UNIVERSITI TEKNIKAL MALAYSIA MELAKA

OPTIMIZATION OF COOLING VARIATION OF CORE AND CAVITY TEMPERATURES FOR HDPE IN INJECTION MOULDING PROCESS

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DOCTOR OF PHILOSOPHY

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A thesis submitted
in fulfillment of the requirements for the degree of
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2025

DECLARATION

I declare that this thesis entitled " Optimization of Cooling Variation of Core and Cavity Temperature on HDPE in Injection Moulding Process" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature :

Name : WAN NOOR AZRINA BINTI WAN AZHARI

Date : 17 SEPTEMBER 2025

APPROVAL

I hereby declare that I have read this thesis and in my opinion, this thesis is sufficient in terms of scope and quality for the award of the degree of Doctor of Philosophy.

Signature   :

Supervisor Name   :   ASSOCIATE PROFESSOR IR. DR. MOHD AMRAN BIN

                              MD ALI

Date   :   17 SEPTEMBER 2025

DEDICATION

This thesis is lovingly dedicated to my family, whose unwavering support, endless patience, and constant encouragement have been the cornerstone of my academic journey. Their belief in me made this achievement possible. To my husband and parents, for their endless love, sacrifice, and belief in me even during the most challenging times. To my friends, for their companionship and understanding, which made this journey enjoyable and meaningful. Especially my colleagues and my mentor at ADTEC JTM Kampus Tangkak, whose guidance, wisdom, and inspiration have shaped both my research and personal growth.

This accomplishment would not have been possible without each of you. I will always be grateful for everything they did.

ABSTRACT

Plastic injection moulding is a widely used process for producing thermoplastic parts, yet warpage and shrinkage remain major challenges that compromise quality. This study employed a Box-Behnken Design with 17 experimental runs under the Response Surface Methodology (RSM) framework in Minitab to investigate the effects of core temperature, cavity temperature, and cooling time on five critical responses: warpage, volumetric shrinkage, ultimate tensile strength (UTS), Young's modulus, and percentage elongation. The Analysis of Variance (ANOVA) confirmed that all three parameters significantly influenced the responses, with cavity temperature having the strongest effect on warpage, while core temperature dominated volumetric shrinkage, UTS, Young's modulus, and elongation. Optimization results revealed that warpage could be reduced below 2.48 mm with lower core and cavity temperatures; volumetric shrinkage minimized to below 20.38% at a core temperature of 15 °C and cooling time of 12.5 s; UTS maximized above 19.52 N/mm² at 129.9 °C core temperature and 12.5 s cooling time; Young's modulus improved beyond 4.91 N/mm² at 15 °C core temperature and 17.55 s cooling time; and % elongation enhanced above 91.79 mm at 15 °C for both core and cavity temperatures. Validation showed minimal percentage errors between experimental and model predictions where 2.40% (warpage), 0.02% (shrinkage), 0.85% (UTS), 0.48% (Young's modulus), and 1.34% (elongation), confirming the robustness of the regression models. The real-world experimental validation using the optimal predicted value of 44°C, 15°C dan 37.5s, demonstrated a strong agreement between the predicted and experimental results, confirming that the developed quadratic regression models were statistically significant and capable of reliably representing the relationships between process parameters and responses. The minor deviations observed can be attributed to natural variations in machine performance, material behaviour, or environmental conditions during moulding. The importance of this study lies in its ability to tackle two of the most persistent defects in injection moulding of warpage and shrinkage while simultaneously improving the mechanical performance of HDPE parts. Beyond addressing these challenges, the study contributes to knowledge by establishing a robust multi-response optimization framework that highlights not only the main effects but also the interactions of core temperature, cavity temperature, and cooling time. This framework provides manufacturers with a practical tool for improving dimensional accuracy, enhancing mechanical reliability, reducing material waste, and increasing production efficiency, thereby bridging the gap between theoretical modelling and real-world manufacturing applications.

ABSTRAK

Pengoptimum perbezaan suhu penyejukan dalam teras dan rongga untuk HDPE bagi proses suntikan acuan

Proses acuan suntikan plastik merupakan kaedah yang meluas digunakan untuk menghasilkan komponen termoplastik, namun kecacatan seperti ledingan dan pengecutan masih menjadi cabaran utama yang menjejaskan kualiti. Kajian ini menggunakan Reka Bentuk Box-Behnken dengan 17 ujikaji lari di bawah kerangka Kaedah Gerak Balas Permukaan (RSM) dalam perisian Minitab untuk mengkaji kesan suhu teras, suhu rongga, dan masa penyejukan terhadap lima tindak balas kritikal iaitu ledingan, pengecutan isipadu, kekuatan tegangan muktamad, Modulus Young, dan peratus pemanjangan. Analisis Varians (ANOVA) mengesahkan bahawa ketiga-tiga parameter memberi pengaruh yang signifikan terhadap tindak balas, dengan suhu rongga memberikan kesan paling kuat terhadap ledingan, manakala suhu teras mendominasi pengecutan isipadu, kekuatan tegangan muktamad, Modulus Young, dan pemanjangan. Keputusan pengoptimuman menunjukkan bahawa ledingan dapat dikurangkan kepada kurang daripada 2.48 mm dengan suhu teras dan suhu rongga yang lebih rendah; pengecutan isipadu dapat diminimumkan kepada kurang daripada 20.38% pada suhu teras 15 °C dan masa penyejukan 12.5 s; kekuatan tegangan muktