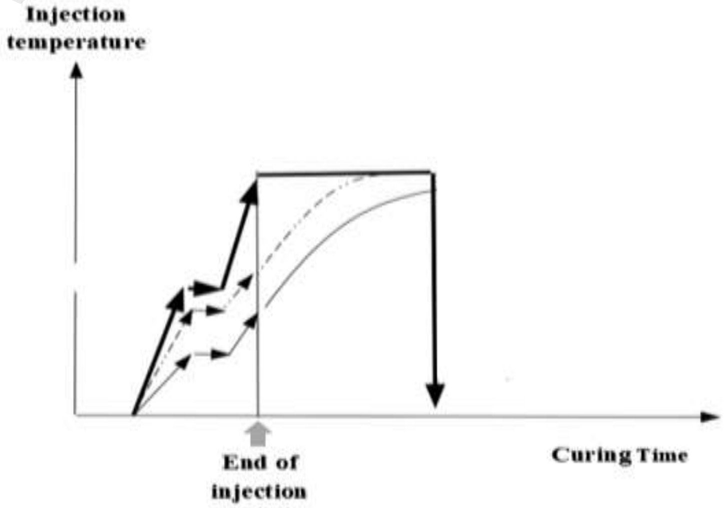


Figure 2.21: Curing time versus injection temperature. Line chart from Dr. Hans-Joachim Graf (2014).

Refer to Figure 2.21: when the temperature rises, the rubber becomes softer and flows easily to fill up mould cavity, then forming the rubber product as soon as possible. The crosslink of rubber chain is bonding faster together when greater heat generated, from rubber molecular friction during injection process (K.L. Mok, 2017). Therefore, injection time is shorter and indirectly the cycle time is faster.

Mould temperature, which is curing temperature increases can reducing the scorch time (is a time before rubber cures as a product) as shown in Figure 2.22 (Dr. Hans-Joachim Graf, 2014).

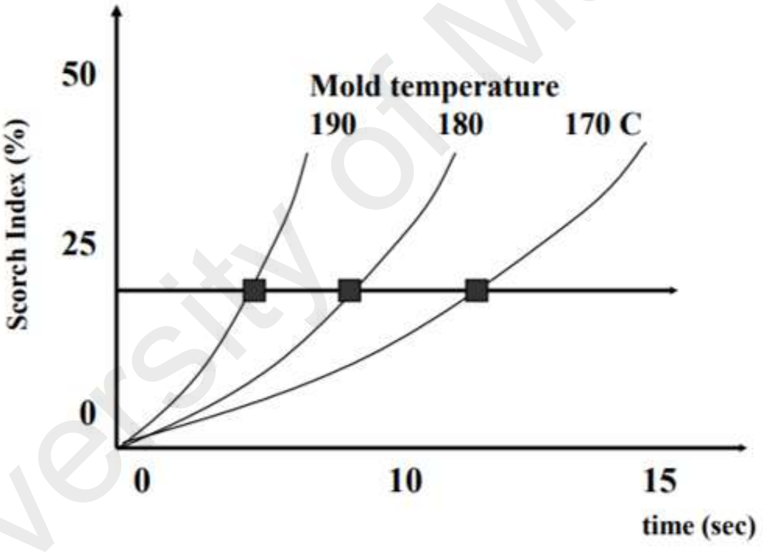


Figure 2.22: Scorch time versus different mould temperature. Line chart from Dr. Hans-Joachim Graf (2014).

Refer to Figure 2.22, cure time can reduces with higher mould temperature. When the temperature higher, the rubber become softer. So, the injected rubber flows faster into mould cavity (A.I. Isayev, 1989). This occurrences at the same time, is also shorter the cycle time.

Rubber product becomes distortion, as shown in Figure 2.23, caused by mould temperature too high (D.E. Packham, 2002). This distortion occur because rubber chains break, then rubber molecular in deformation. The product is softer and out of shape (David M. Sadler, 1989).

Figure 2.23: Products distortion.

2.4 Rubber Material

Characteristics of rubber for injection moulding are (Adam Skrobak, 2013 and A.I. Isayev, 1989):-

- Lower shear rate: Lower energy to generate lower heat, from friction between rubber and injection barrel. This can reduce rubber compound overheating and scorching.
- Lower viscosity: Rubber compound can injected to fill in the mould cavity easily.
- Optimum cure time: Rubber compound start to vulcanize after injected to fill-up the mould cavity.
- Higher rebound resilience or elasticity: Rubber compound able to spring back into shape.

- Lower compression set: Rubber compound has better resistance for permanent deformation.
- Rubber compound is highly non-Newtonian fluid, which is not follow Newton's law of viscosity, viscosity can change when under force to either more liquid or more solid.

Table 2.1: Application of common compound ingredients.

Compound Ingredients	Application
Carbon black	To strengthen the rubber molecules crosslink, which are increase in stiffness, tensile strength and abrasion resistance (A. Mostafa, 2010).
Plasticiser	To increase the viscosity of rubber for improve in flow rate (Raju, 2008).
Sulphur	To crosslink rubber macro-molecules together (L. González, 2005).
Zinc oxide	For cross-linking of rubber efficiently, reduces heat build-up and abrasion resistance (G. Heideman, 2004).
MBT	For rubber vulcanization faster at lower temperature (Ch. S. S. R. Kumar, 1997).
Amina	To deter the aging of rubber product (Vorapong Pimolsiriphol, 2007).

When the rubber temperature increases, heat is generating by shearing and friction, between rubber and the screw of injection barrel, as shown in Figure 2.24. The rubber can scorch because high shear rate (Hitoshi Nishizawa, 2015).

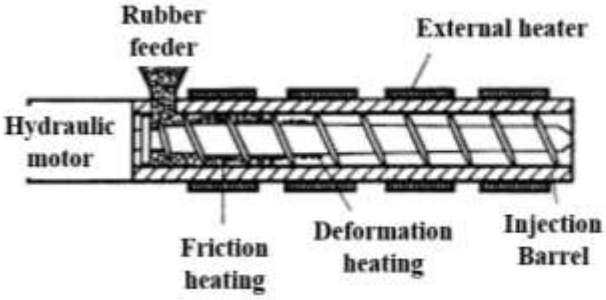


Figure 2.24: Heat is generating by shearing between rubber and the screw. Schematic diagram from Hitoshi Nishizawa (2015).

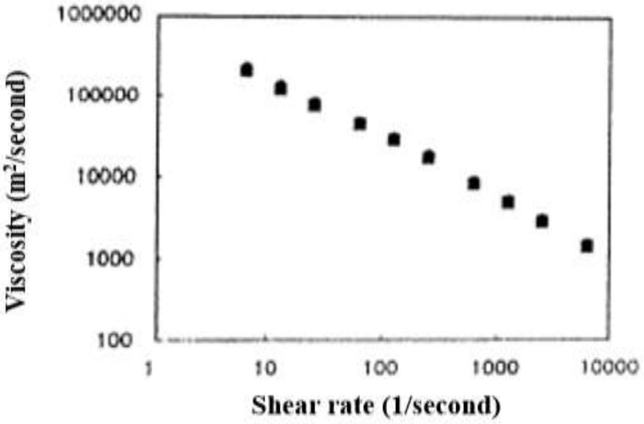


Figure 2.25: Shear rate versus viscosity. Graph from Hitoshi Nishizawa (2015).

Figure 2.25 shows that shear rate reduces with viscosity rises. The shearing between rubber and injection screw of barrel able to create higher temperature of the rubber, then the injected rubber becomes softer and flows into mould cavity is faster. Thus, the rubber viscosity is lower (Hitoshi Nishizawa, 2015 and Timco Rubber, 2019).

Good quality of rubber product is manufacturing must contained with optimum cure time. Hence, the rubber injection moulding manufacturer competent to produce parts with economical cost. Optimum cure time of rubber product is also as the time to reach optimum modulus (which is flat modulus) of quality product, as shown in Figure 2.26.

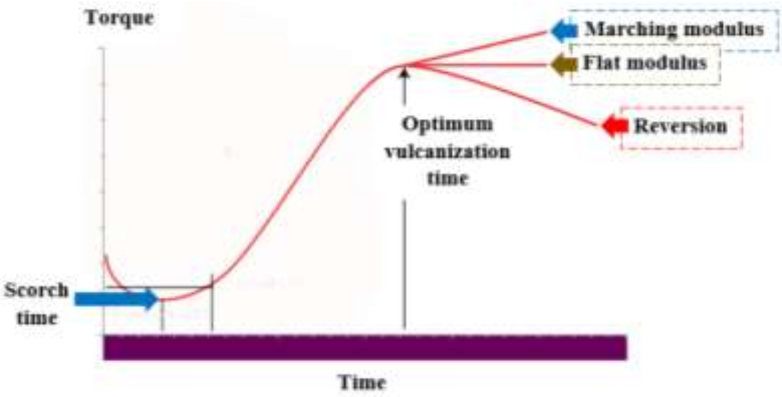


Figure 2.26: Rheograph shows optimum cure time of optimum modulus. Diagram from Akrochem Corporation.

The power energy applied to the rubber for distortion and reverted back to the original shape, this is interpret as rebound resilience (or also known as elasticity). The subject factors are: types of rubber, curing circumstances, and rubber compound formulations (Dr. Nabel Kadum Abd Ali, 2017). Figure 2.27 shows a test equipment for rubber rebound resilience (which is follow standard test method ASTM D1054).

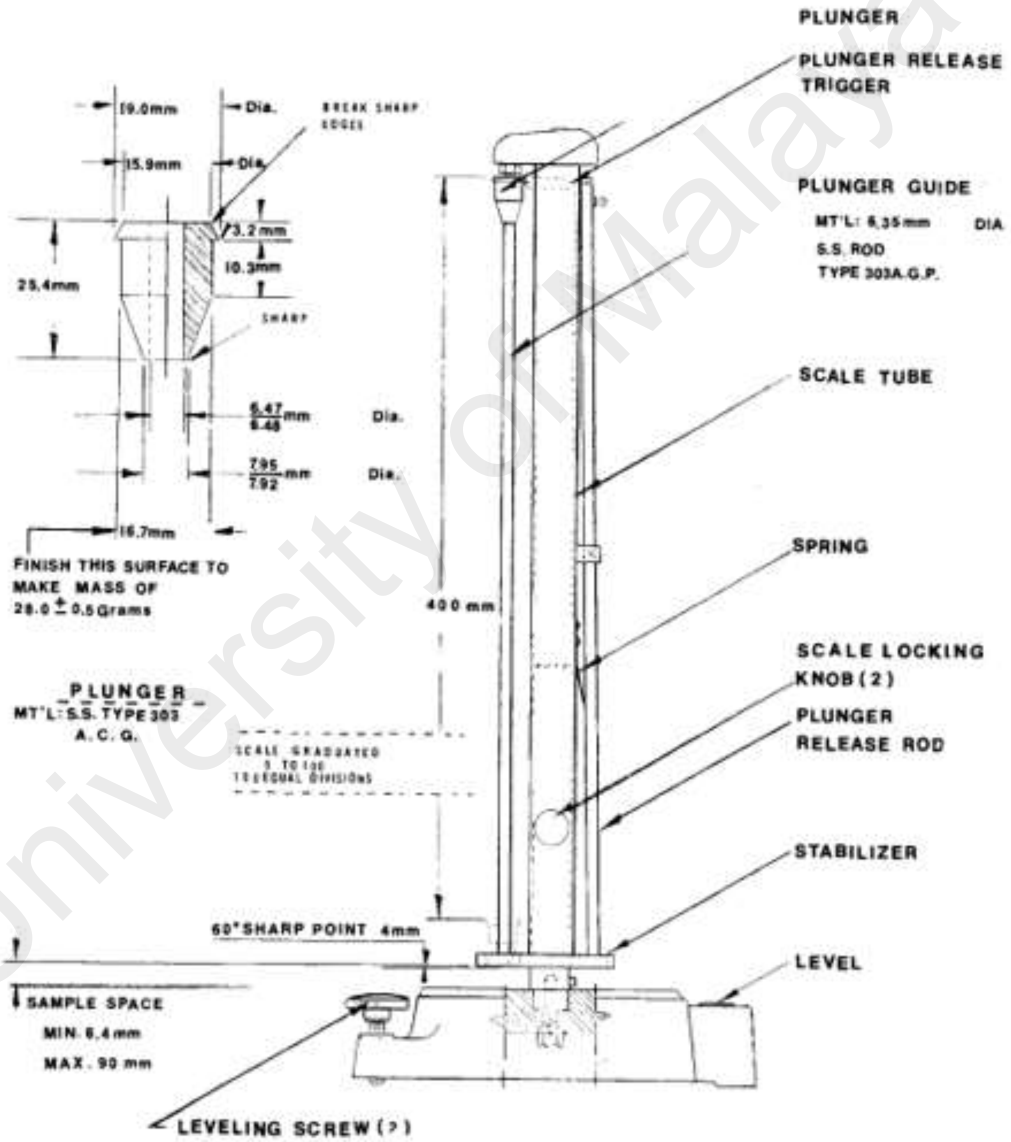


Figure 2.27: Standard test equipment for rubber rebound resilience by vertical rebound. Schematic diagram from ASTM International.

Permanent deformation of rubber product happens while the product compressed to a specified deformation, at a specified time and a specified temperature. This is a test, which is known as compression set. The product hardness increases with better crosslinking, the compression set is lower (Puspalatha D/O Sethu, 2006). Figure 2.28 shows a test equipment for rubber compression set. The standard test method is ASTM D395, which is follow from ASTM International.

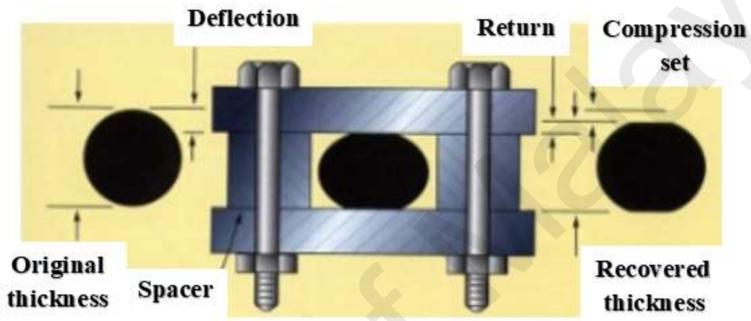


Figure 2.28: Test equipment for rubber compression set. Schematic diagram by Rick Hudson (2013).

Rubber is a non-Newtonian fluid. The viscosity of non-Newtonian fluid will affected by shear stress, which is known as pressure. The stress applied to the rubber, the rubber can becomes thicker and solid; the rubber also can becomes thinner and liquid.

Figure 2.29 shows that type of rubber behaviour on stress and viscosity. For shear thickening of rubber behaviour, the rubber viscosity rises by increased stress. In the contrasting behaviour of rubber for shear thinning, the rubber viscosity drops when stress is higher (Pokapū Akoranga Pūtaiao, 2010).

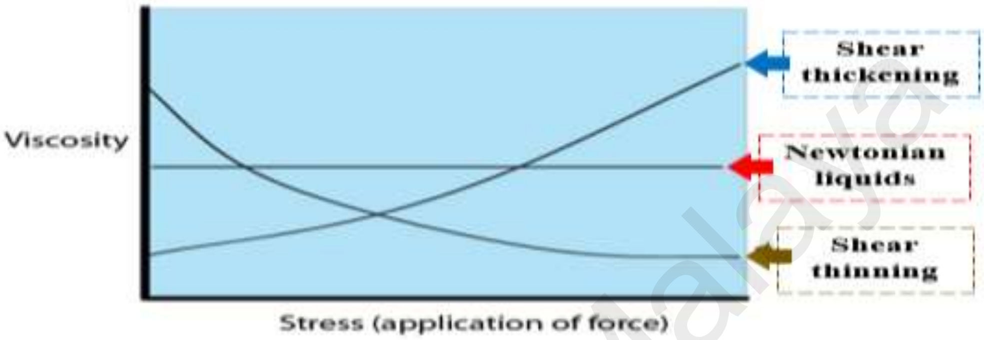


Figure 2.29: Type of rubber behaviour on stress and viscosity. Line chart from Pokapū Akoranga Pūtaiao (2010).

2.5 Mould of Rubber Injection Moulding

Rubber injection mould design with selected basic considerations (Karthik G L, 2015 and Chamnarn Thongmark, 2016) –

- Rubber product shrinkage
- Clamping force on the mould
- Particular type of rubber injection moulding machine
- Number of cavities inside the mould
- Types of mould
- Gate structure of mould
- Mould venting
- Mould maintenance

The mould with less effective parts to prevent extra cost. Nevertheless, in the long-lasting production, the mould can recover rubber product performance. Consequently, decreasing overall costs. Rubber injection mould made-up in design flexibilities with dimensional accuracy. Appropriately, it is to demand and develop promptly of the rubber products with superior features.

2.5.1 Rubber Product Shrinkage

Rubber products shrink after moulding and during moulding processes. The amount of shrink differs, is mostly determined by the rubber compound. Rubber mould is also affect shrinkage if being used the mould not considered for that specific compound.

The mould tolerances tend to be greater than the rubber product tolerances. The products made from silicone rubbers and fluorocarbon rubber have higher shrinkage matter. So, tolerance classes M1 and M2 are very tough to acquire in these rubbers. The product is unescapably distorted during de-mould from the mould, the products dimensions can be affected, and tolerances needed. The flash, which is from the extra rubber, tends to affect the product dimensions during the mould completely closing (ISO 3302-1: 2014).

Coefficient of thermal expansion of the mould leads to rubber products shrinkage. The coefficient of thermal expansion is the ratio of a material enlarges with differences in temperature.

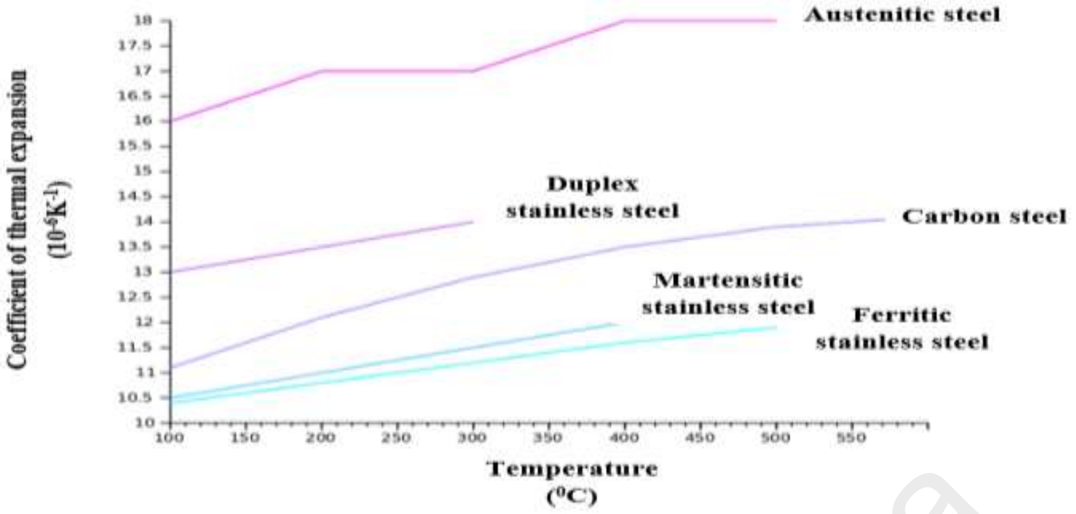


Figure 2.30: Coefficient of thermal expansion for some steel grades. Diagram by Jacek Halicki.

Figure 2.30 shows that the coefficient of thermal expansion versus temperature for some steel grades: ferritic stainless steel, martensitic stainless steel, carbon steel, duplex stainless steel and austenitic steel. The temperature increases when the coefficient of thermal expansion rises.

The rubber products weight decrease leads to shrinkage. The extreme pressure is used to inject rubber for fill up the mould cavity, this will affects the rubber in higher stress condition. The injection temperature raises, the soften rubber fill up the cavity too fast, and cause the excessive rubber flow out from the cavity. The rubber starts cure to become product with lightweight. The product distort will during de-moulding from the cavity. This also effects the product shrinkage at a later time (GLS Corporation, 2015).

2.5.2 Clamping Force on the Mould

The powerful force applied to a mould by the clamping unit of an injection moulding machine as shown in Figure 2.31. The clamping unit of a rubber injection moulding machine which is safe guaranteed and powerful holding together of the mould with clamping plates. The force unit is in tons such as, a 200 ton machine is capable to produce a maximum 200 tons of clamping force. Excessive flash can be solve by select a capable machine (Denny Scher, 2019).

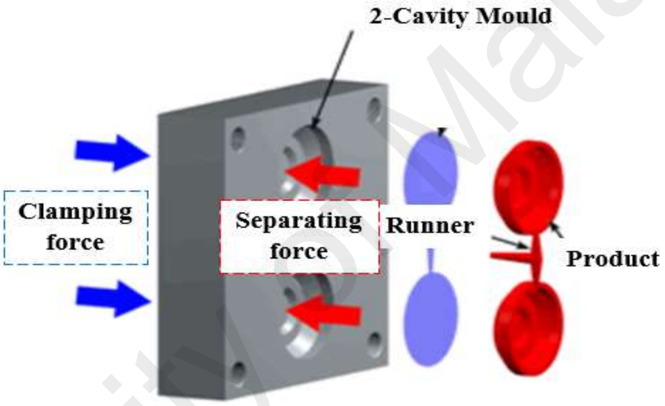


Figure 2.31: Clamping force applied to a mould. Schematic diagram from Denny Scher (2019).

2.5.3 Number of Cavities inside the Mould

Only single cavity is built for larger rubber product inside the mould. Multi cavities are: 2, 4, 6, 8, 12, 16, 24, 32, are built for rubber injection moulding on cost effectively. These numbers are designated for easily arranged in symmetry pattern, to ensure equal clamping force for each cavity (Professor Joseph Greene, 2000).

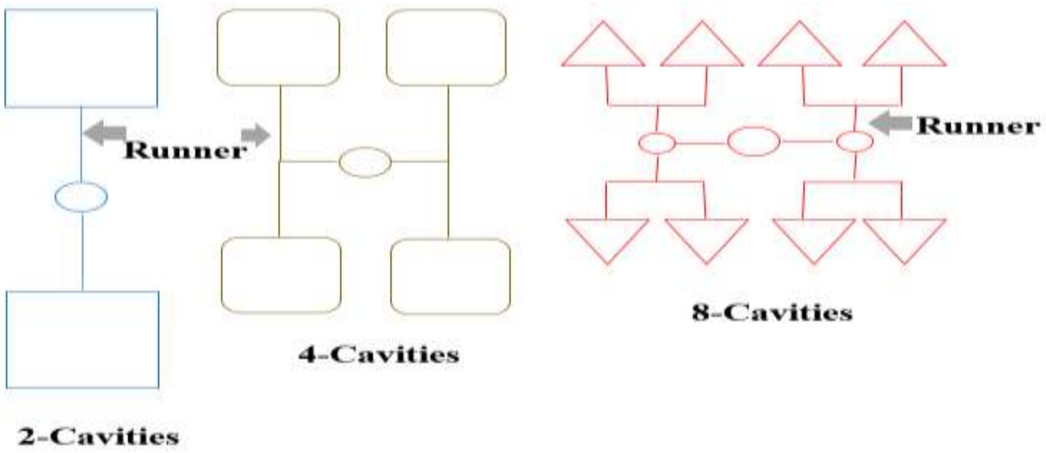


Figure 2.32: Examples for numbers of cavities layout.

Figure 2.32 shows that symmetry pattern for the multi cavities layout. Balanced flow into the cavities is a requirement for a quality product. This can be done by altering the runner size and length. The product becomes short mould caused by the runner diameter reducing too much.

2.5.4 Types of Mould

More commonly types of injection mould are: two plate mould as shown in Figure 2.33, and three plate mould as shown in Figure 2.34. Mould dimensions with tight tolerances. It must be heat treated to withstand high injection pressure and clamping force. Injection mould is the most expensive because with long life time, complexity design and difficulty in fabrication.

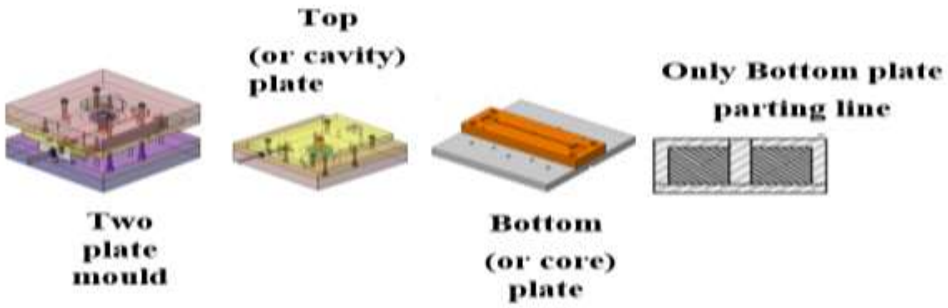


Figure 2.33: Two plate mould. Schematic diagram by K. Kyas (2012) and Robinson (2015).

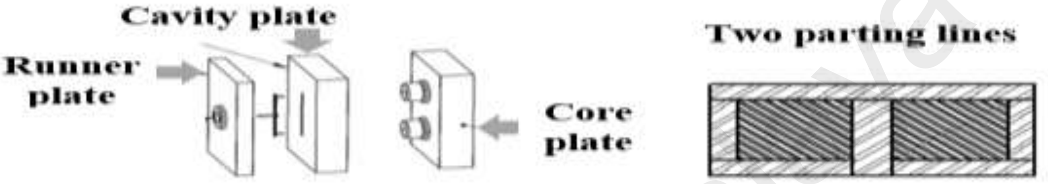


Figure 2.34: Three plate mould. Schematic diagram by Mark T. Maclean-Blevins (2018) and Robinson (2015).

Refer to Figure 2.33 and compare with Figure 2.34, two plate mould has one parting line (which is at core plate only), but three plate mould has two parting line (which is at both plate: core plate and cavity plate).

2.5.5 Gate Structure of Mould

An entrance for soften rubber injected through nozzle, and flows to the sprue of mould sprue, then lastly enters the mould cavity, as shown in Figure 2.35 (Vannessa Goodship, 2004). Two types of gates for injection moulding: manually trimmed gate and automatically trimmed gate.

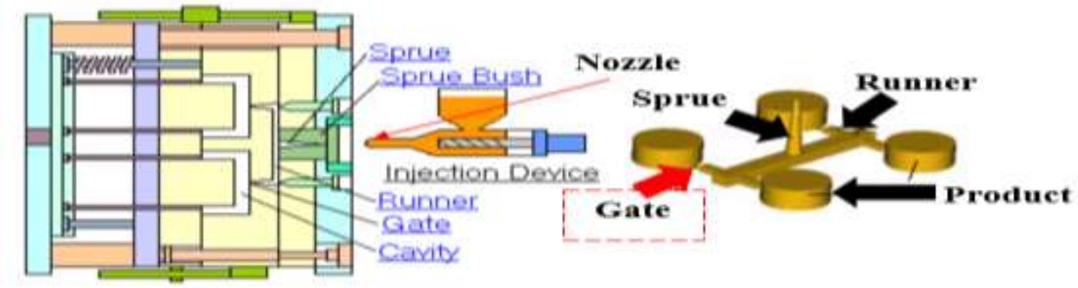


Figure 2.35: Gate location. Schematic diagram from Vannessa Goodship (2004).

Figure 2.35 shows that the gate is linking between the runner and the moulded product. The gate lets sufficient rubber flows to fill up the mould cavity and benefit to reduce shrinkage of the product.

Manually trimmed gate needs an operator using trimming tool to trim products from the runners because some rubber, such as natural rubber has high tensile strength and difficult to trim. This types of gate are: fan gate and diaphragm gate (or disk gate).

Automatically trimmed gate which is for rubber known as tear trimmed gate, an operator separate the products from the runners, without using trimming tool. This gate is sustaining cycle time constantly and minimizing gate marks. This types of gate are: pin gate and tunnel gate (Santa Clara University, 2006).

2.5.6 Mould Venting

Mould venting provide with an outlet for air or gas to escape to the atmosphere during bumping time (Indian Institutes of Technology, 2006). The venting design at the grooves, where opposite the gate of cavity. A vacuum system can be attached for alternative technique to troubleshoot air trapped (M.A. Wheelans, 1974).

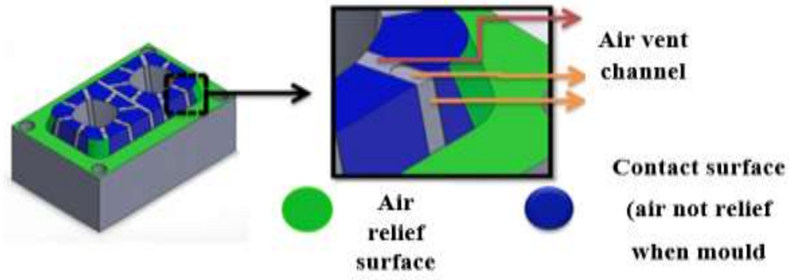


Figure 2.36: Example for air vent channel in the mould cavity. Schematic diagram from Diego Alves de Miranda (2019).

Figure 2.36 shows that air vent channel in the mould cavity (Diego Alves de Miranda, 2019).

2.5.7 Mould Maintenance

The product dimension is more accurately, the mould maintenance is more expensive. Common mould maintenance are (as shown in Figure 2.37): clean and lubricate the pins and bush, and clean the flash off.

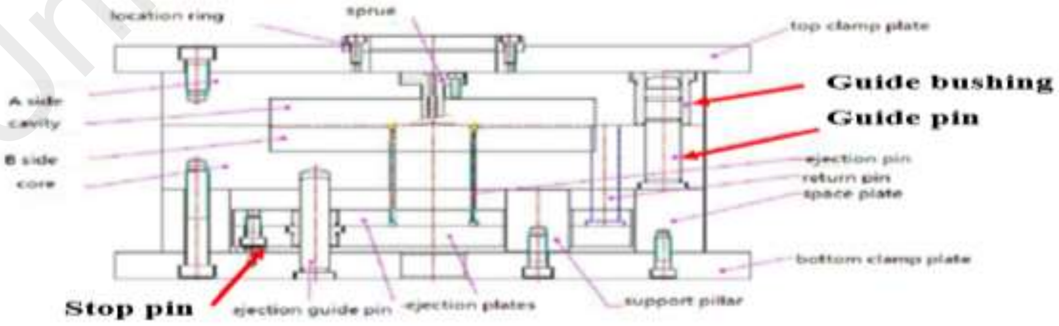


Figure 2.37: The guide pin and the guide bushing, must clean and lubricate after production run. Schematic diagram from Aco Mold (2019).

The mould cavity surface must clean beyond the parting line, checking then greasing pins and bushings, lastly stored at clean area with low humidity environment, as shown in Figure 2.38. This can prolong the mould life.

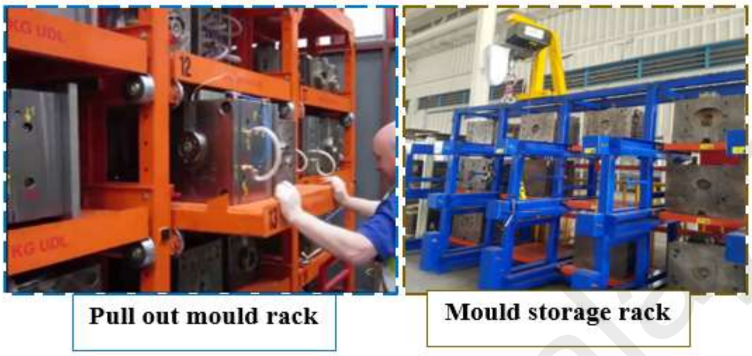


Figure 2.38: The mould stored at racking system. Photo from METSTO.

2.6 Taguchi Method

Genichi Taguchi was developing Taguchi methods to optimize the process parameters and improve the quality of products (Shyam Kumar Karna, 2012) in year 1950. Taguchi method is also used to identify an optimal combination of control factors in the process optimization. Taguchi philosophy defines that a product quality variation reduces will decrease the harm to manufacturing sector. This method is a Design of Experimental (DOE) to use Taguchi Orthogonal Array (OA) and Signal-to-Noise (S/N) ratio for study the performance characteristics in manufacturing industries (Kam Hoe Yin, 2015).

2.6.1 Taguchi Orthogonal Array (OA)

OA is a type of general factional factorial. OA is used to select subset of combinations of control factors at multiple levels at balanced equally (Yong Guo, 2003).

Table 2.2: Example for OA table. Table by Jüri Majak (2016).

		Number of Parameters (P)										
		2	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Number of Levels (L)	**2**	L4	L4	L8	L8	L8	L8	L12	L12	L12	L12	L16
	3	L9	**L9**	L9	L18	L18	L18	L18	L27	L27	L27	L27
	4	L16	L16	L16	L16	L32	L32	L32	-	-	-	-
	5	L25	L25	L25	L25	L25	L50	L50	L50	L50	L50	L50

Table 2.2 shows that example for OA table. From the Table 2.2, consider an experiment with 3 parameters and 3 levels of each parameter (P = 3 and L = 3). So, choose **L9** in this example as the experiment.

2.6.2 Signal-to-Noise Ratio (S/N Ratio)

S/N ratio is a measurement that compares the level of desired signal to the level of background noise. S/N ratio identify control factor settings that minimize the effects the noise factors. Taguchi stated that quadratic loss is the cost incurred after the product sale, which quality characteristic changes from the target value. Three most important of S/N ratios to well-defined for a variation of problems are (Ali Azadeh, 2012) -

1) Larger-the-better:

   S/N_L ratio = $-10 \log_{10} (1/n \sum^{n}_{i=1} 1/y_i^2)$, where n = the number of replications.

   This is used for problems where maximization of the quality characteristics.

2) Smaller-the-better:

   S/N_S ratio = $-10 \log_{10} (1/n \sum^{n}_{i=1} y_i^2)$

   This is designated for problems where minimisation of the quality characteristics.

3) Nominal-the-best:

   S/N_N ratio = $10 \log_{10} (\mu^2/\sigma^2)$, where μ = mean and = standard deviation.

   This is selected for problems where to minimize the mean square (μ^2) error to a specific target value.

The higher the S/N ratio is the best result for each category of characteristic.

2.7 Analysis Of Variance (ANOVA)

ANOVA is a statistical study for identifying changes in group (which is known as level) means when there is one parametric (or parameter) reliant on variable and one or more independent variable (which is as known as factor) (Steven F. Sawyer, 2009). There are two important ANOVA techniques: one-way ANOVA and two-way ANOVA.

2.7.1 One-Way ANOVA

The one-way ANOVA is a single factor ANOVA, which is only one independent variable or factor. The one-way ANOVA compares the means of the samples or groups in order to make inferences about the population means (Robert A. Horn, 2008). Table 2.3 shows that a one-way ANOVA table (Thomas Scofield, 2000).

Table 2.3: A one-way ANOVA calculations. Table from Thomas Scofield (2000).

Source	**SS**	**df**	**MS**	**F**
Model / Group	SSG	k -1	MSG	MSG / MSE
Residual / Error	SSE	n - k	MSE	-
Total	SST	n-1	-	-

From the Table 2.3 -

k = the number of groups

n = the (total) sample, irrespective of groups

df = degrees of freedom

SST = sum of squares total

SSG = variability between group means

SSE = variability within groups means

SS = sum of squares

MS = mean square

MSE = mean square of the error

MSG = mean square of the group

F = F statistic (or F value)

2.7.2 Two-Way ANOVA

Two-way ANOVA has two independent variables. This ANOVA is more effective to study two factors concurrently, rather than individually. A two-way ANOVA is considered to evaluate the interrelationship of two independent variables on a dependent variable. This ANOVA compares numerous groups of two factors. The ANOVA has multiple samples for each variable. A two-way ANOVA has three principles: replication, randomization and local control (Ruairi J Mackenzie, 2018).

2.8 Conclusion

Rubber injection moulding manufacturers have a challenging process to make rubber products, which is meeting the customer requirements at minimum cost, effectiveness of productivity and best quality. In the worldwide competition, industrialists using many method to optimize process parameters. So, the process optimization in this research resolved by using Taguchi method and ANOVA.

CHAPTER 3: METHODOLOGY

3.1 Introduction

This chapter introduces the Taguchi method used for this research. In the process optimization, the method used to test and assess experiments by define the control factors at the best levels. This chapter defines optimum parameter conditions with cycle time reducing and material saving, but products (Figure 3.1) quality is maintained and meeting customers' requirements at the lowest cost.

Figure 3.1: Experimental product.

3.2 Experimental Methodology

Research methodology in flow chart shown in Figure 3.2. It identifies method to complete every experiment in the process optimization.

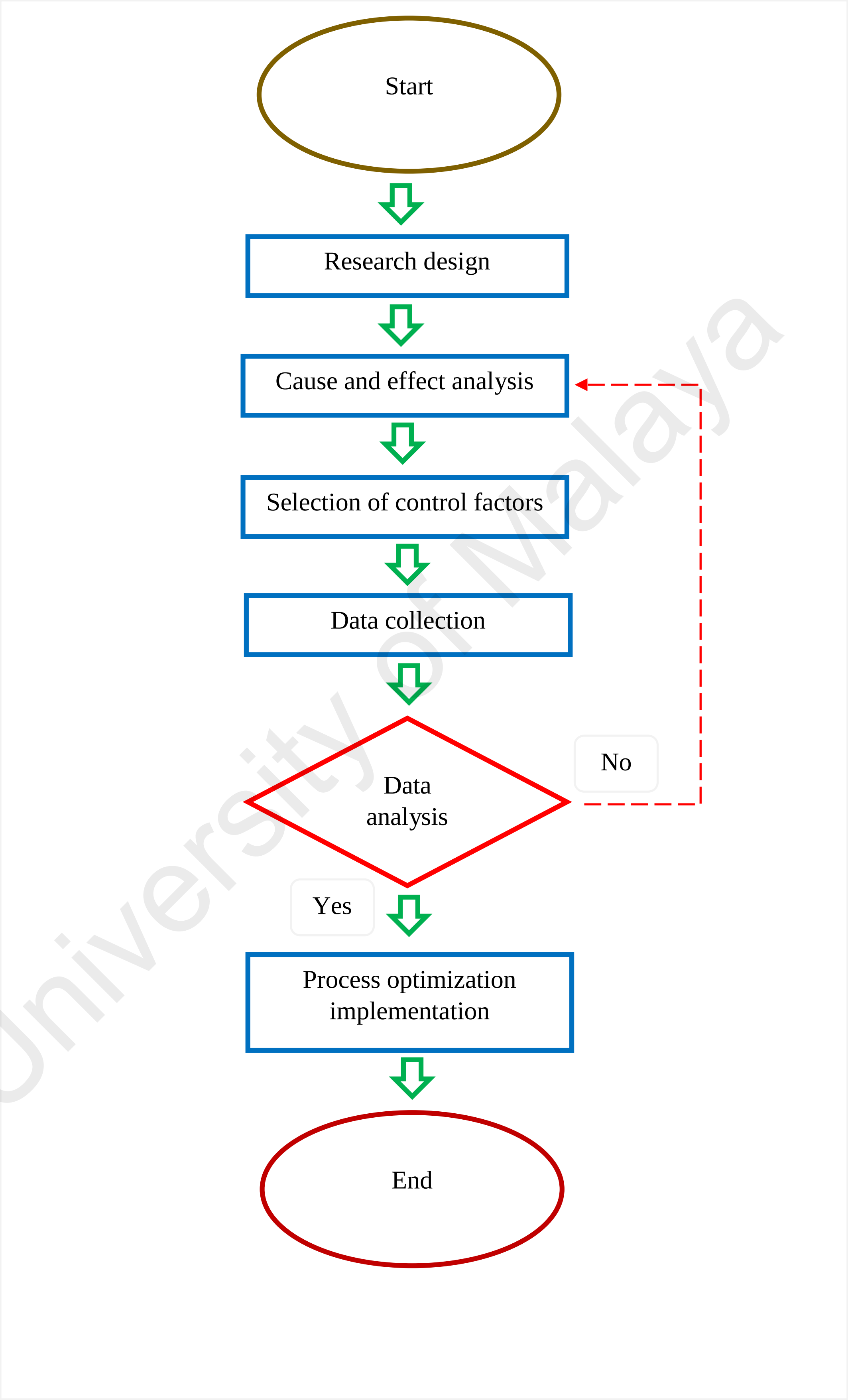


Figure 3.2: Flow chart of research methodology.

3.2.1 Research Design

This methodology characteristic is to gather information on process parameters (temperature, speed and pressure) for process optimization by using Taguchi method. It studies all the control factors and define their main effects. It develops a method based on Taguchi method for optimum process.

The research have been performed by using Taguchi method (orthogonal array and SN ratio) and ANOVA analysis (one-way ANOVA).

The key element of Taguchi method in the parameter design is to optimize the rubber injection moulding process for sustaining products quality without an increase in cost. Taguchi orthogonal array is used to analyse the experiments data and predict the products quality. SN ratio is used to reduce inconsistency in a process or product by reducing the effects of uncontrollable (noise) factors.

ANOVA analysis is used to test differences between two or more means. The one-way ANOVA analysis is used to compare the means between the groups and determines whether any of those means are statistically significantly different from each other.

3.2.2 Cause and Effect Analysis

This methodology characteristic is to identify something happened or might happen by categorizing the potential causes of a problem. It shows relationships between contributing factors.

Cause and effect analysis was developed to determine the potential root cause before experiment started to test and prove it. It is used to explore five major categories: machine, method, material, man and mould.

The analysis for longer cycle time as shown in Figure 3.3. This experiment will study machine parameters: speed, pressure and temperature.

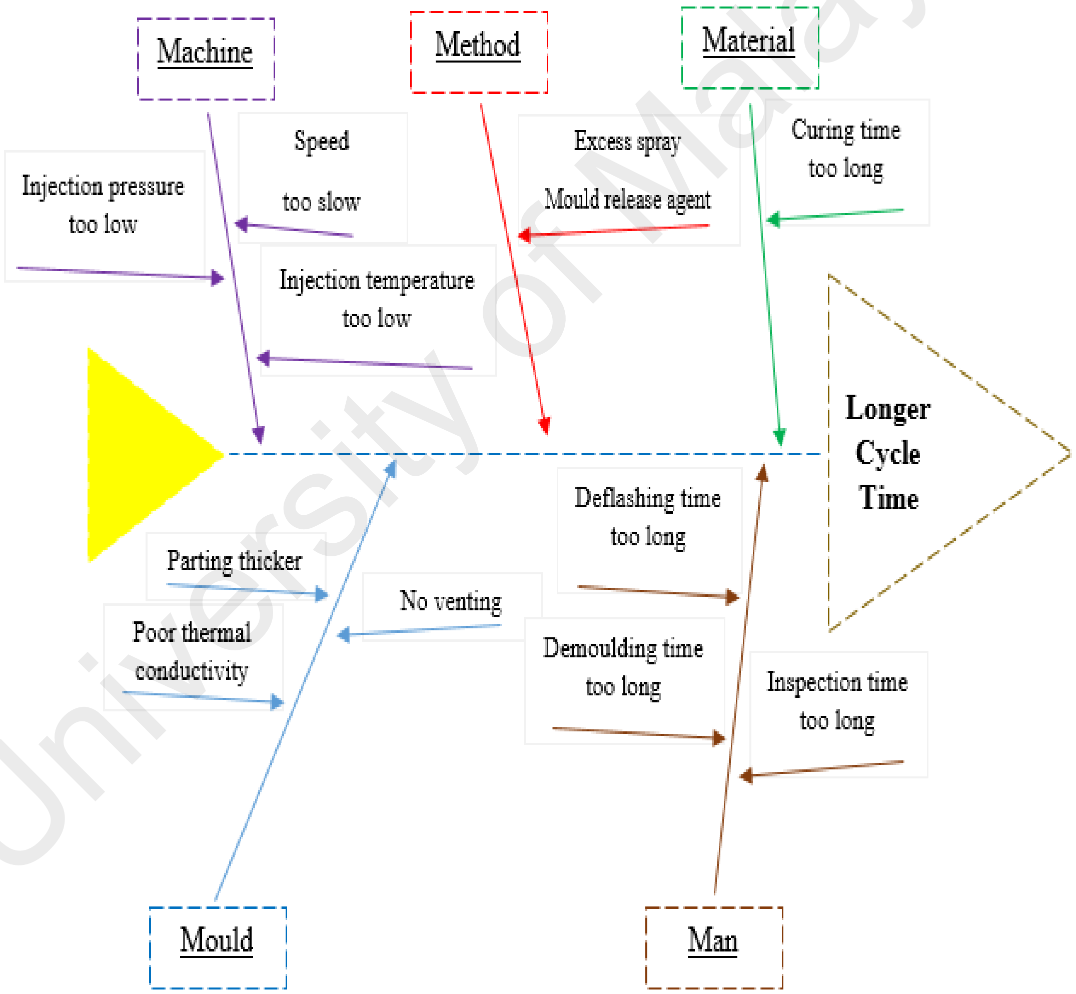


Figure 3.3: Fish bone diagram for longer cycle time in rubber injection moulding.

The analysis for material saving as shown in Figure 3.4. This experiment will also study machine parameters: speed, pressure and temperature.

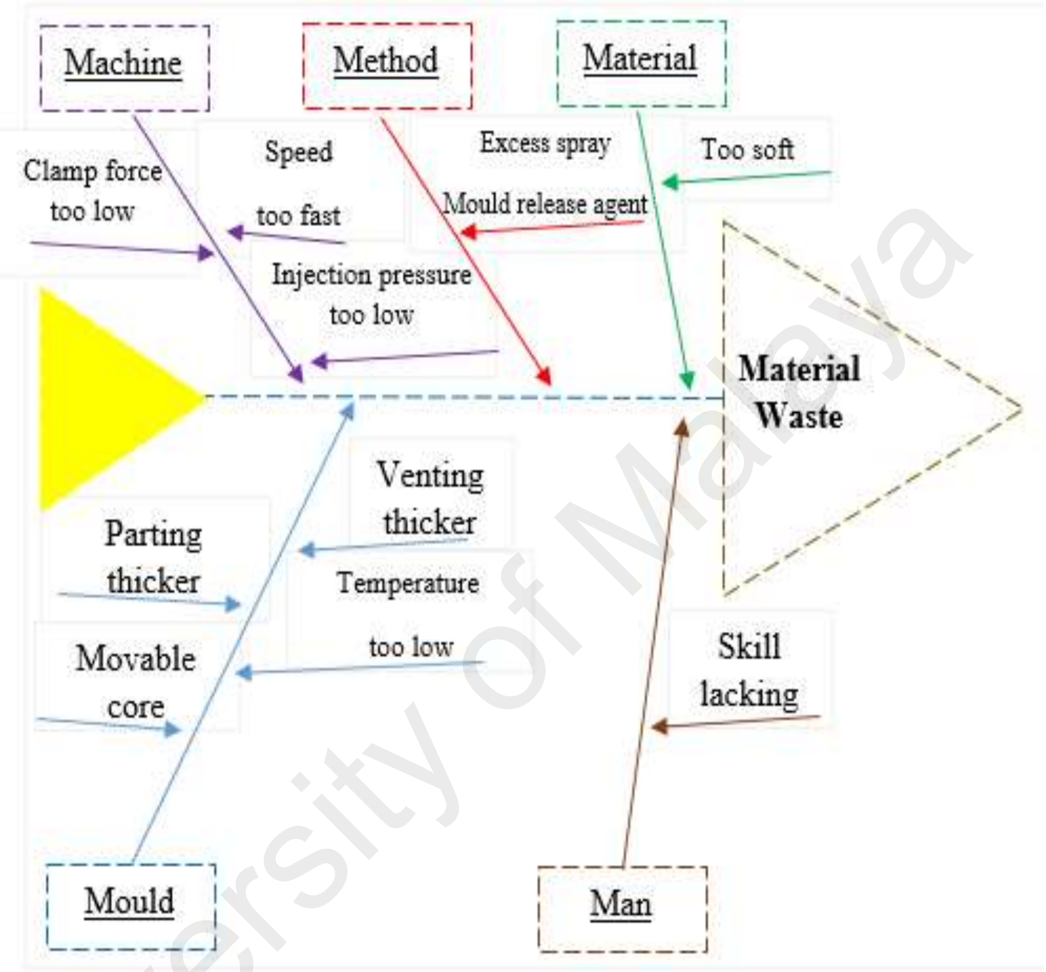


Figure 3.4: Fish bone diagram for material waste in rubber injection moulding.

The analysis for maintaining products quality: hardness and dimension as shown in Figure 3.5. This experiment, remain as same to study machine parameters: speed, pressure and temperature.

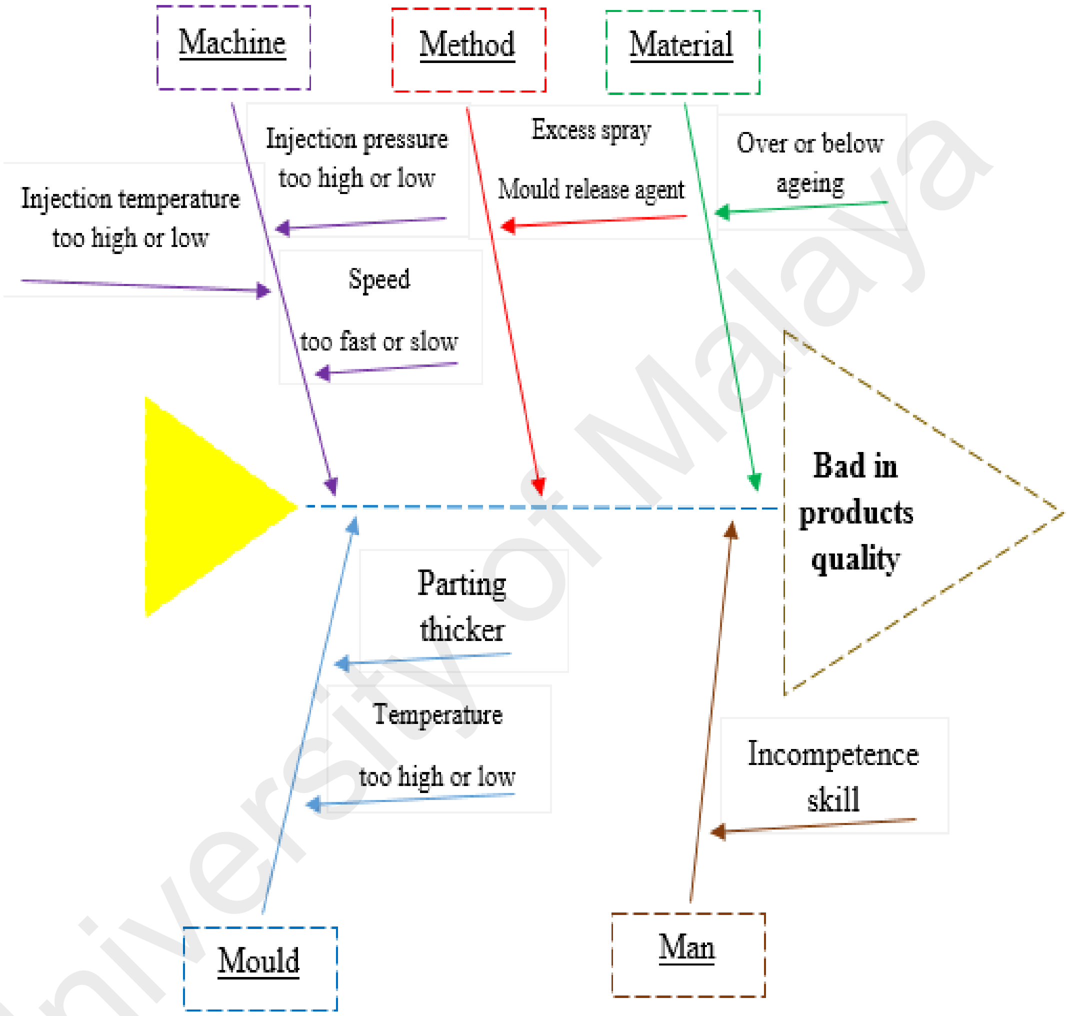


Figure 3.5: Fish bone diagram for bad products quality in rubber injection moulding.

Table 3.1 shows the severity ranking for Potential Failure Mode and Effect Analysis (PFMEA) on machine parameters. Risk Priority Number (RPN) is calculated by multiplying severity, occurrence and detection.

Table 3.1: Table for PFMEA on machine parameters.

Potential Failure Modes	Potential Effect (s) of Failure	Severity	Current Process Controls (Prevention)	Occurrence	Current Process Controls (Detection)	Detection	RPN
High or low pressure / speed to feed in compound.	Products short mould.	5	Preventive maintenance on machine.	5	Double visual inspection.	5	125
High or low feeding temperature.	Products short mould.	5	Preventive maintenance on machine.	5	Double visual inspection.	5	125
High or low injection temperature.	Products cosmetic defects.	5	Preventive maintenance on machine.	5	Double visual inspection.	5	125
High or low ejection pressure / speed.	Products torn.	5	Preventive maintenance on machine.	5	Double visual inspection.	5	125
High or low injection pressure / speed.	Products cosmetic defects.	5	Preventive maintenance on machine.	5	Double visual inspection.	5	125
High or low cure temperature.	Products migration.	6	Verification by portable thermometer.	5	* Cutting product to check under cure. * Check product hardness.	5	150
Long or short cure time.	Products migration.	6	Performed buy-off check.	5	* Cutting product to check under cure. * Check product hardness.	5	150
High or low cure pressure.	Product lifetime shorten.	6	Preventive maintenance on machine.	5	* Automatic stop during bumping.	5	150

Refer to Table 3.1, to discover possible failures in process optimization. This table helps to reduce failure during process improvement. PFMEA has two stages: classify potential failure and recognise their impact.

3.2.3 Selection of Control Factors

The control factors are selected for process optimization on machine parameters, mould design, material used and experimental methods. Taguchi orthogonal array is selected for experimentation.

Table 3.2 shows the control factors selection from the Figure 3.6. The factors are selected because it will affect Signal-to-Noise ratio.

Table 3.2: Control factors selection.

Number of Selection	Control Factors
1	Machine parameter
2	Mould
3	Material
4	Method

3.2.3.1 Experimental Machine Parameter

Rubber injection moulding has advantages over compression and transfer moulding in terms of part quality and efficiencies. Figure 3.6 shows injection machine parameters of touch screen controller: up down setting, mould slide setting, feeding & inject setting, and bumping setting.

Figure 3.6: Machine parameters are displayed on a touch screen.

It involves automatic feeding, heating and plasticization of the rubber mix. The injection moulding process has adjustment control with utilities requirement shown in Table 3.3 by Dr. Hans-Joachim Graf (2015).

Table 3.3: Rubber injection moulding process has four common adjustment control.

Factors Requirement	Control Requirement			
	Feeding	Injection	Bumping	Curing
Pressure (kg/cm^2)	100 to 130	60 to 160	60 to 80	Subjected to mould size.
Speed (%)	45 to 70	30 to 90	30 to 80	Not applicable.
Temperature (^{0}C)	75 to 80	75 to 100	Subjected to rubber material.	Subjected to rubber material.

3.2.3.2 Experimental Mould

The rubber injected through a runner and gates into mould cavity under much pressures. A. Skrobak (2013) note that, higher mould temperatures 150 to 200 ^{0}C can be applied, because of smaller temperature differences inside and outside the product. This can shortens the vulcanization time, reference from Dr. Hans-Joachim Graf (2014). The force of the clamping unit keeps the mould closed which allows to produce parts with high precision.

Products dimension depends on mould (Figure 3.7) material shown in Table 3.4. Table 3.4 shows that the most common mould properties reflected in rubber injection moulding, which are indirectly expose on product quality.

Table 3.4: Experimental mould properties.

Mould Characteristics	Mould Properties
Polish ability	Roughness 0.029 µm minimum and flatness of products surface. Note from Michal Stanek (2013).
Surface treatment	Chroming 20 micron minimum for abrasion resistant surface to the mould. Note from Menges (2001).
Thermal conductivity	Conduct heat 0.90 W/(m.K) to the natural rubber with 81% to 100%. Note from Charles A. Harper (2004).
Compression strength	Must be withstand the minimum force up to 1 ton/cm^2 of projected surface. Steel of hardness is 38 to 60 HRC. Note from Randy Kerkstra (2016).
Class M	Metric tolerances in class M3, used by ISO 3302-1, which is also used for good quality product. This class indicates a commercial product.

Figure 3.7: Experimental mould is a two plate mould with 16 cavities.

Figure 3.8 shows that fan gate with measured dimension for experimental mould. Fin gate is a wide edge gate. It permits rapid filling into the cavity through a large entry gate. It is used to have product dimension accurately and solve product warpage (which is known as shape bend).

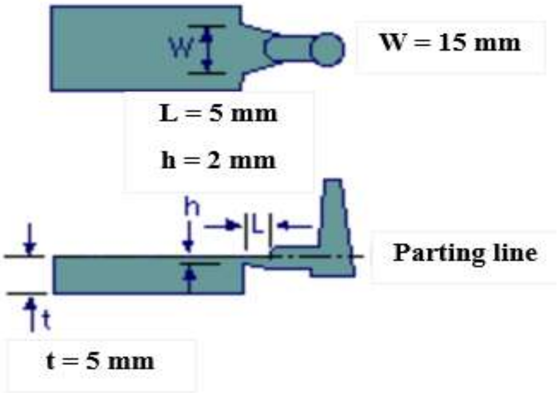


Figure 3.8: Fan gate of experimental mould.

3.2.3.3 Experimental Material

Experimental material for curing system in rubber injection moulding shown in Table 3.5, reference from Läroverket AB, (2007). Table 3.5 shows that compound formulation is to chemically crosslinks together at rubber molecular level, forming networks or long chain between the molecules, and transforming to become product with improved strength and elasticity.

Table 3.5: Curing system in common use.

Compound Formulation	Parts per Hundred Rubber
Natural rubber (polymer of isoprene)	100
Filler (carbon black as shown in Figure 3.9, silica)	50
Processing aid (plasticiser as shown in Figure 3.10)	5
Vulcanizing agent (sulphur as shown in Figure 3.11)	1.4
Activator (zinc oxide as shown in Figure 3.12, stearic acid)	3
Accelerator (MBT as shown in Figure 3.13, MBTS, DPG)	0.5
Anti-degradant (Amina as shown in Figure 3.14)	1

Figure 3.9: Carbon black.

Figure 3.10: Plasticiser.

Figure 3.11: Sulphur.

Figure 3.12: Zinc oxide.

Figure 3.13: MBT.

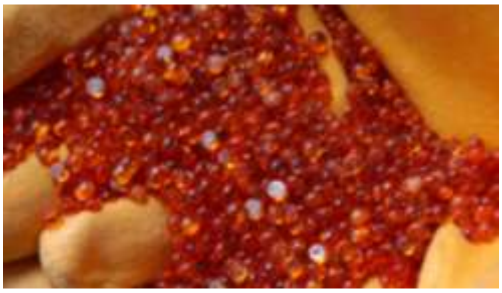


Figure 3.14: Amina.

3.2.3.4 Experimental Method of Process Flow

Process flow for rubber injection moulding shown in Figure 3.15. The flow is describing, executing and developing for process optimization in rubber injection moulding. This also help to has clear prospect, idea and foresee for those improvement.

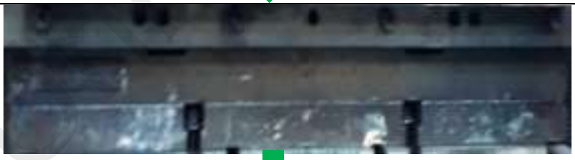
	1) Plastification step: I. Feeding rubber from the feeding screw. II. Soften rubber inside the injection barrel.
	2) Injection step: filling of mould cavity: I. The heating platen hold the mould by clamping system during injection.
	3) Vulcanization step: I. The clamping system hold the mould during vulcanization.
	4) De-moulding step.

Figure 3.15: Process steps for injection moulding of rubber.

Figure 3.16 as below shows the control structure of rubber injection moulding machine. This structure is important for machine to work without breakdown. So, machine maintenance is frequently implemented to guarantee optimum working conditions and extend the life time of the machine parts.

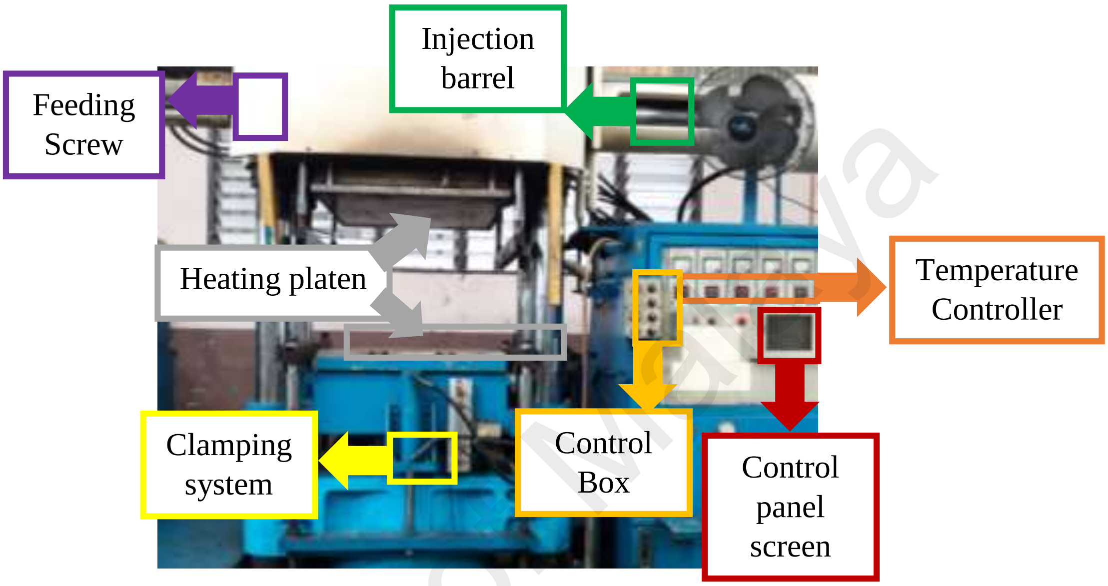


Figure 3.16: Control structure of rubber injection machine.

Table 3.6 as below shows the function of rubber injection moulding machine components.

Table 3.6: Function of rubber injection moulding machine components.

Item	Components	Function
1	Feeding screw	Rubber enter the injection barrel through the feeding screw.
2	Injection barrel	1) To plasticize the rubber before pushes the soften rubber to the injection unit. 2) The heated rubber is kept inside the injection barrel and queued-up before next injection cycle.
3	Heating platen	1) The injection mould is heated by this platen. 2) The movable or bottom platen moves up mould with clamping force, during rubber injection and curing process.
4	Clamping system	1) The mould is holds together by clamping system under pressure. 2) It pushes by opening and closing the mould.

5	Temperature controller	To control temperature of: 1) Mould. 2) Feeding 3) Injection 4) Runner plate.
6	Control box	To control movement manually of: 1) Opening and closing mould. 2) Emergency button. 3) Feeding and injection unit.
7	Control panel screen	To control parameters of: 1) Temperature. 2) Pressure. 3) Speed. 4) Time.

3.2.3.5 Experimental Method by Using Taguchi Method

The Taguchi method used to optimize the process with orthogonal array (shown in Table 3.7) robust design. The Signal-to-Noise (S/N) ratio (shown in Table 3.8) and the one-way Analysis Of Variance (ANOVA) (shown in Table 3.9) are employed to study the performance characteristics.

Table 3.7: Orthogonal Array.

		Number of Parameters									
		2	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Number of Levels	**2**	L4	L4	L8	L8	L8	L8	L12	L12	L12	L12
	3	L9	L9	L9	L18	L18	L18	L18	L27	L27	L27

Table 3.8: S/N ratio formulas. Reference from Zillur Rahman (2008).

Characteristic	**S/N ratio**
Nominal-is-best	$10 \log_{10} [\bar{y}^2/s^2]$
Smaller-is-better	$-10 \log_{10} [\sum (y^2/n)]$
Larger-is-better	$-10 \log_{10} [\sum (1/y^2)/n]$

Table 3.9: One-way ANOVA table formulas. Reference from Douglas C. Montgomery (2009).

Source	Sum of Square, SS	degree of freedom, df	Mean Square, MS	F statistic
Group	$SSG := \sum_{i=1}^{k} n_i(\bar{x}_i - \bar{x})^2$	k - 1	$MSG = \frac{SSG}{k-1}$	$\frac{MSG}{MSE}$
Error	$SSE := \sum_{i=1}^{k}\sum_{j=1}^{n_i}(x_{ij} - \bar{x}_i)^2$	n - k	$MSE = \frac{SSE}{n-k}$	
Total	SST = SSG + SSE	n - 1		

In process design of Taguchi method, there are three stages shown in Table 3.10. Note by Shyam Kumar Karna (2012).

Table 3.10: Three stages for process design of Taguchi method.

Stages	Design	Process
1	System	System selection for given objective function.
2	Parameter	Parameter selection with optimum levels.
3	Tolerance	Tolerance determination for each parameter level.

3.2.4 Data Collection

Data collected to gather information for process optimization, achieve research objectives, and assess results. Data collection is a process of gathering data to reduce cost, time and waste. Data collected based on actual experimental work. The data is defined base on control factors by using Taguchi method.

Four steps to collect data -

1) Classify problems:
    i. Conduct an assessment.
    ii. Explore potential causes of a problem.

        iii. Situation consideration such as customer requirements.

2) Choose matters and set objectives:
    i. Align with research purpose.
    ii. To have a written plan.
3) Organise data collection:
    i. Qualitative data which is in the form of words to describe qualities or characteristics by using statement or surveys.
    ii. Quantitative data which is in the form of numbers to address “how many” aspects of a research objectives by using instruments.
4) Gather or collect data.

3.2.5 Experimental Analysis

Data analysis is to check and convert the result by using S/N Ratio to achieve an optimum parameter. Data analysis using One-way ANOVA analysis to validate the results, analyse the differences among the means of the group based on their variances and identify the significant parameters.

As in rubber injection moulding manufacturing processes, testing can be summarized into 4 categories:

1) Quality assurance test as specified in ISO 17025.
2) Specifications such dimension (ASTM D3767), weight and density (ASTM D297) are referenced by both manufacturer and customer.
3) Material tests like hardness (ASTM D2240), rheology (ASTM D3835) and Mooney viscosity (ASTM D1646).
4) Performance tests (not applicable on this experiment).

3.2.5.1 ISO 17025

ISO 17025 is the key standard used by testing and calibration laboratories. It specifies the general requirements for the competence to be able to execute tests and calibrations.

The ISO needed for:

1) To assurance in the test results.
2) To assurance on quality.
3) To show technical competency.
4) To show for generating valid results.

3.2.5.2 Digital Calliper

The use of digital calliper is for measuring dimensions ≥ 30 mm on rubber as specified in ASTM D3767. Apply normal pressure on thumb roller to close the outside measuring faces, start to measure on the product as shows in Figure 3.17.

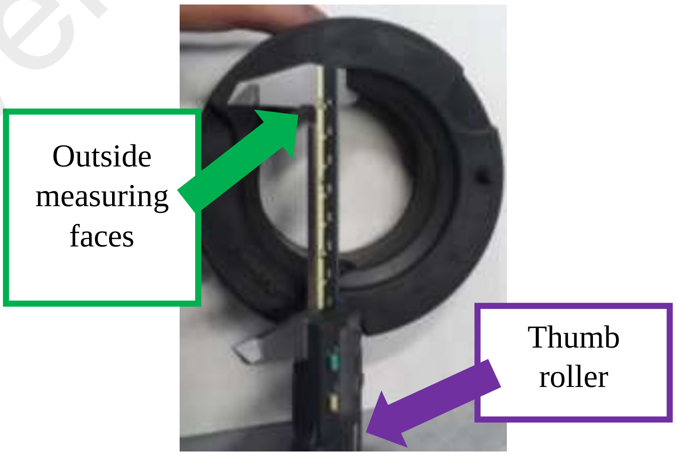


Figure 3.17: Digital calliper.

3.2.5.3 Digital Weighing Scale

Place the product on the weighing platform to weigh as shows in Figure 3.18. Take the reading when the stable indicator is displayed.

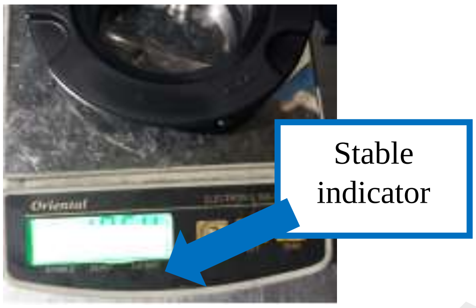


Figure 3.18: Digital weighing scale.

3.2.5.4 Densimeter

The densimeter or specific gravity tester shows in Figure 3.19, used to measure solid and liquid specific gravity of the moulded rubber as specified in ASTM D297.

Procedures to measure as below:

1) Place the test piece gently on the sensor. The weight of test piece will be displayed.
2) Press “Enter” key after the stable mark “o” appeared.
3) Pick the test piece and place the test piece softly into the middle of water tank.
4) Press “Enter” key.
5) Take the reading on the display after the stable mark “o” appeared.

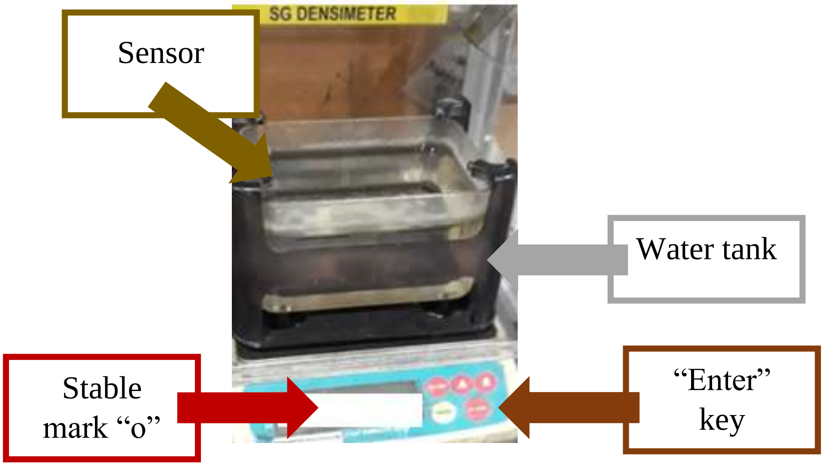


Figure 3.19: Densimeter.

3.2.5.5 Hardness Tester

The “Shore A” durometer or hardness tester shows in Figure 3.20, is to measure hardness of a rubbers product as specified in ASTM D2240.

Measuring steps as below:

1) Mounting the durometer to the stand.
2) Place the product at bottom of the durometer.
3) Pressurized on the flat surface of the product.
4) Take the reading on the display.

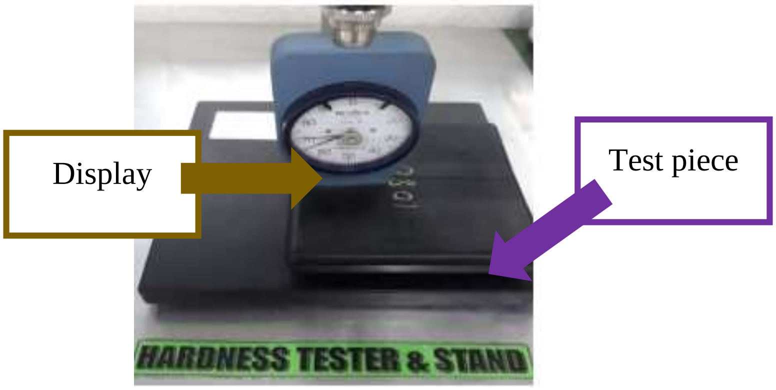


Figure 3.20: “Shore A” durometer.

3.2.5.6 Rheometer

The rheometer shows in Figure 3.21, used for process design in rubber injection moulding, which is to analyse the flow properties of soften rubber at high shear levels as specified in ASTM D3835.

A test piece of rubber compound is placed into the cavity of the rheometer, the door of rheometer closed which puts the test piece at a specific constant temperature. The rheometer start to measure and plot a rheometer curve.

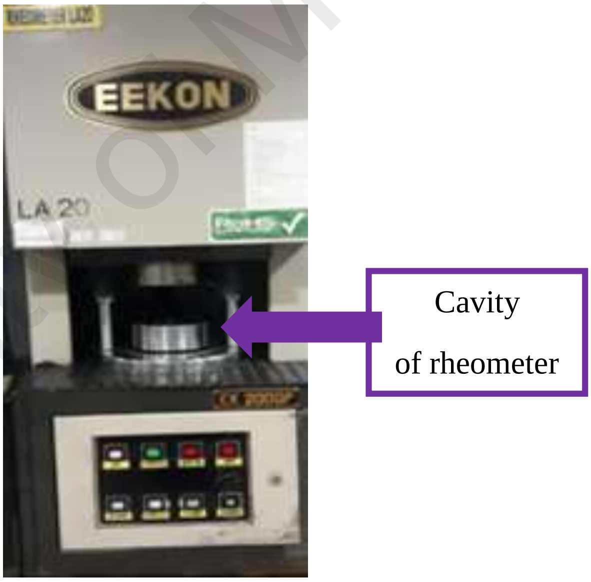


Figure 3.21: Rheometer.

3.2.5.7 Mooney Viscometer

The Mooney viscometer shows in Figure 3.22, is used for measure the viscosity of rubbers as specified in ASTM D1646.

A test piece is placed above and below the rotor. The platens then closed under pressure with the temperature of the dies is accurately maintained. The torque exerted on the rotated rotor head is measure and plot a Mooney viscometer graph.

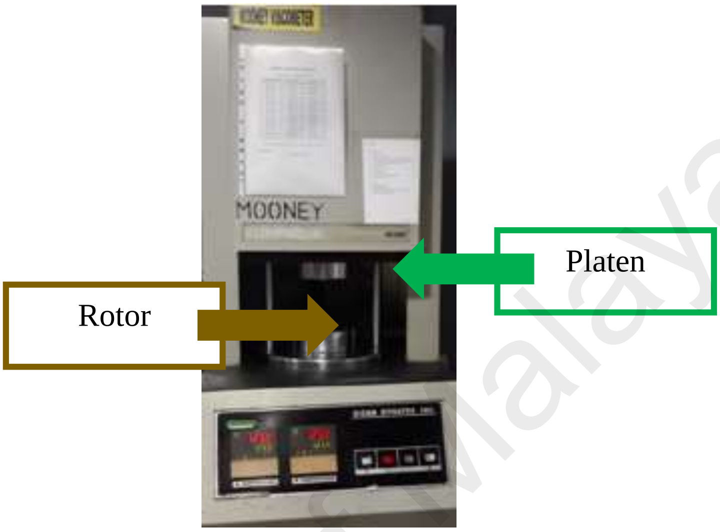


Figure 3.22: Mooney viscometer.

3.2.6 Implementation for Process Optimization

Process optimization is a fine-tuning process to improve some parameters without violating quality control.

Six basic principles to implement process optimization –

1) Emphasis on customer requirements.
2) Figure out the workflow.
3) Reduce cycle time and material saving.
4) Track numbers by evidence.
5) Empower the people operating the process effectively.
6) Follow all this principles in an organized method.

3.3 Conclusions

The methodology in this research has been aimed to optimize process in rubber injection moulding. The analyse works of research methodology based on approaches including Taguchi method and ANOVA analysis.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction

This chapter is to present the results on process optimization in rubber injection moulding. This research study is carry out to establish the time reducing, material saving, and meet the specifications of the product towards the process optimization.

Data analysis using S/N ratio, and One-way ANOVA analysis with result using auto generated by Minitab Release 16.

4.2 Rheometer Curve for Experimental Material

Rheometer curve is to show for measuring visco-elastic properties of experimental rubber during the vulcanization process, which is to measure the rubber compound flows at the required temperature within the curing time when the forces apply on the rubber compound.

Experimental material is testing by using Rheometer and results as shown in Figure 4.1. Scorch time (TS2) for assessing, which is to certify no wasting time in rubber moulding, and will not make a bad product. Optimum cure time (TC90) for evaluating, which is to foresee factors that can affect vulcanization process.

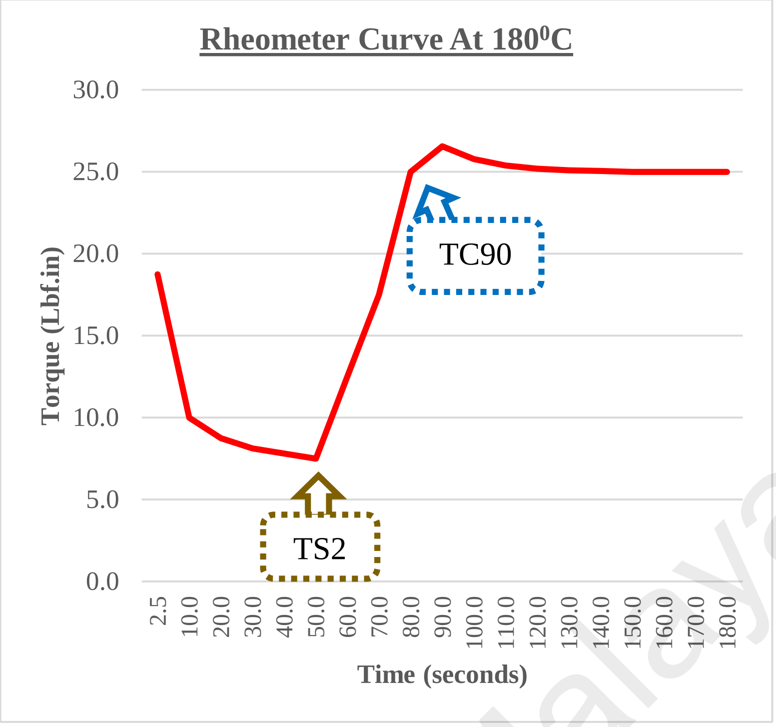


Figure 4.1: Rheometer curve for the experimental material.

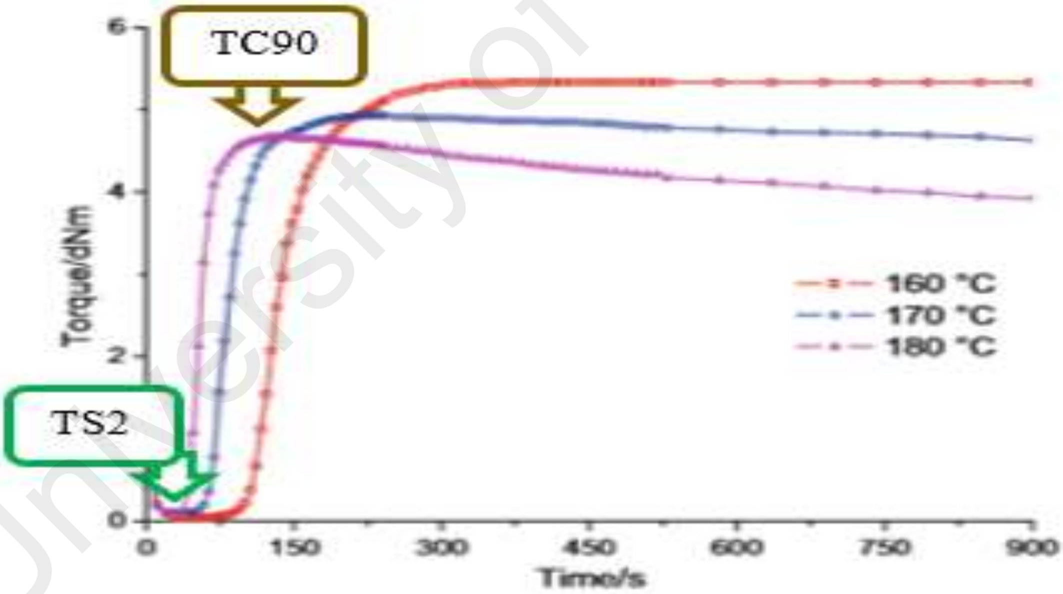


Figure 4.2: Rheometer curve for samples of natural rubber at different temperature. The graph is given by Thai Khang (2012).

Refer to Figure 4.1 and compare with Figure 4.2, this results at temperature 180 ^{0}C: the time are similar at parameters which are, TS2 is 51 seconds (is a scorch time) and TC90 is 82 seconds (is a 90% of optimum cure time).

4.3 Mooney Viscosity Graph for Experimental Material

Mooney viscosity graph is shows for measuring the viscosity of experimental rubber. It is to define the shearing by torque apply at temperature required within the viscosity time. Experimental material is testing by using Mooney viscometer and the result as shown in Figure 4.3.

Refer to Figure 4.3 and compare with Figure 4.4, this results at temperature 100 ^{0}C: the Mooney viscosity is similar at parameter “ML 1+4” which is 46.41 units in time 4 minutes.

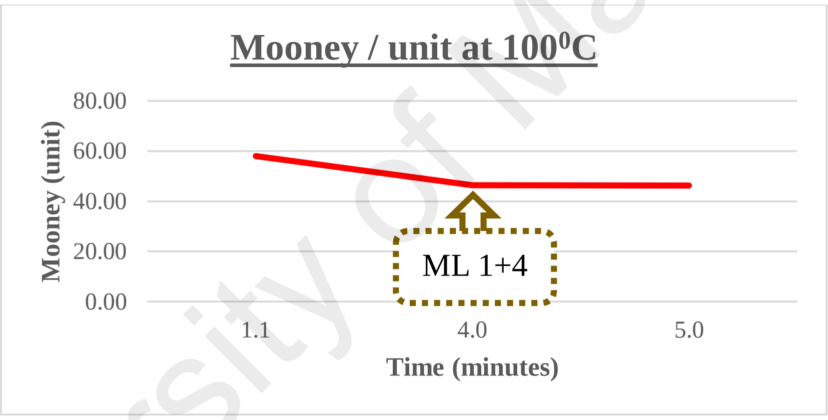


Figure 4.3: Mooney viscosity graph for experimental material.

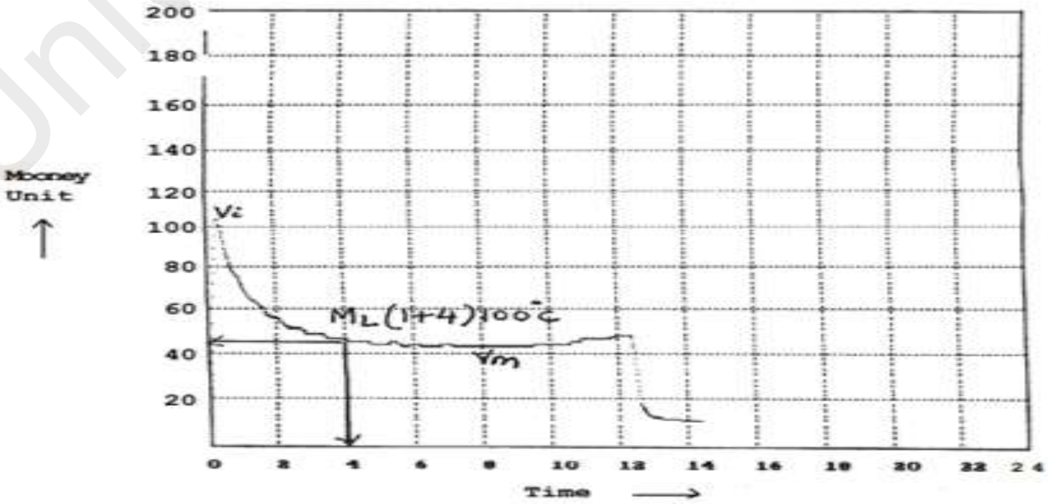


Figure 4.4: Mooney viscosity graph for rubber injection moulding. The graph is given by T.Z. Zaeimoedin (2012).

4.4 S/N Ratio on Cycle Time Study

The process optimization is to reduce the cycle time, which is faster and shorter the cycle time. So, refer to Table 3.8, chosen “smaller-is-better” of characteristic for cycle time.

4.4.1 S/N Ratio on Cycle Time Study for Speed Factor

Number of values L4 orthogonal array is selecting for four levels. It consists of three factors: feeding speed, injection speed and bumping speed. The results of S/N Ratio, which is average of cycle time study from 5 cycles, as shown in Figure 4.5. The calculation data is using S/N ratio formulas and attaching in the Appendices List.

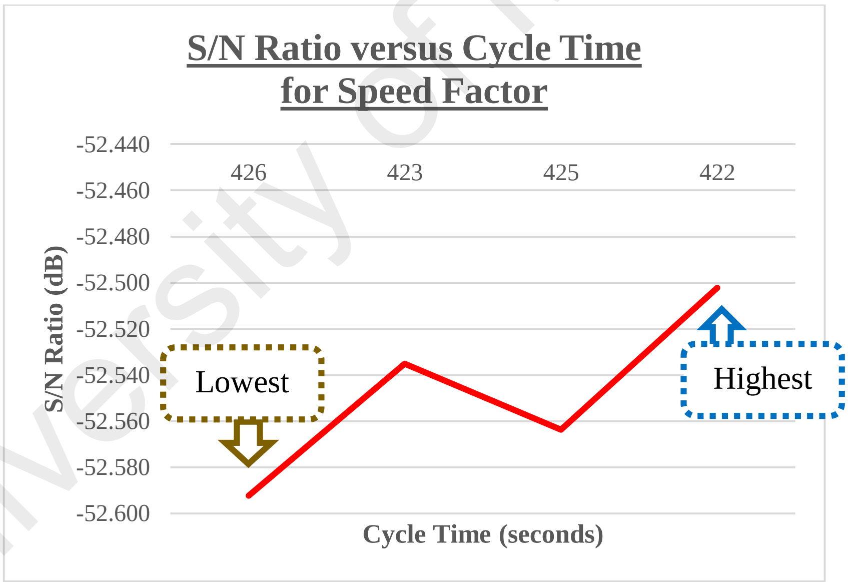


Figure 4.5: S/N ratio versus cycle time for speed factor.

From Figure 4.5: The S/N ratio is lowest at cycle time 426 seconds before process optimization. The S/N ratio is highest, which is “smaller-is-better” at cycle time 422 seconds after process optimization. Cycle time is indirectly proportional to speed. Cycle time is shorter when speed is faster, which is speed in percentage (%) is higher. This result is similar to journal by M. Fasching (2014).

The machine parameters of speed for reducing cycle time, before and after process optimization as shown in Figure 4.6.

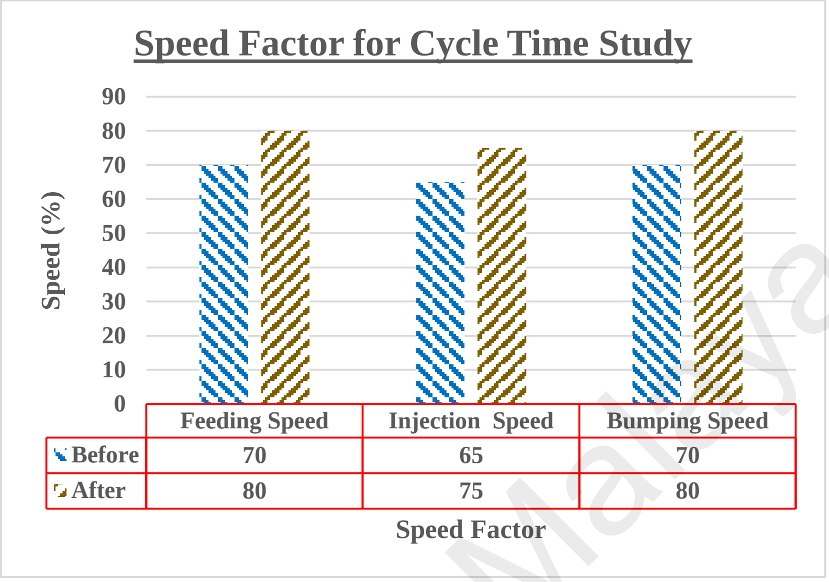


Figure 4.6: Parameters of reducing cycle time for speed factor.

Refer to Figure 4.6, cycle time reducing after process optimization: feeding speed is 80%, injection speed is 75% and bumping speed is 80%.

4.4.2 S/N Ratio on Cycle Time Study for Pressure Factor

Number of values L8 orthogonal array is selecting for eight levels. It consists of four factors: feeding pressure, injection pressure, bumping pressure and curing pressure. The results of S/N Ratio, which is average of cycle time study from 5 cycles, as shown in Figure 4.7. The calculation data is using S/N ratio formulas and attaching in the Appendices List.

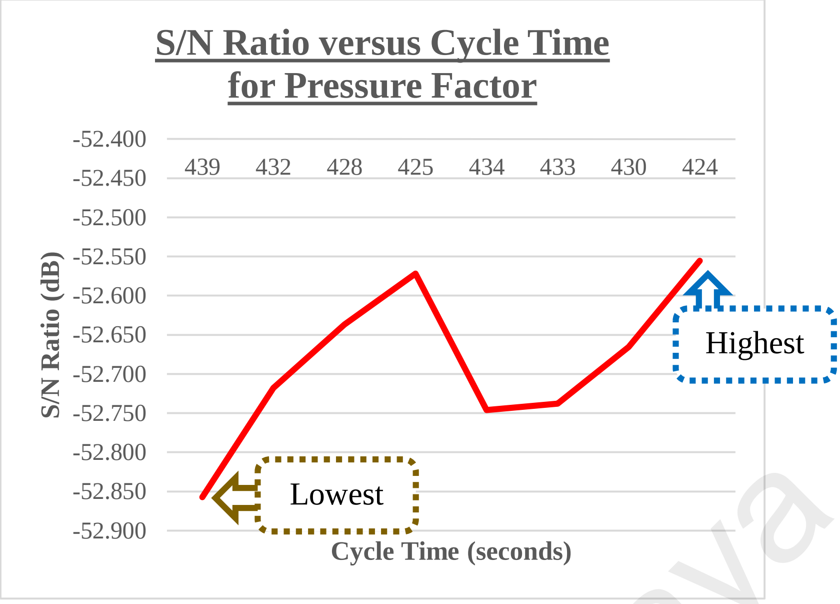


Figure 4.7: S/N ratio versus cycle time for pressure factor.

Refer to Figure 4.7: The S/N ratio is lowest at cycle time 439 seconds before process optimization. The S/N ratio is highest, which is “smaller-is-better” at cycle time 424 seconds after process optimization.

Injection pressure is increase, filling time is shorter, which is larger rubber volume injecting to flow faster into mould. Thus, cycle time is reduce when pressure is higher. This result is similar by Zhang Di (2015).

The machine parameters of pressure for reducing cycle time, before and after process optimization as shown in Figure 4.8.

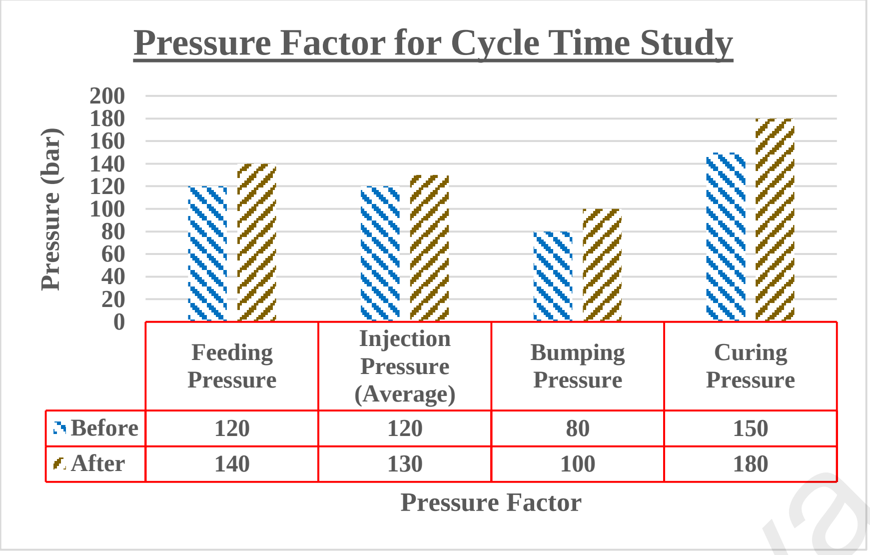


Figure 4.8: Parameters of reducing cycle time for pressure factor.

Refer to Figure 4.8, cycle time reducing after process optimization: feeding pressure is 140 bar, injection pressure is 130 bar, bumping pressure is 100 bar and curing pressure is 180 bar.

4.4.3 Results and Discussion of S/N Ratio on Cycle Time Study for Temperature Factor

Number of values L4 orthogonal array is selecting for four levels. It consists of three factors: feeding temperature, injection temperature, and curing temperature. The results of S/N Ratio, which is average of cycle time study from 5 cycles, as shown in Figure 4.9. The calculation data is using S/N ratio formulas and attaching in the Appendices List.

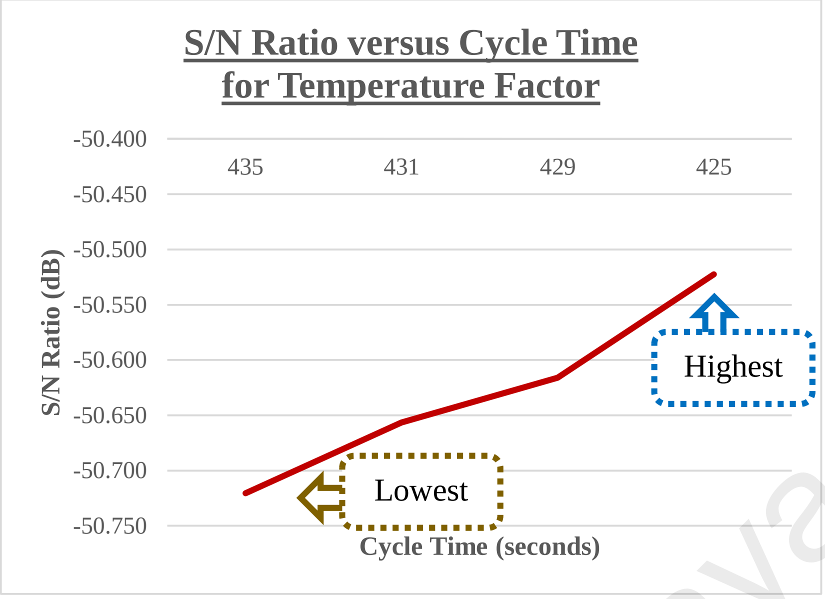
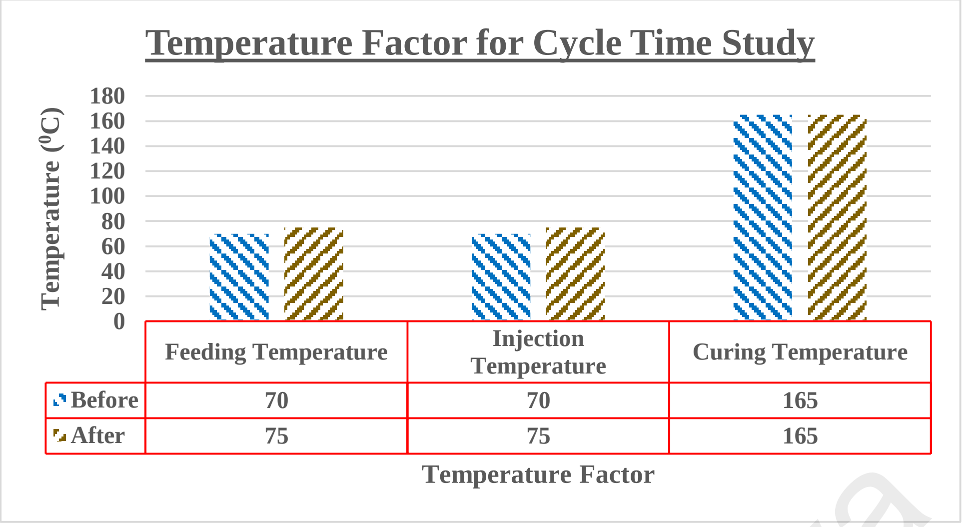


Figure 4.9: S/N ratio versus cycle time for temperature factor.

Refer to Figure 4.9: The S/N ratio is lowest at cycle time 435 seconds before process optimization. The S/N ratio is highest, which is “smaller-is-better” at cycle time 425 seconds after process optimization.

Feeding and injection temperature are higher, a higher specific energy is generating to shear and stress much higher on rubber inside the barrel. The rubber will become more soften, to flow and fill into mould, within shorter filling time and cure time. Hence, cycle time is reduce when temperature is higher. This result is similar by C. Hopmann (2015) and K. Kyas (2012).

The machine parameters of temperature for reducing cycle time, before and after process optimization as shows in Figure 4.10.



	Feeding Temperature	Injection Temperature	Curing Temperature
Before	70	70	165
After	75	75	165

Figure 4.10: Parameters of reducing cycle time for temperature factor.

Refer to Figure 4.10, cycle time reducing after process optimization: feeding temperature is 75 ^{0}C bar, injection temperature is 75 ^{0}C bar and curing temperature is remain same as 165 ^{0}C.

4.4.4 S/N Ratio on Cycle Time Study for All Control Factors Combination

Number of values L12 orthogonal array is selecting for twelve levels. It consists of ten factors: feeding speed, injection speed, bumping speed, feeding pressure, injection pressure, bumping pressure, curing pressure, feeding temperature, injection temperature, and curing temperature. The results of S/N Ratio, which is average of cycle time study from 5 cycles, as shown in Figure 4.11. The calculation data is using S/N ratio formulas and attaching in the Appendices List.

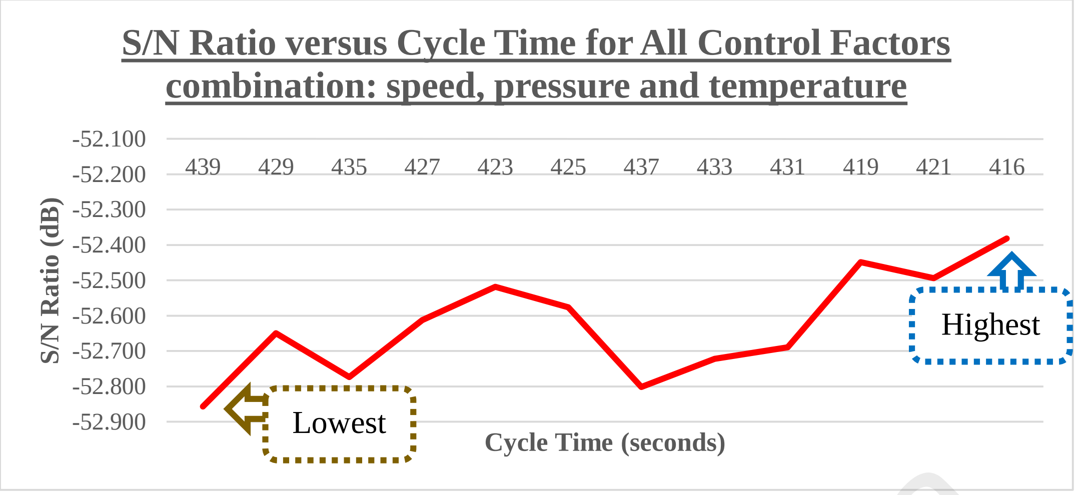


Figure 4.11: S/N ratio versus cycle time for all control factors combination: speed, pressure, and temperature.

Refer to Figure 4.11: The S/N ratio is lowest at cycle time 439 seconds before process optimization. The S/N ratio is highest, which is “smaller-is-better” at cycle time 416 seconds after process optimization.

The machine parameters of all control factors combination: speed, pressure and temperature for reducing cycle time, before and after process optimization as shows in Figure 4.12.

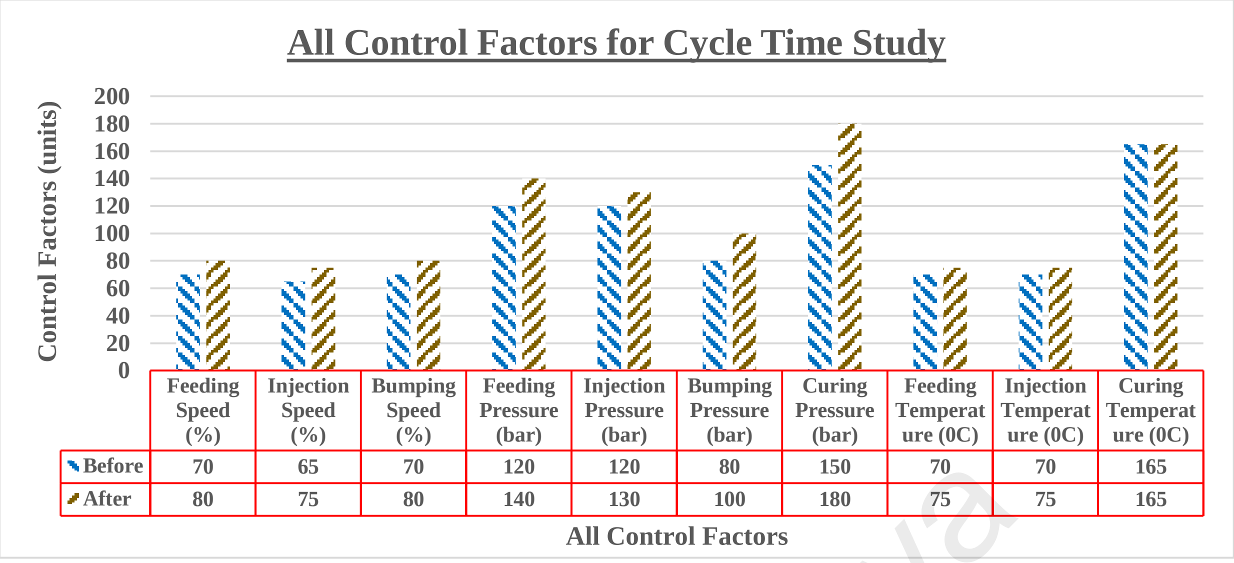


Figure 4.12: Parameters of all control factors combination (speed, pressure and temperature) for reducing cycle time.

From Figure 4.12, cycle time reducing after process optimization for all control factors combination:

For speed factor of combination: feeding is 80%, injection is 75% and bumping is 80%.

For pressure factor of combination: feeding is 140 bar, injection is 130 bar, bumping is 100 bar and curing is 180 bar.

For temperature factor of combination: feeding is 75 ^{0}C, injection is 75 ^{0}C and curing is remain same as 165 ^{0}C.

4.5 S/N Ratio on Material Weight Study

The process optimization on material weight saving, which is products and flash are lightweight. Consequently, refer to Table 3.8, chosen “smaller-is-better” of characteristic for material weight. Experimental material split into 3 categories, which are products, flashes and runner.

4.5.1 S/N Ratio on Materials Weight Study for Speed Factor

In this experiment is to control speed, materials weight to study are products weight and flashes weight, in the process optimization of rubber injection moulding.

4.5.1.1 S/N Ratio on Products Weight Study for Speed Factor

Number of values L4 orthogonal array is selecting for four levels. It consists of three factors: feeding speed, injection speed and bumping speed. The results of S/N Ratio, which is average of cycle time study from 5 cycles, as shown in Figure 4.13. The calculation data is using S/N ratio formulas and attaching in the Appendices List.

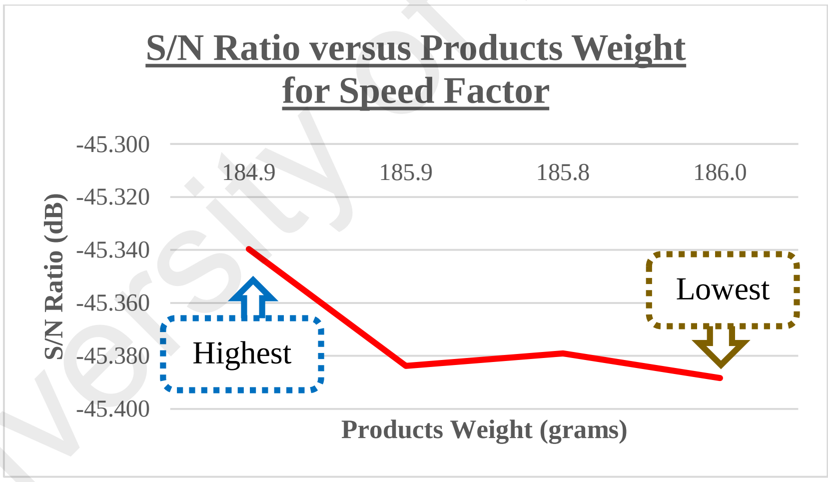
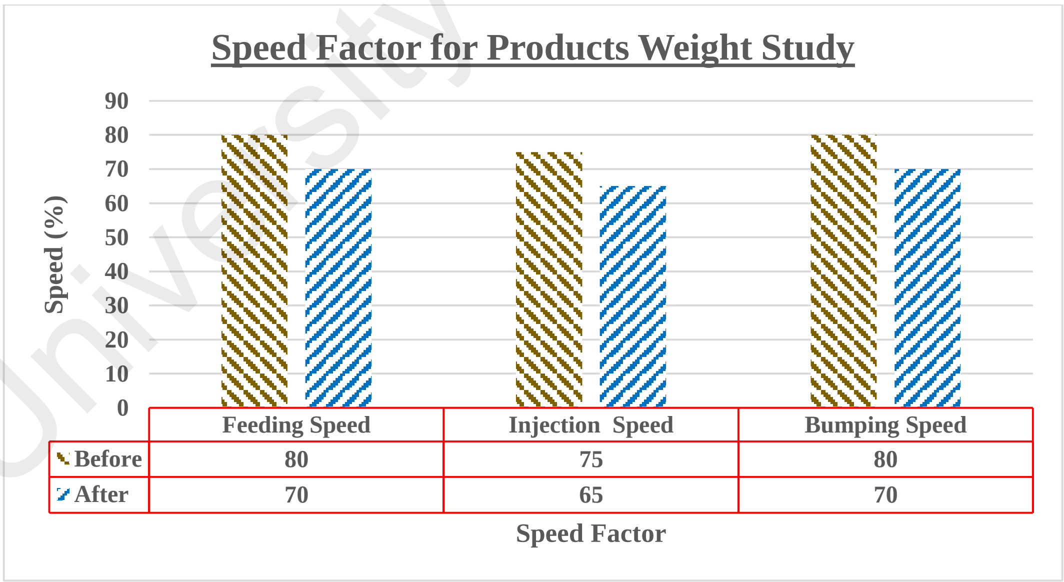


Figure 4.13: S/N ratio versus products weight for speed factor.

From Figure 4.13: The S/N ratio is lowest for products weight 186.0 grams before process optimization. The S/N ratio is highest, which is “smaller-is-better” for products weight 184.9 seconds after process optimization.

The products weight increase leads to a specific gravity increase, and products density is rises. The specific gravity is rises because the temperature of rubber product is increases. The higher energy is to break chemical bonds of the rubber chains, so crosslink density of the rubber is higher. The energy is generating heat or temperature during breaking or shearing the rubber crosslink inside the injection barrel. The inject temperature is increases because the injection time is reduces, which is injection speed is fast or high. As a result, rubber products weight increasing when factor speed is higher. This result is similar by B. S. Kreps (1933), Brian James (2015), Dr. Hans-Joachim Graf (2014) and K. L. Mok (2017).

The machine parameters of speed for reducing products weight, before and after process optimization as shows in Figure 4.14.



	Feeding Speed	Injection Speed	Bumping Speed
▧ Before	80	75	80
▨ After	70	65	70

Figure 4.14: Parameters of speed factor for reducing products weight.

Refer to Figure 4.14, products weight reducing after process optimization: feeding speed is 70%, injection speed is 65% and bumping speed is 70%.

4.5.1.2 S/N Ratio on Flashes Weight Study for Speed Factor

Number of values L4 orthogonal array is selecting for four levels. It consists of three factors: feeding speed, injection speed and bumping speed. The results of S/N Ratio, which is average of cycle time study from 5 cycles, as shown in Figure 4.15. The calculation data is using S/N ratio formulas and attaching in the Appendices List.

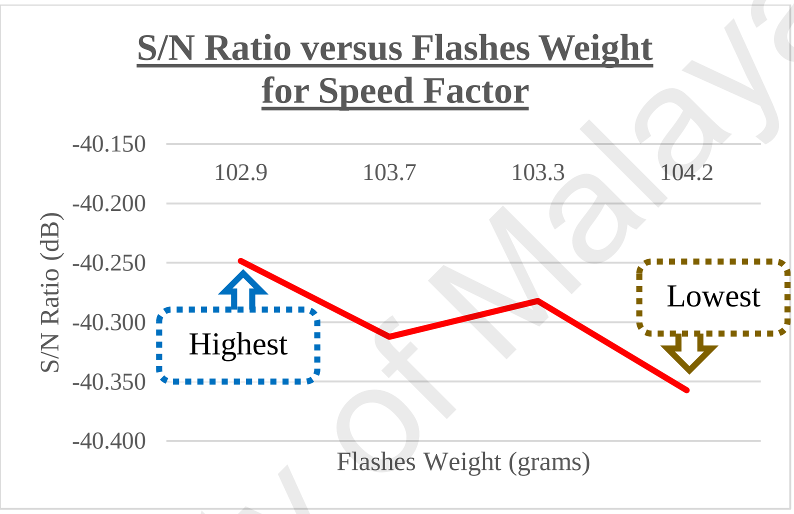


Figure 4.15: S/N ratio versus flashes weight for speed factor.

From Figure 4.15: The S/N ratio is lowest for products weight 104.2 grams before process optimization. The S/N ratio is highest, which is "smaller-is-better" for products weight 102.9 seconds after process optimization.

When rubber injection speed is high during pre-curing process, then the rubber become soften, and rubber injection is fast. The "extra" rubber will over flow outside the mould cavity, the rubber become "extra" flash or flash weight is heavier. The result is same by John A Lindsay (2012).

The machine parameters of speed for reducing flashes weight, before and after process optimization as shows in Figure 4.16.

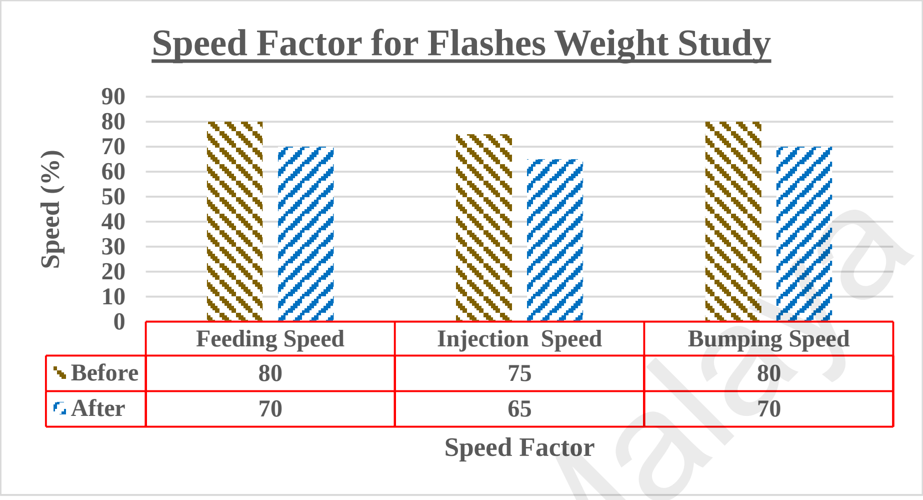


Figure 4.16: Parameters of speed factor for reducing products weight.

Refer to Figure 4.16, products weight reducing after process optimization: feeding speed is 70%, injection speed is 65% and bumping speed is 70%.

4.5.1.3 S/N Ratio on Total Material Weight Study for Speed Factor

Number of values L4 orthogonal array is selecting for four levels. It consists of three factors: feeding speed, injection speed and bumping speed. The results of S/N Ratio, which is average of cycle time study from 5 cycles, as shown in Figure 4.17. The calculation data is using S/N ratio formulas and attaching in the Appendices List.

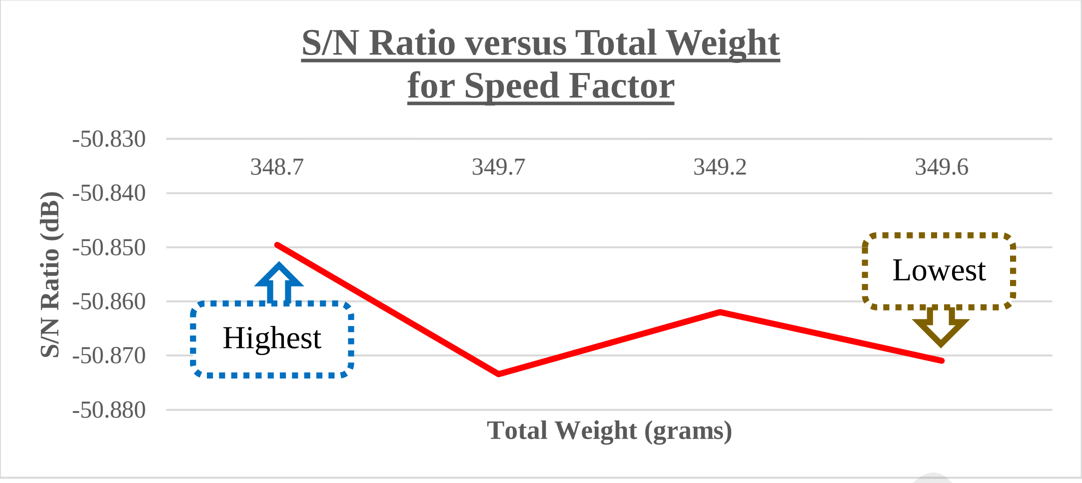


Figure 4.17: S/N ratio versus total material weight for speed factor.

Refer to Figure 4.17: The S/N ratio is lowest for total weight 349.6 grams before process optimization. The S/N ratio is highest, which is “smaller-is-better” for total weight 348.7 grams after process optimization.

The machine parameters of speed factor for material saving, before and after process optimization as shows in Figure 4.18.

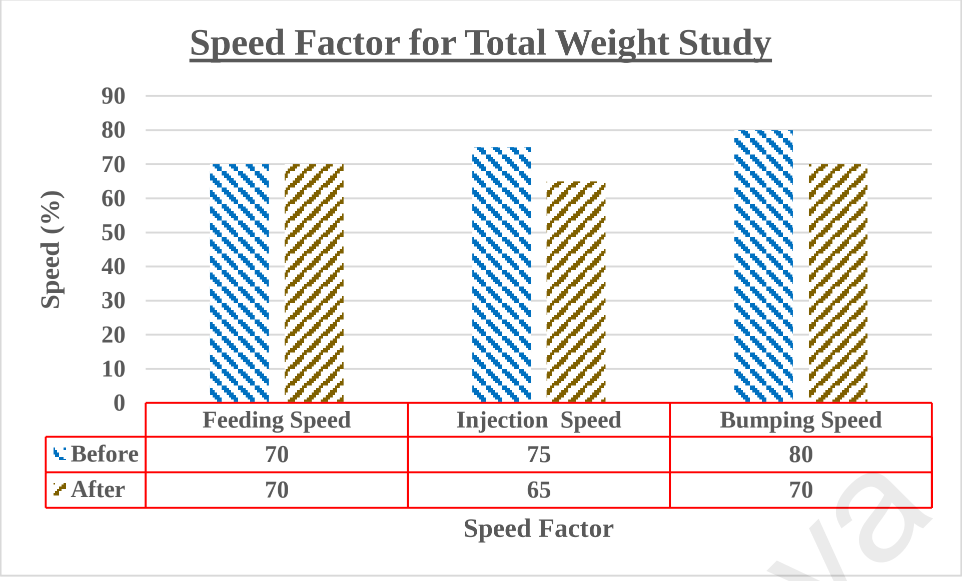


Figure 4.18: Parameters of speed factor for reducing total material weight.

Refer to Figure 4.18, total weight saving after process optimization for speed factor: feeding is remain as 70%, injection is 65% and bumping is 70%.

Total weight is lightweight when injection speed is slower, and with lower bumping speed. The result is as same by Vannessa Goodship (2004).

4.5.2 S/N Ratio on Materials Weight Study for Pressure Factor

In this experiment is to control pressure, materials weight to study are products weight and flashes weight, in the process optimization of rubber injection moulding.

4.5.2.1 S/N Ratio on Products Weight Study for Pressure Factor

Number of values L8 orthogonal array is selecting for eight levels. It consists of four factors: feeding pressure, injection pressure, bumping pressure, and curing pressure.

The results of S/N Ratio, which is average of cycle time study from 5 cycles, as shown in Figure 4.19. The calculation data is using S/N ratio formulas and attaching in the Appendices List.

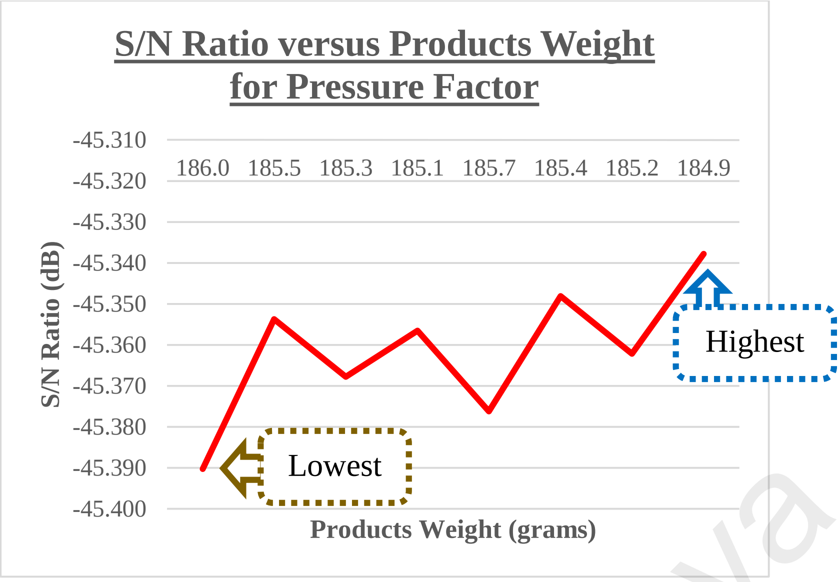
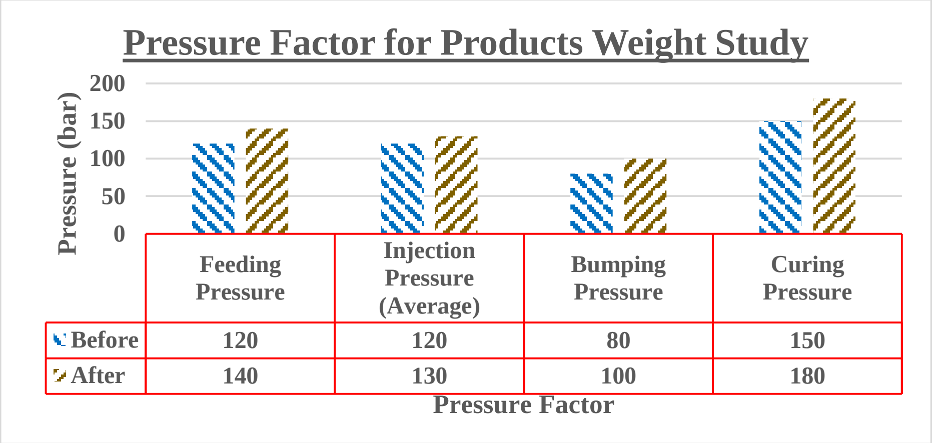


Figure 4.19: S/N ratio versus products weight for pressure factor.

Refer to Figure 4.19: The S/N ratio is lowest for products weight 186.0 grams before process optimization. The S/N ratio is highest, which is "smaller-is-better" for products weight 184.9 grams after process optimization.

The machine parameters of pressure factor for products weight saving, before and after process optimization as shows in Figure 4.20.



	Feeding Pressure	Injection Pressure (Average)	Bumping Pressure	Curing Pressure
Before	120	120	80	150
After	140	130	100	180

Figure 4.20: Parameters of pressure factor for reducing products weight.

Refer to Figure 4.20, products weight saving after process optimization for pressure factor: feeding pressure is 140 bar, injection pressure is 130 bar, bumping pressure is 100 bar and curing pressure is 180 bar.

Injection pressure is increasing, the rubber viscosity is lower, and then the product weight decreases. This happen because the rubber compound stressing by higher kinetic energy inside the injection screw, to generate greater heat. At the same time, the soften rubber flows fastest, and extra rubber which is flash flows out form the mould cavity. This incident causes the rubber not able to fully fill up the mould during cure time period. Hence, the rubber becomes product where the product is lightweight. This result as same by Zhang Di (2015).

4.5.2.2 S/N Ratio on Flashes Weight Study for Pressure Factor

Number of values L8 orthogonal array is selecting for eight levels. It consists of four factors: feeding pressure, injection pressure, bumping pressure, and curing pressure.

The results of S/N Ratio, which is average of cycle time study from 5 cycles, as shown in Figure 4.21. The calculation data is using S/N ratio formulas and attaching in the Appendices List.

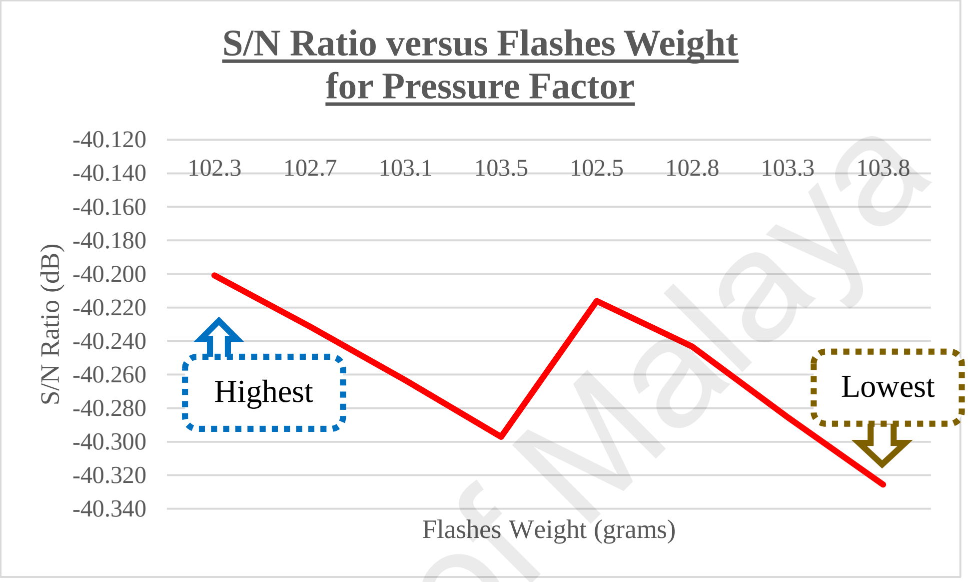


Figure 4.21: S/N ratio versus flashes weight for pressure factor.

Refer to Figure 4.21: The S/N ratio is lowest for flashes weight 103.8 grams before process optimization. The S/N ratio is highest, which is “smaller-is-better” for total weight 102.3 grams after process optimization.

The machine parameters of pressure factor for flashes weight saving, before and after process optimization as shows in Figure 4.22.

When the injection pressure is lower, the bumping pressure is lower, and curing pressure is lower, then the flash will be reduced to a minimum. The flash-less caused by minimum pressure to force the rubber, and to fill up the mould cavity in properly. The results are same stated as Oliver Knack (2015), Prashant Bendre (2014) and John Sommer (2013).

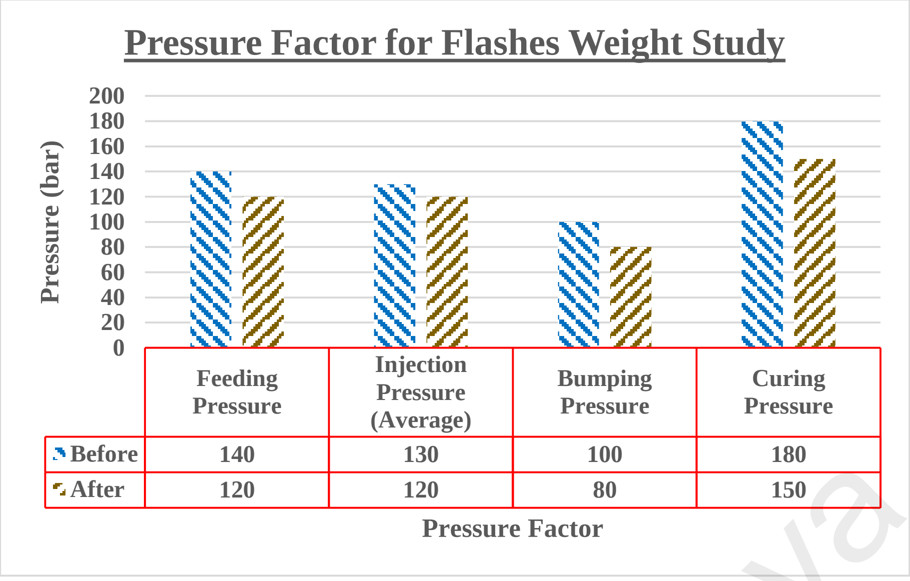


Figure 4.22: Parameters of pressure factor for reducing flashes weight.

Refer to Figure 4.22, flashes weight saving after process optimization for pressure factor: feeding pressure is 120 bar, injection pressure is 120 bar, bumping pressure is 80 bar and curing pressure is 150 bar.

4.5.2.3 S/N Ratio on Total Material Weight Study for Pressure Factor

Number of values L4 orthogonal array is selecting for four levels. It consists of three factors: feeding speed, injection speed and bumping speed. The results of S/N Ratio, which is average of cycle time study from 5 cycles, as shown in Figure 4.23. The calculation data is using S/N ratio formulas and attaching in the Appendices List.

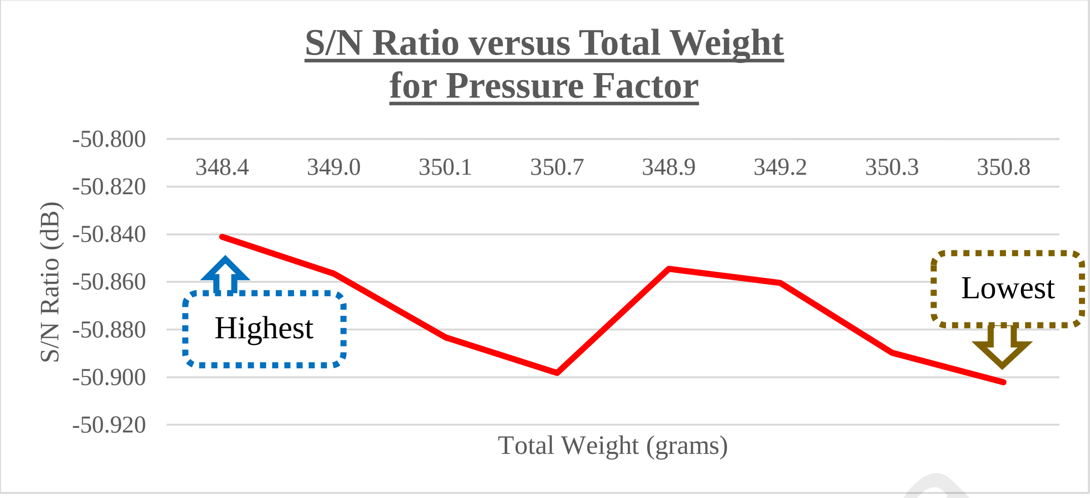


Figure 4.23: S/N ratio versus total material weight for pressure factor.

Refer to Figure 4.23: The S/N ratio is lowest for total weight 350.8 grams before process optimization. The S/N ratio is highest, which is “smaller-is-better” for total weight 348.4 grams after process optimization.

The machine parameters of pressure factor for flashes weight saving, before and after process optimization as shows in Figure 4.24.

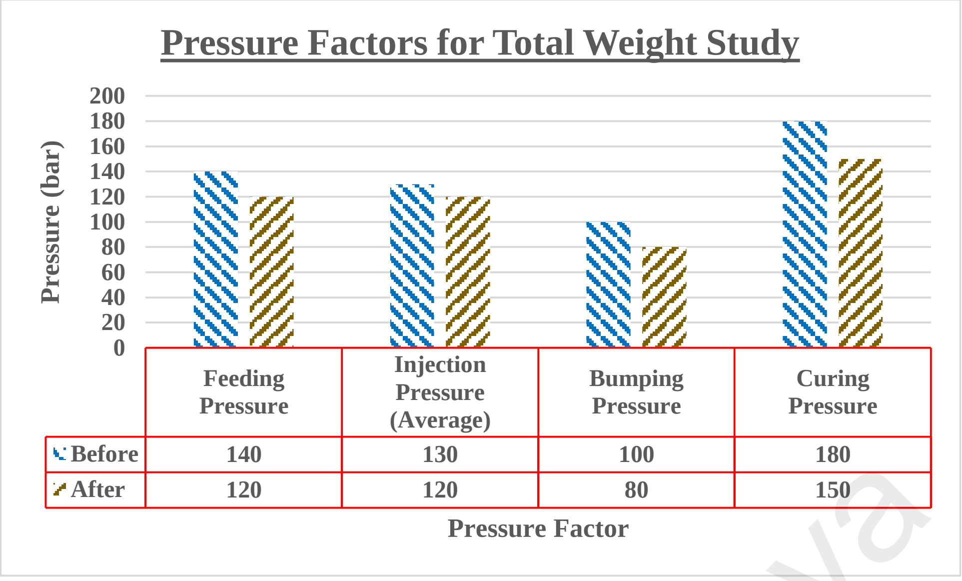


Figure 4.24: Parameters of pressure factor for reducing total material weight.

Refer to Figure 4.24, total material weight saving after process optimization for pressure factor: feeding pressure is 120 bar, injection pressure is 120 bar, bumping pressure is 80 bar and curing pressure is 150 bar.

4.5.3 S/N Ratio on Materials Weight Study for Temperature Factor

In this experiment is to control temperature, materials weight to study are products weight and flashes weight, in the process optimization of rubber injection moulding.

4.5.3.1 S/N Ratio on Products Weight Study for Temperature Factor

Number of values L4 orthogonal array is selecting for four levels. It consists of three factors: feeding temperature, injection temperature, and curing temperature. The results of S/N Ratio, which is average of cycle time study from 5 cycles, as shown in Figure 4.25. The calculation data is using S/N ratio formulas and attaching in the Appendices List.

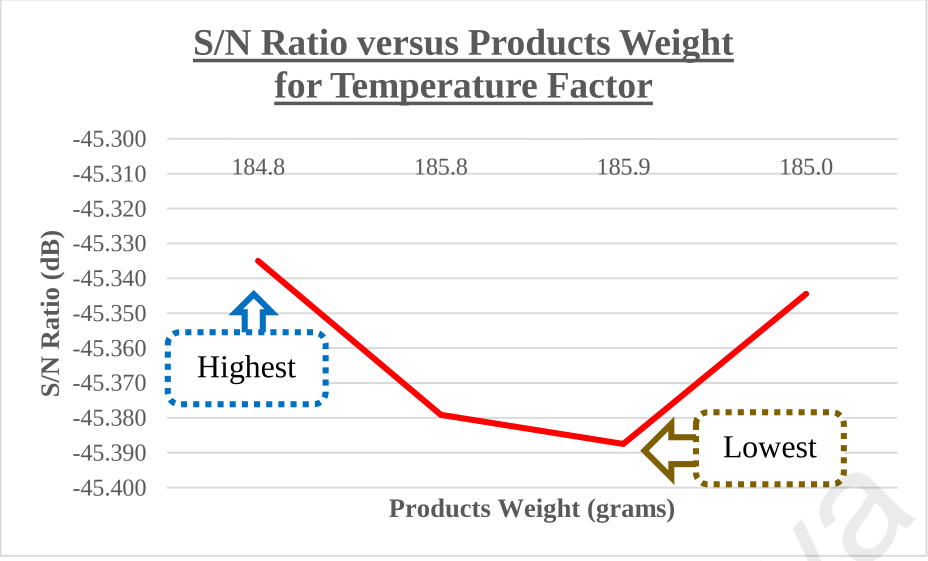


Figure 4.25: S/N ratio versus products weight for temperature factor.

Refer to Figure 4.25: The S/N ratio is lowest for products weight 184.8 grams before process optimization. The S/N ratio is highest, which is "smaller-is-better" for products weight 185.0 grams after process optimization.

From the formulation, Q = mCΔT where: Q is the amount of heat energy, m is the mass which is weight, C is the specific heat, and ΔT is the changing temperature. So, the weight is related with the temperature. The amount of heat energy Q is higher at the specific heat C is remain, then the weight m is heavier when the temperature ΔT is increasing. As the result, the temperature decreases, the products weight is lightweight. This result is similar by Hitoshi Nishizawa (2015).

The machine parameters of temperature factor for products weight saving, before and after process optimization as shows in Figure 4.26.

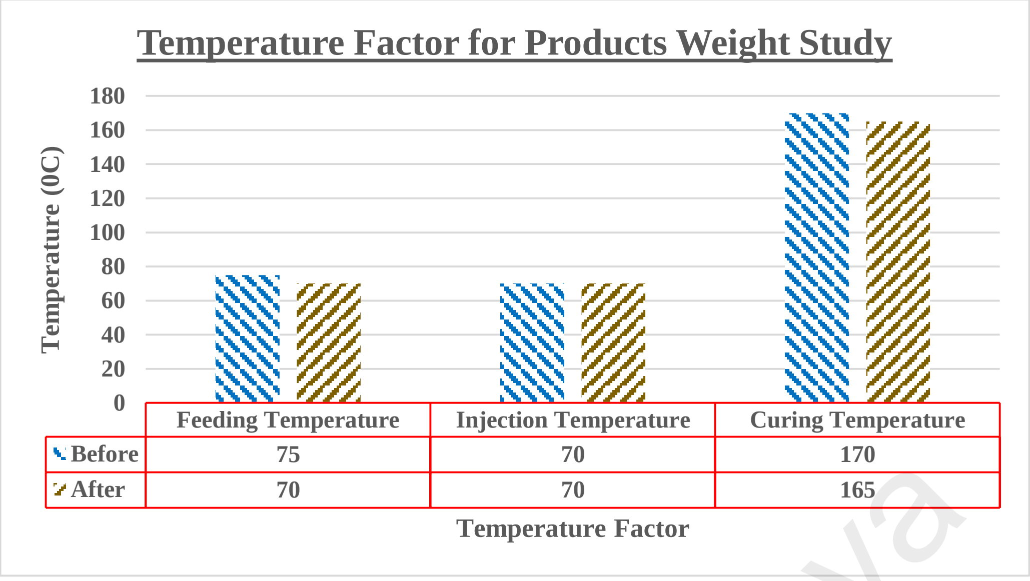


Figure 4.26: Parameters of temperature factor for reducing products weight.

Refer to Figure 4.26, products weight saving after process optimization for temperature factor: feeding temperature is 70 ^{0}C, injection temperature is remain as 70 ^{0}C, and curing temperature is 165 ^{0}C.

4.5.3.2 S/N Ratio on Flashes Weight Study for Temperature Factor

Number of values L4 orthogonal array is selecting for four levels. It consists of three factors: feeding temperature, injection temperature, and curing temperature. The results of S/N Ratio, which is average of cycle time study from 5 cycles, as shown in Figure 4.27. The calculation data is using S/N ratio formulas and attaching in the Appendices List.

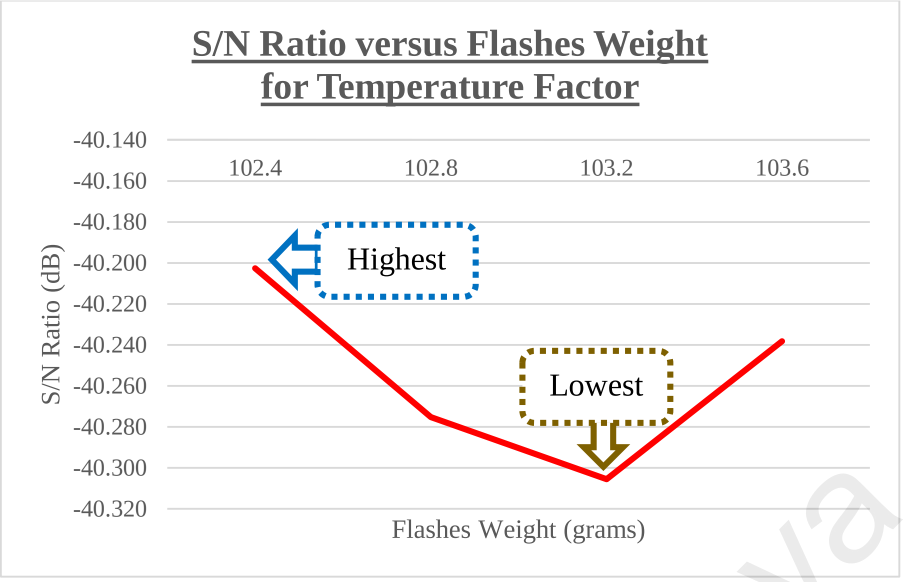


Figure 4.27: S/N ratio versus flashes weight for temperature factor.

Refer to Figure 4.27: The S/N ratio is lowest for flashes weight 103.2 grams before process optimization. The S/N ratio is highest, which is “smaller-is-better” for flashes weight 102.4 grams after process optimization.

Temperature decrease when the rubber flashes weight reduce. The flash over-filled at the mould because the temperature increase with rubber thermal expansion increase. This result is similar by Läroverket AB (2007) and Hayato Kato (2015).

The machine parameters of temperature factor for flashes weight saving, before and after process optimization as shows in Figure 4.28.

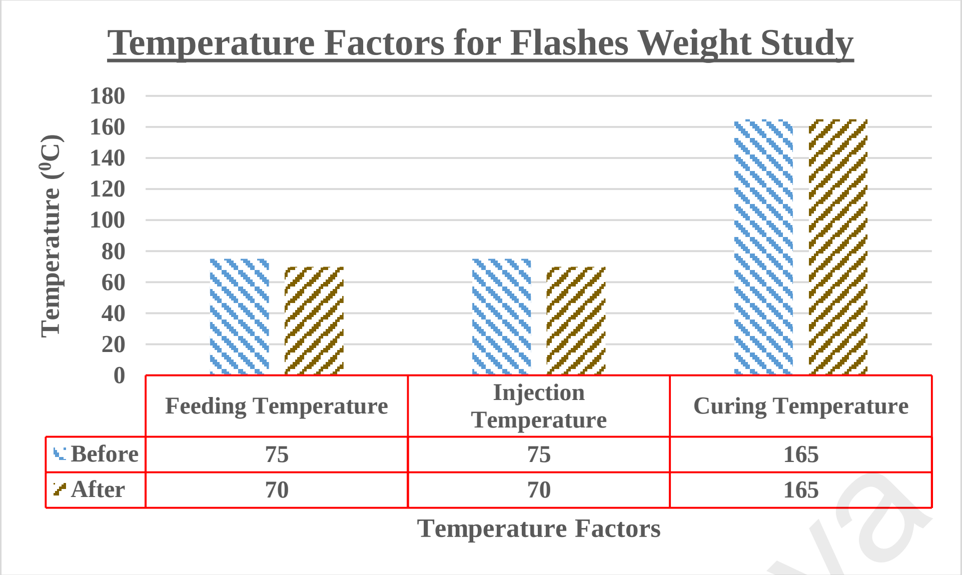


Figure 4.28: Parameters of temperature factor for reducing flashes weight.

Refer to Figure 4.28, flashes weight saving after process optimization for temperature factor: feeding temperature is 70 ^{0}C, injection temperature is remain as 70 ^{0}C, and curing temperature is 165 ^{0}C.

4.5.3.3 S/N Ratio on Total Material Weight Study for Temperature Factor

Number of values L4 orthogonal array is selecting for four levels. It consists of three factors: feeding temperature, injection temperature, and curing temperature. The results of S/N Ratio, which is average of cycle time study from 5 cycles, as shown in Figure 4.29. The calculation data is using S/N ratio formulas and attaching in the Appendices List.

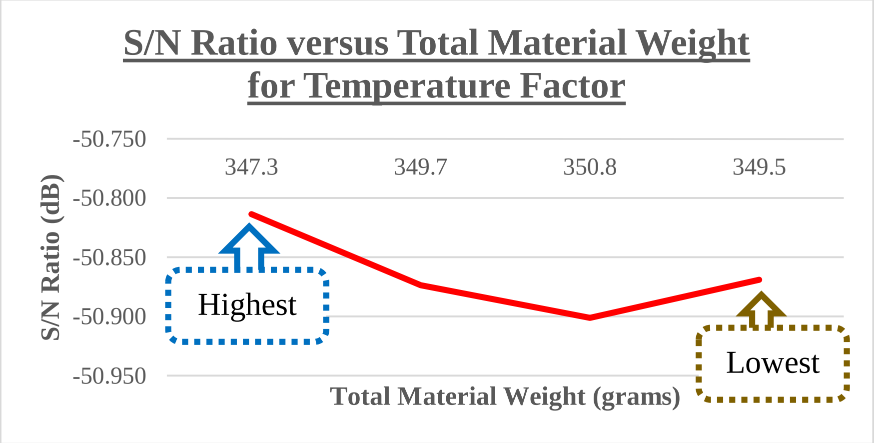


Figure 4.29: S/N ratio versus total material weight for temperature factor.

Refer to Figure 4.29: The S/N ratio is lowest for total material weight 349.5 grams before process optimization. The S/N ratio is highest, which is “smaller-is-better” for total material weight 347.3 grams after process optimization.

The machine parameters of temperature factor for total material weight saving, before and after process optimization as shows in Figure 4.30.

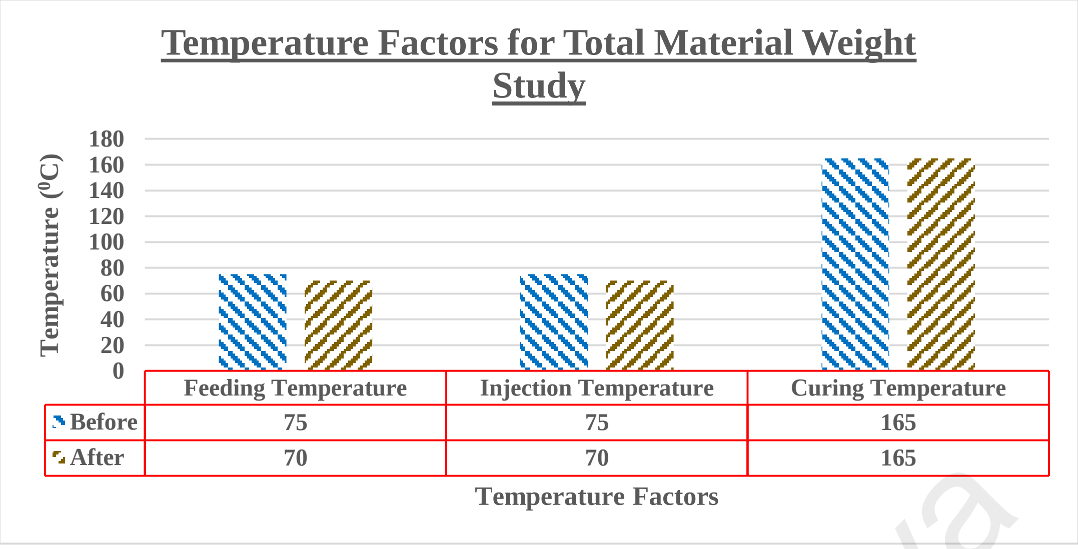


Figure 4.30: Parameters of temperature factor for reducing total material weight.

Refer to Figure 4.30, total material weight saving after process optimization for temperature factor: feeding temperature is 70 ^{0}C, injection temperature is 70 ^{0}C and curing temperature is 165 ^{0}C.

4.5.4 S/N Ratio on Total Material Weight Study for All Control Factors Combination

Number of values L12 orthogonal array is selecting for twelve levels. It consists of ten factors: feeding speed, injection speed, bumping speed, feeding pressure, injection pressure, bumping pressure, curing pressure, feeding temperature, injection temperature, and curing temperature. The results of S/N Ratio, which is average of total material weight study from 5 cycles, as shown in Figure 4.31. The calculation data is using S/N ratio formulas and attaching in the Appendices List.

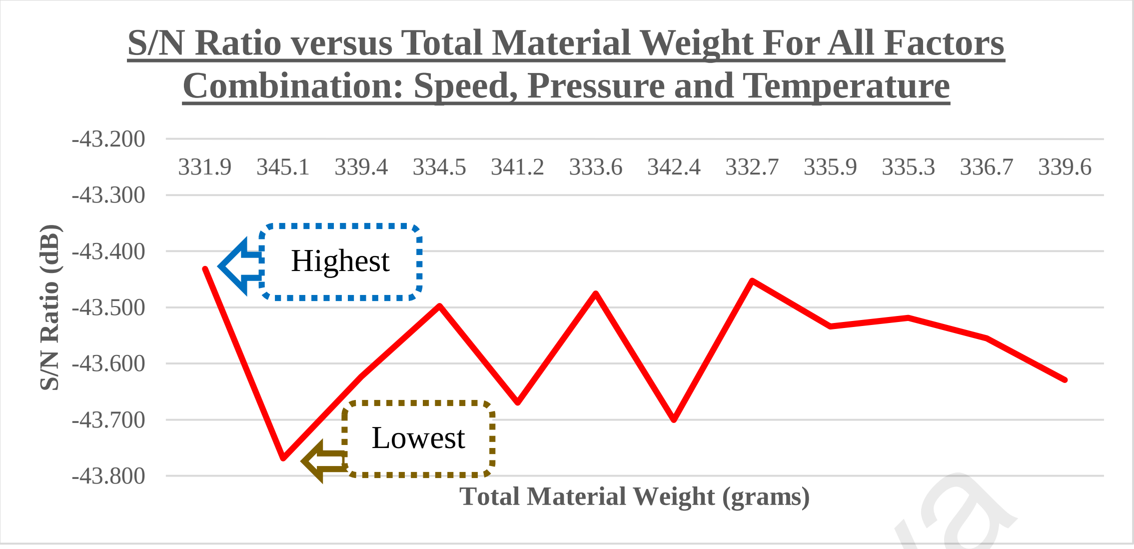
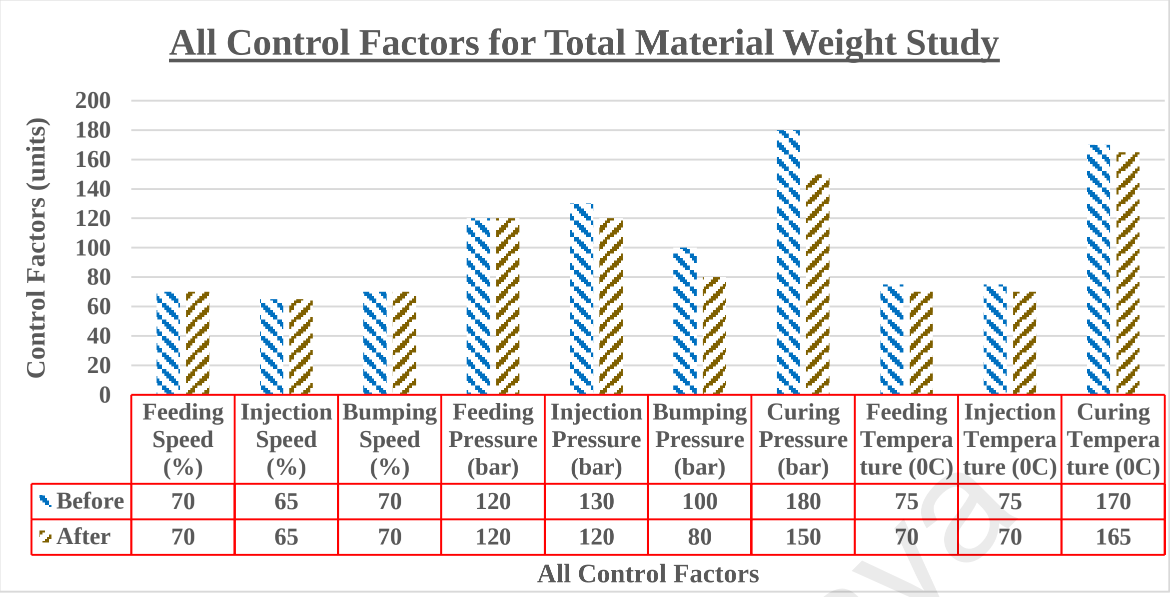


Figure 4.31: S/N ratio versus total material weight for all factors combination (speed, pressure and temperature).

Refer to Figure 4.31: The S/N ratio is lowest for total material weight 345.1 grams before process optimization. The S/N ratio is highest, which is "smaller-is-better" for total material weight 331.9 grams after process optimization.

The machine parameters of temperature factor for total material weight saving, before and after process optimization as shows in Figure 4.32.



	Feeding Speed (%)	Injection Speed (%)	Bumping Speed (%)	Feeding Pressure (bar)	Injection Pressure (bar)	Bumping Pressure (bar)	Curing Pressure (bar)	Feeding Temperature (0C)	Injection Temperature (0C)	Curing Temperature (0C)
Before	70	65	70	120	130	100	180	75	75	170
After	70	65	70	120	120	80	150	70	70	165

Figure 4.32: Parameters of total weight saving for all factors combination (speed, pressure and temperature).

From Figure 4.32, material saving after process optimization for all control factors combination:

For speed factor of combination, all results are remain same as: feeding is 70 %, injection is 65 % and bumping is 70 %. For pressure factor of combination: only feeding is remain same as 120 bar, injection is 120 bar, bumping is 80 bar and curing is 150 bar. For temperature factor of combination: feeding is 70 ^{0}C, injection is 70 ^{0}C and curing is 165 ^{0}C.

4.6 S/N Ratio on Products Hardness Study

The process optimization is to maintain product quality, which is product hardness. So, refer to Table 3.8, chosen “nominal-is-best” of characteristic for product hardness.

4.6.1 S/N Ratio on Products Hardness Study for Speed Factor

Number of values L4 orthogonal array is selecting for four levels. It consists of three factors: feeding speed, injection speed and bumping speed. The results of S/N Ratio, which is average of cycle time study from 5 cycles, as shown in Figure 4.33. The calculation data is using S/N ratio formulas and attaching in the Appendices List.

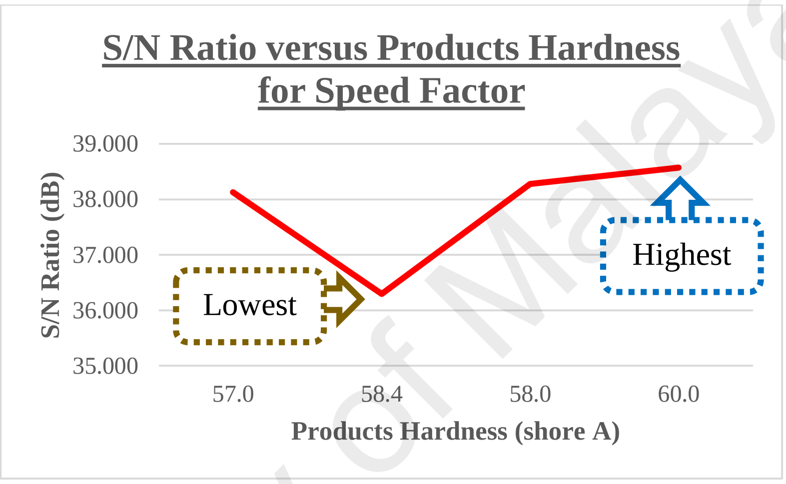
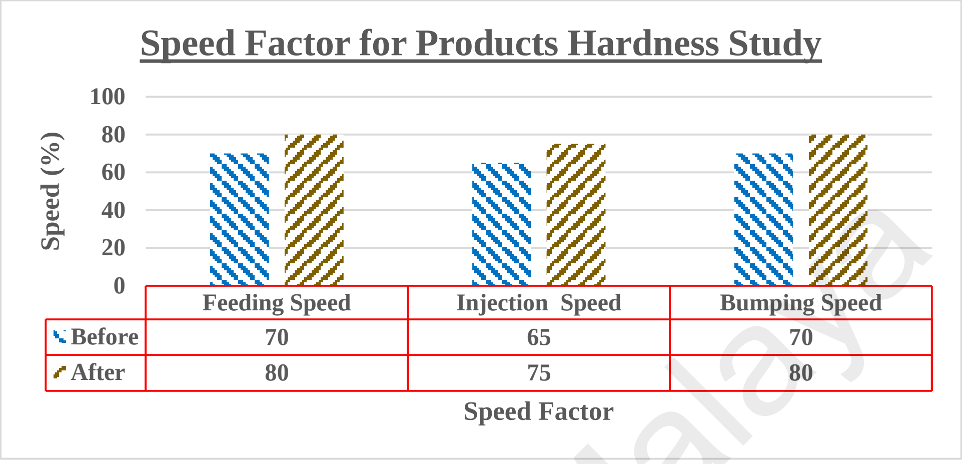


Figure 4.33: S/N ratio versus products hardness for speed factor.

From Figure 4.33: The S/N ratio is lowest for products hardness 58.4 shore A before process optimization. The S/N ratio is highest, which is "nominal-is-best" for products hardness 60.0 shore A after process optimization.

Products hardness increase when feeding temperature rises. This is study by Vannessa Gooodship (2004). Florian Mieth (2016) states that injection speed also higher. The rubber molecules accelerate the cross linkage together and become solidity faster during temperature rises. This is study by Rattapol Pornprasit (2016). So, the rubber product becomes solider, stiffer and harder. This result is similar as Ronald J. Schaefer (2018).

The machine parameters of speed for nominating products hardness, before and after process optimization as shows in Figure 4.34.



	Feeding Speed	Injection Speed	Bumping Speed
Before	70	65	70
After	80	75	80

Figure 4.34: Parameters of speed factor for nominating products hardness.

Refer to Figure 4.34, products hardness after process optimization for speed factor: feeding speed is 80 %, injection speed is 75 %, and bumping speed is 80 %.

4.6.2 S/N Ratio on Products Hardness Study for Pressure Factor

Number of values L8 orthogonal array is selecting for eight levels. It consists of four factors: feeding pressure, injection pressure, bumping pressure, and curing pressure. The results of S/N Ratio, which is average of cycle time study from 5 cycles, as shown in Figure 4.35. The calculation data is using S/N ratio formulas and attaching in the Appendices List.

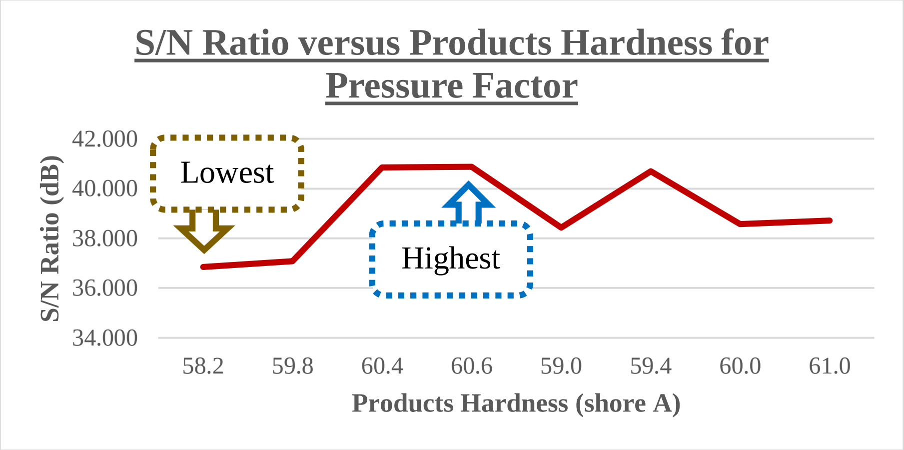


Figure 4.35: S/N ratio versus products hardness for pressure factor.

From Figure 4.35: The S/N ratio is lowest for products hardness 58.2 shore A before process optimization. The S/N ratio is highest, which is "nominal-is-best" for products hardness 60.6 shore A after process optimization.

Rubber products hardness increases when injection pressure higher. This happen because the higher abrasion energy creates heat during the rubber is shearing and stressing, inside the injection screw. So, the rubber becomes soften and is injecting into mould cavity with viscosity rises, which is flows faster. This is study by Zhang Di (2015). Subsequently, the rubber molecules quicken the cross linkage to bond together and become solidity faster. Then, the rubber product becomes solider, stiffer and harder.

The machine parameters of pressure for nominating products hardness, before and after process optimization as shows in Figure 4.36.

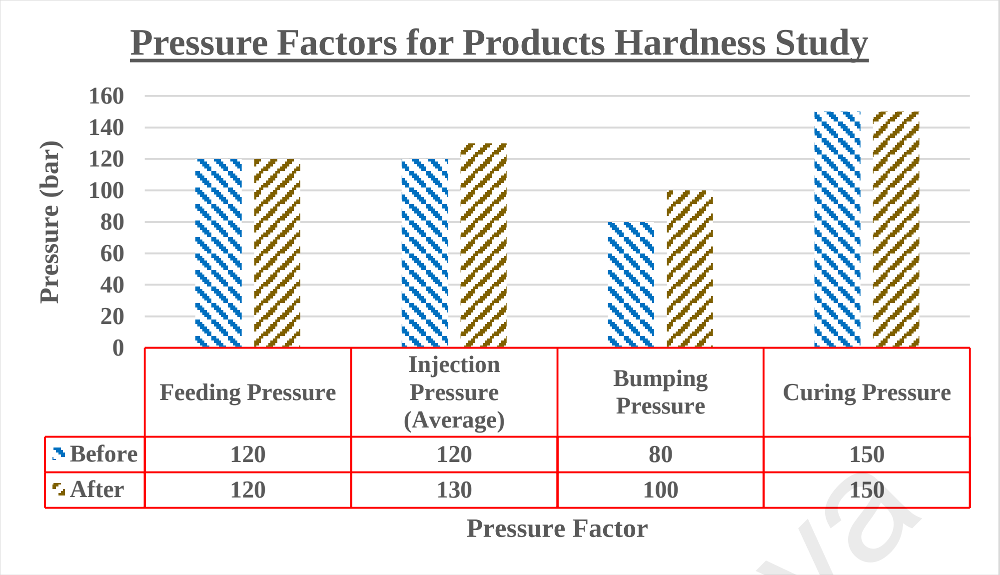


Figure 4.36: Parameters of speed factor for nominating products hardness.

Refer to Figure 4.36, products hardness after process optimization for pressure factor: feeding pressure is remain same as 120 bar, injection pressure is 130 bar, bumping pressure is 100 bar, and curing pressure is remain same as 150 bar.

4.6.3 S/N Ratio on Products Hardness Study for Temperature Factor

Number of values L4 orthogonal array is selecting for four levels. It consists of three factors: feeding temperature, injection temperature, and curing temperature. The results of S/N Ratio, which is average of cycle time study from 5 cycles, as shown in Figure 4.37. The calculation data is using S/N ratio formulas and attaching in the Appendices List.

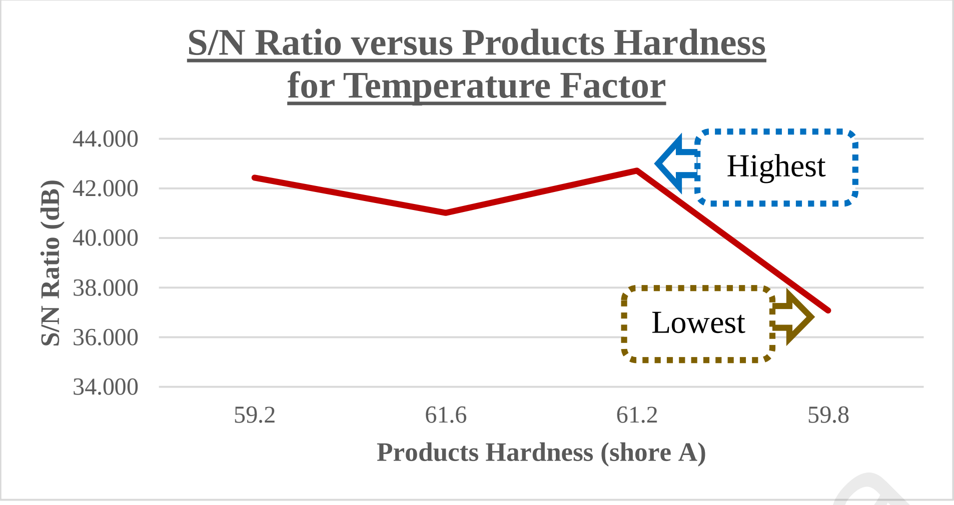


Figure 4.37: S/N ratio versus products hardness for temperature factor.

From Figure 4.37: The S/N ratio is lowest for products hardness 59.8 shore A before process optimization. The S/N ratio is highest, which is "nominal-is-best" for products hardness 61.2 shore A after process optimization.

Products hardness rises when curing temperature higher. This result is same as Ana Pilipović (2010). Huan Zhang (2015) studies that the hardness is increasing because cross-link density rises during post cure effect, which is the rubber contacts to higher temperature to speed up the curing process. At this period, the rubber molecules have greater chemical bonds with increasing cross-link. So, it is to prevent the rubber chains break easily and the product becomes harder. This study is by K.L. Mok (2017).

The machine parameters of temperature for nominating products hardness, before and after process optimization as shows in Figure 4.38.

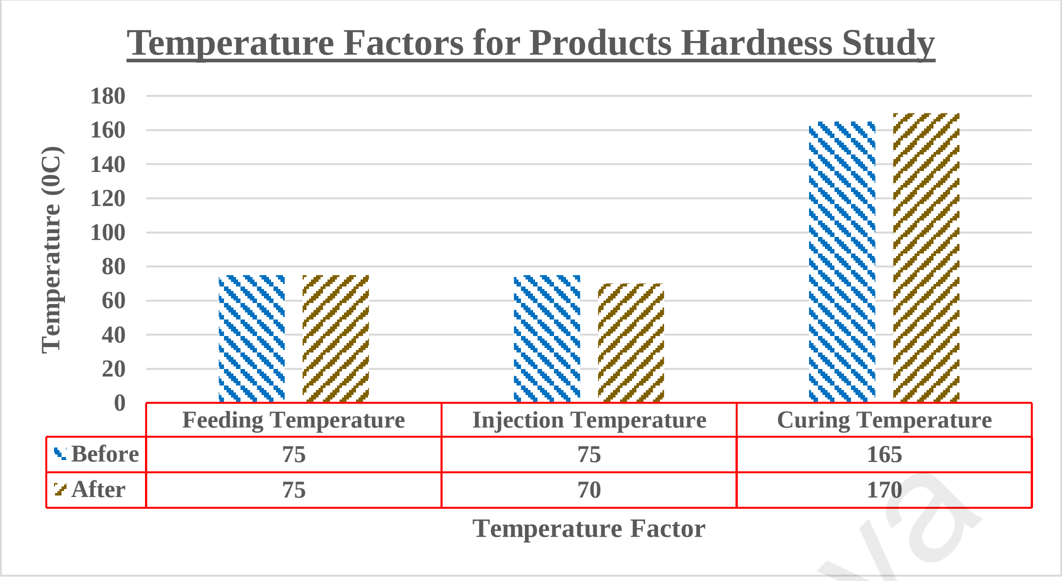


Figure 4.38: Parameters of temperature factor for nominating products hardness.

Refer to Figure 4.38, products hardness after process optimization for temperature factor: feeding temperature is remain same as 75 ^{0}C, injection temperature is 70 ^{0}C, and curing temperature is 170 ^{0}C.

4.6.4 S/N Ratio on Products Hardness Study for All Control Factors Combination

Number of values L12 orthogonal array is selecting for twelve levels. It consists of ten factors: feeding speed, injection speed, bumping speed, feeding pressure, injection pressure, bumping pressure, curing pressure, feeding temperature, injection temperature, and curing temperature. The results of S/N Ratio, which is average of cycle time study from 5 cycles, as shown in Figure 4.39. The calculation data is using S/N ratio formulas and attaching in the Appendices List.

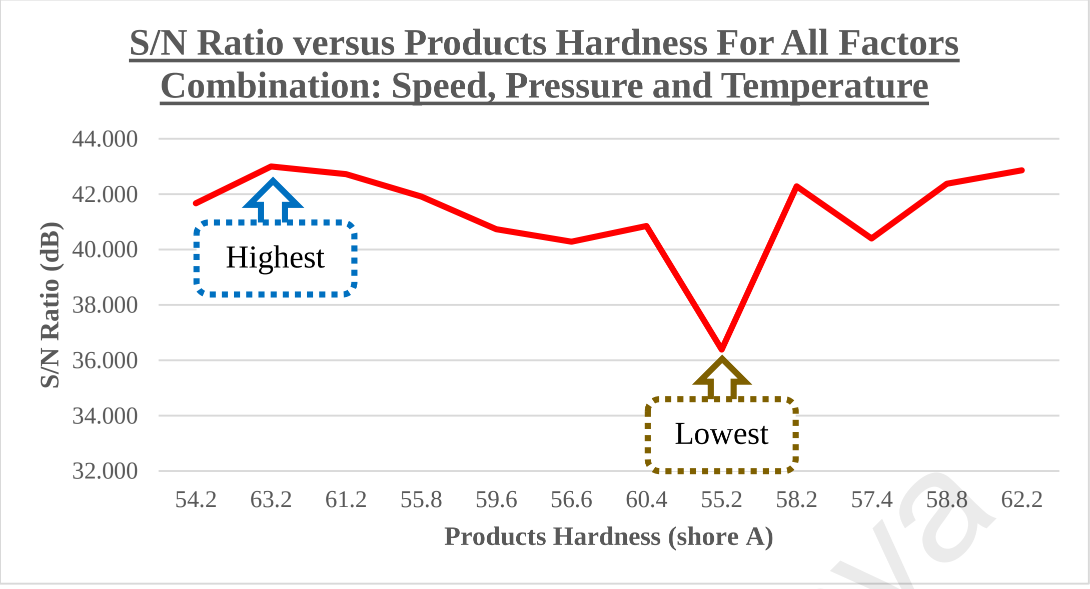


Figure 4.39: S/N ratio versus products hardness for all factors combination (speed, pressure and temperature).

Refer to Figure 4.39: The S/N ratio is lowest for products hardness 55.2 shore A before process optimization. The S/N ratio is highest, which is “nominal-is-best” for products hardness 63.2 shore A after process optimization.

The machine parameters of all factors for products hardness, before and after process optimization as shows in Figure 4.40.

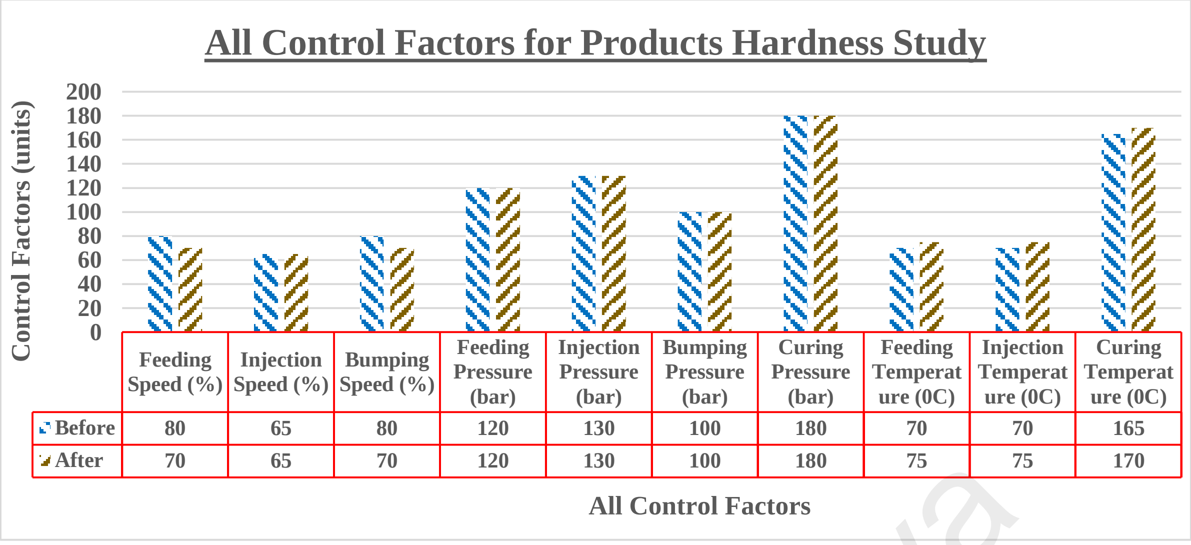


Figure 4.40: Parameters of all factors for nominating products hardness.

From Figure 4.40, products hardness after process optimization for all control factors combination -

For speed factor of combination: feeding is 70 %, only injection is remain same as 65 % and bumping is 70 %. For pressure factor of combination, all results are remain same as: feeding is 120 bar, injection is 130 bar, bumping is 100 bar and curing is 180 bar. For temperature factor of combination: feeding is 75 ^{0}C, injection is 75 ^{0}C and curing is 170 ^{0}C.

4.7 One-Way Analysis of Variance (One-Way ANOVA) to Define Significant Factors

The one-way ANOVA is using to define statistically significant differences between means of control factors: speed, pressure and temperature by machine parameters. The significant factors in this ANOVA of F-ratio is dividing into two levels: greatest significant and smallest significant.

4.7.1 One-Way ANOVA for Cycle Time Study

The calculation data is using one-way ANOVA formulas and attaching in the Appendices List. The ANOVA data using Minitab #16 for cycle time study as shown in Figure 4.41 and Figure 4.42.

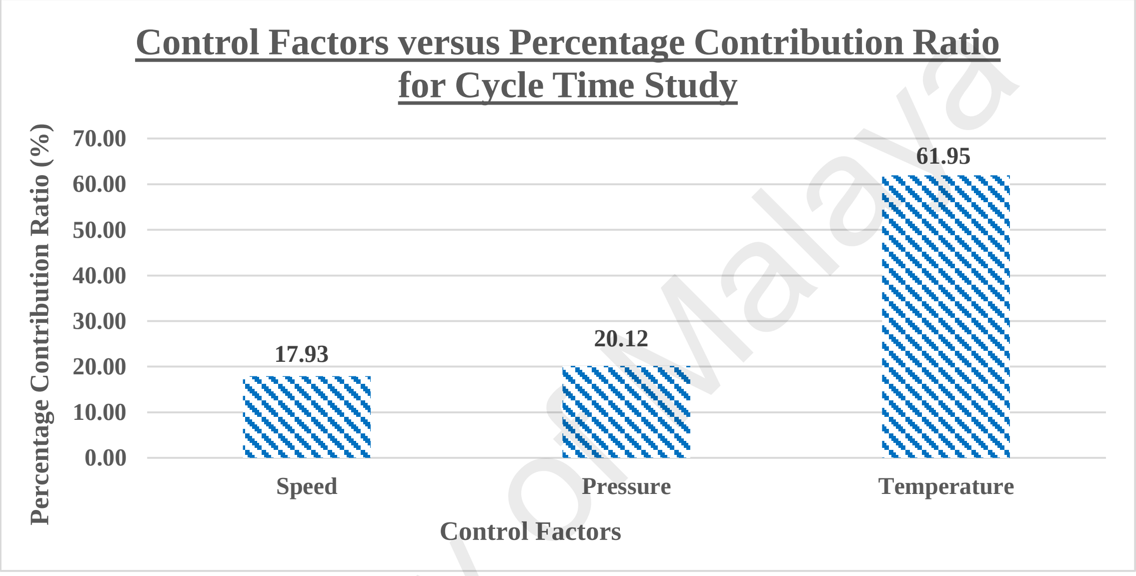


Figure 4.41: Control factors versus percentage contribution ratio for cycle time study.

Figure 4.41 shows that for cycle time study, temperature is the most contribution 61.95 % of control factor, and speed of control factor is the lowest contribution 17.93 %.

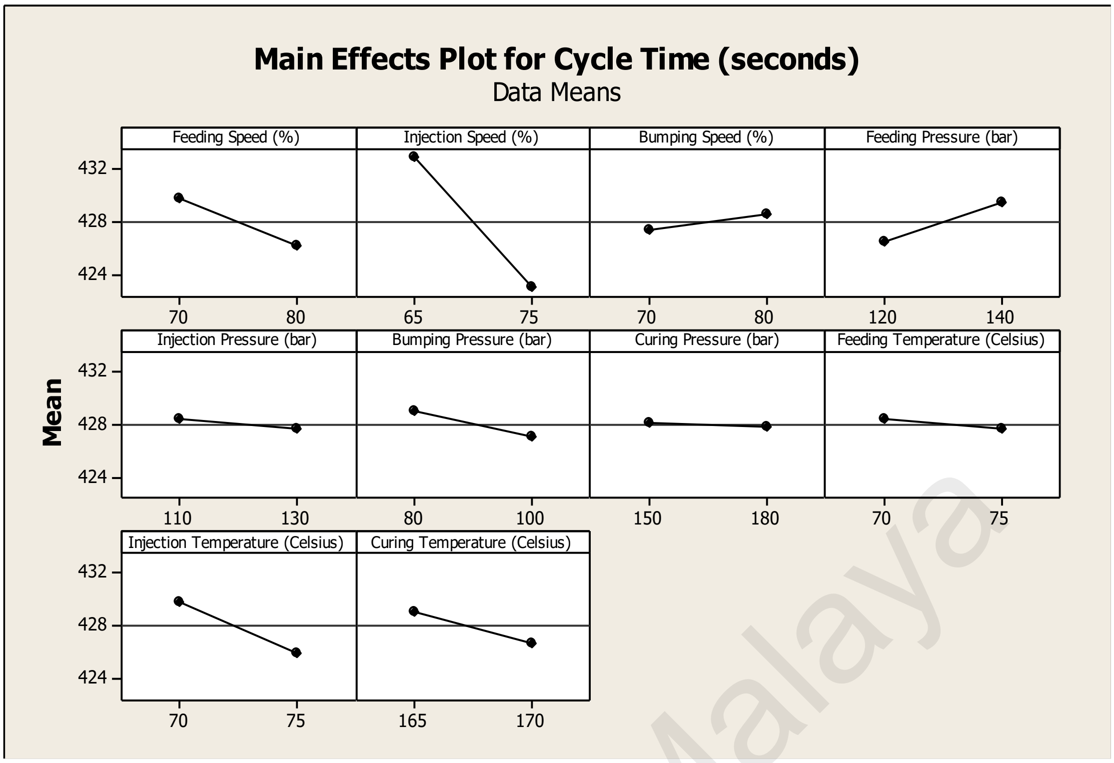


Figure 4.42: Main effects plot of control factor for cycle time study.

Figure 4.42 shows that for cycle time study, injection speed 75 % is the highest effect; and curing pressure 150 bar to 180 bar, is the lowermost effect.

4.7.2 One-Way ANOVA for Material Weight Study

The calculation data is using one-way ANOVA formulas and attaching in the Appendices List. The ANOVA data using Minitab #16 for material weight study as shown in Figure 4.43 and Figure 4.44.

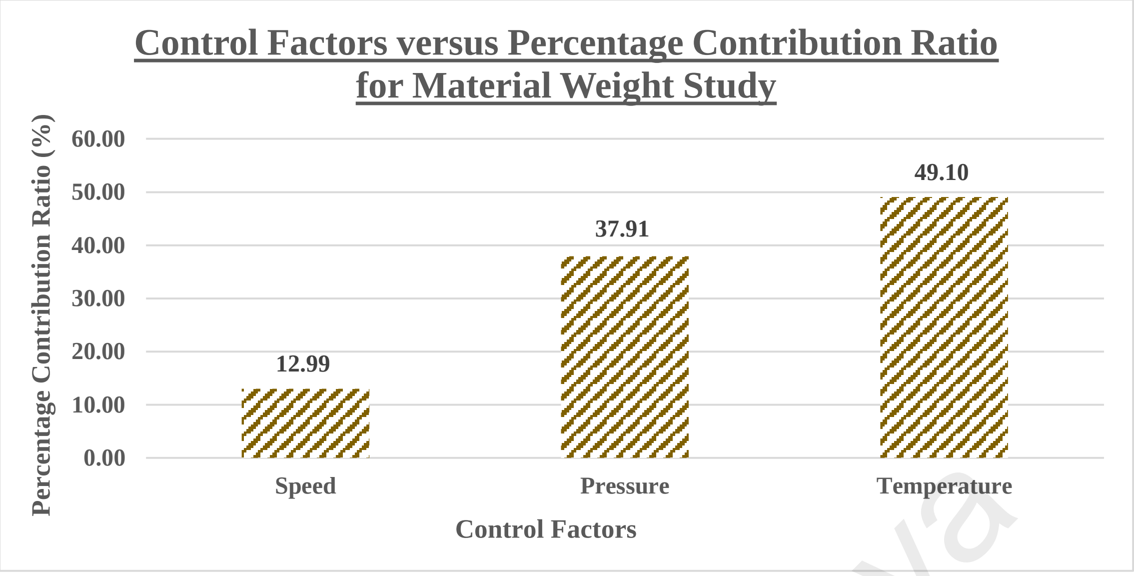


Figure 4.43: Control factors versus percentage contribution ratio for material weight study.

Figure 4.43 shows that for material weight study, temperature is the most contribution 49.10 % of control factor, and speed of control factor is the lowest contribution 12.99 %.

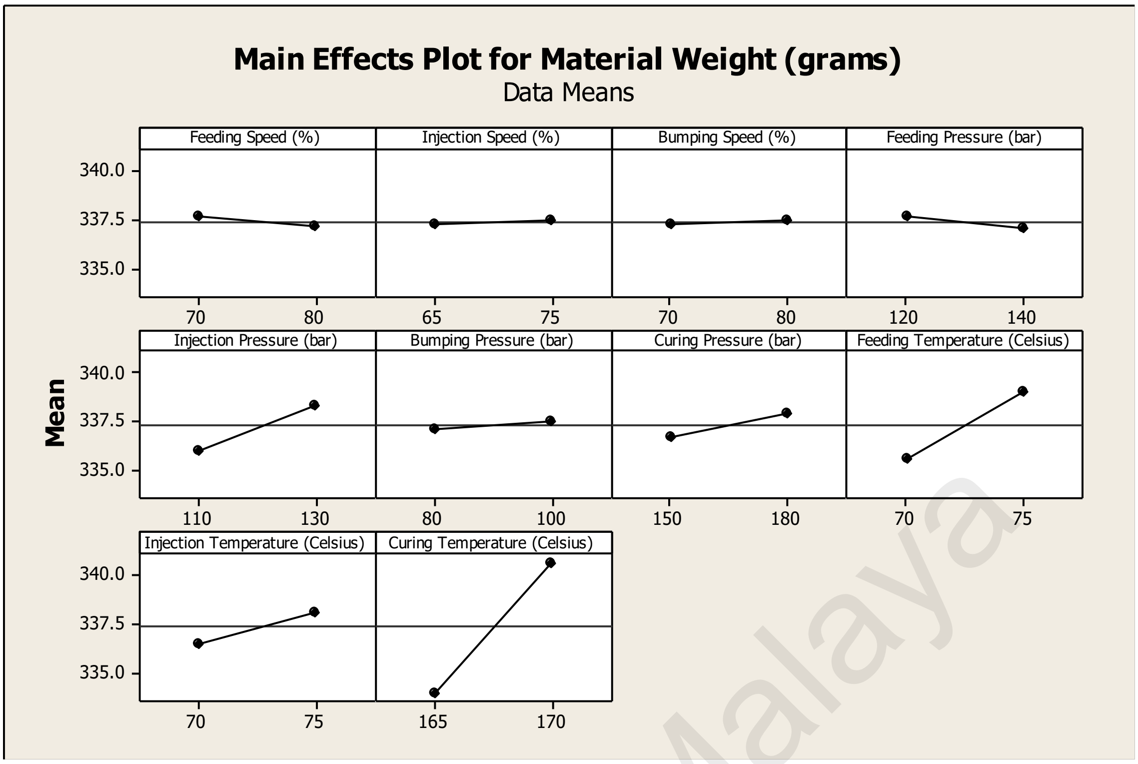


Figure 4.44: Main effects plot of control factor for material weight study.

Figure 4.44 shows that for material weight study, curing temperature at 165 ^{0}C is the highest effect; for lower effect, injection speed is remain same as 65 % to 75 %, and bumping speed is remain same as 70 % to 80 %.

4.7.3 One-Way ANOVA for Products Hardness Study

The calculation data is using one-way ANOVA formulas and attaching in the Appendices List. The ANOVA data using Minitab #16 for products hardness study as shown in Figure 4.45 and Figure 4.46.

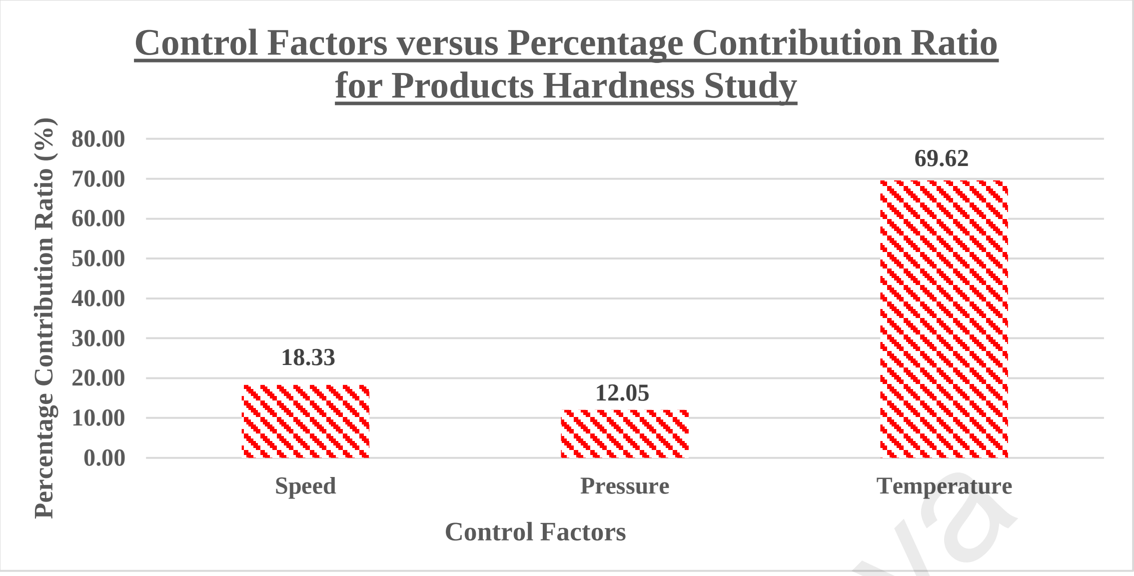


Figure 4.45: Control factors versus percentage contribution ratio for products hardness study.

Figure 4.45 shows that for products hardness study, temperature is the most contribution 69.62 % of control factor, and pressure of control factor is the lowest contribution 12.05 %.

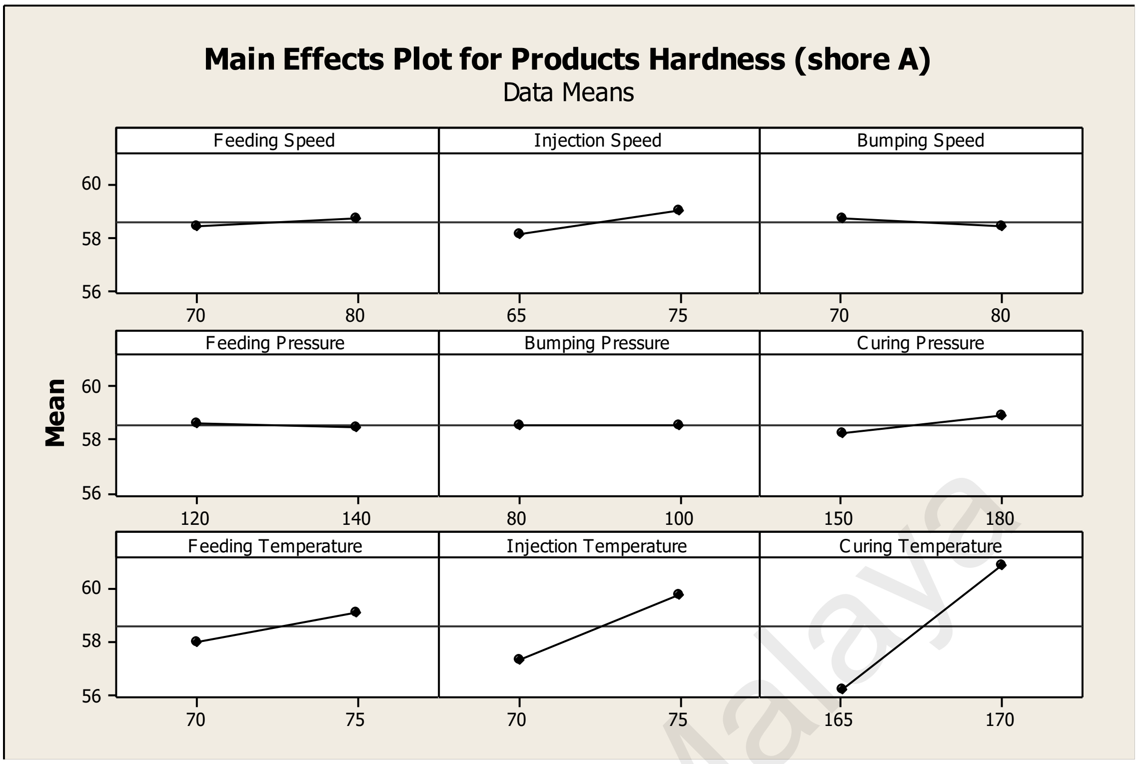


Figure 4.46: Main effects plot of control factor for products hardness study.

Figure 4.46 shows that products hardness study, feeding temperature at 170 ^{0}C is the highest effect; and for lowest effect, bumping pressure is remain same as 80 bar to 100 bar.

4.8 Conclusion

The result of rheometer curve shows that at temperature 180 ^{0}C: scorch time TS2 is 51 seconds and optimum cure time TC90 is 82 seconds. The Mooney viscosity graph shows that at temperature 100 ^{0}C: Mooney viscosity “ML 1+4” is 46.41 units in time 4 minutes.

S/N ratio “smaller-the better” for cycle time after process optimization with all control factors combination, the result shows that -

For speed factor of combination: feeding is 80%, injection is 75% and bumping is 80%. For pressure factor of combination: feeding is 140 bar, injection is 130 bar, bumping is 100 bar and curing is 180 bar. For temperature factor of combination: feeding is 75 ^{0}C, injection is 75 ^{0}C and curing is remain same as 165 ^{0}C.

S/N ratio “smaller-the better” for material weight after process optimization with all control factors combination, the outcome shows that -

For speed factor of combination, all results are remain same as: feeding is 70 %, injection is 65 % and bumping is 70 %. For pressure factor of combination: only feeding is remain same as 120 bar, injection is 120 bar, bumping is 80 bar and curing is 150 bar. For temperature factor of combination: feeding is 70 ^{0}C, injection is 70 ^{0}C and curing is 165 ^{0}C.

S/N ratio “nominal-the best” for material weight after process optimization with all control factors combination, the result indicates that -

For speed factor of combination: feeding is 70 %, only injection is remain same as 65 % and bumping is 70 %. For pressure factor of combination, all results are remain same as: feeding is 120 bar, injection is 130 bar, bumping is 100 bar and curing is 180 bar. For temperature factor of combination: feeding is 75 ^{0}C, injection is 75 ^{0}C and curing is 170 ^{0}C.

The result of one-way ANOVA for cycle time study after process optimization -

For contribution of control factor: temperature is the most contribution 61.95 %, and speed is the lowest contribution 17.93 %;

For effect of control factor: injection speed 75 % is the highest effect; and curing pressure 150 bar to 180 bar, is the lowermost effect.

One-way ANOVA for material weight study after process optimization, the result shows that -

For contribution of control factor: temperature is the most contribution 49.10 %, and speed is the lowest contribution 12.99 %. For effect of control factor: curing temperature 165 ^{0}C is the highest effect; for lower effect, injection speed is remain same as 65 % to 75 %, and bumping speed is remain same as 70 % to 80 %.

One-way ANOVA for products hardness study after process optimization, the outcomes shows that-

For contribution of control factor: temperature is the most contribution 69.62 %, and pressure is the lowest contribution 12.05 %. For effect of control factor: curing temperature 170 ^{0}C is the highest effect, and bumping pressure is the lowest effect.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This research on process optimization in rubber injection moulding for cycle time reducing, material saving and maintaining products quality by using Taguchi Signal-to-Noise ratio (S/N ratio) methods and one-way Analysis Of Variance (one-way ANOVA).

It can conclude that:

a) This experiment is using S/N ratio “smaller-is-better” has reduced the cycle time from 439 seconds to 416 seconds (reduced by 5.2 %), and total material saving from 345.1 grams to 331.9 grams (saved by 3.8 %).

b) From S/N ratio “nominal-is-best” as shown in Figure 4.39, the optimal process parameter combination parameter by selecting number of values L12 orthogonal array, which is maintaining products quality in hardness 55.2 shore A to 63.2 shore A.

c) The experimental result of one-way ANOVA shows that effect of control factor after process optimization: injection speed 75 % is the highest effect for cycle time, curing temperature 165 ^{0}C is the highest effect for material weight, and curing temperature 170 ^{0}C is the highest effect for products hardness.

d) From the result of one-way ANOVA, the highest contribution of control factor after process optimization is temperature for cycle time (contribution is 61.95 %), material weight (contribution is 49.10 %), and products hardness (contribution is 69.62 %).

5.2 Recommendation for Future Work

The process optimization in rubber injection moulding is selected from the consideration of the experiment. Consequently, control parameters such as speed, pressure and temperature can be well-defined in the beginning of prototyping process.

In addition, process optimization may be improve with adding investment -

a) Mould design to reduce cycle time:
    - Chroming less than 20 micron for abrasion resistant surface. This can causes rubber flow faster into mould cavity.

b) Rubber cool-runner injection machine to reduce runners and flashes waste.
    - The runners are kept at the minimum temperature inside the cold runner plate, which is rubber runners not yet cure and able to re-inject into mould cavity with minimum flashes.

c) Handling automation to reduce cycle time:
    - Using computer integrated tool to fix manual task which is important for delivery on time.

d) Material formulation to reduce cycle time and maintaining products quality.
    - Accelerators (such as TMTD, ZDEC) used to increase cure rate.
    - Reinforcing fillers (such as carbon black) used to improve the rubber modulus of elasticity (is known as hardness).

e) Products quality inspection by automatically control:
    - Industrial computed tomography scanning used for inspection.

f) Working in comfortable environment:
    - Improve the lighting at working table.
    - Improve the air ventilation at working station.

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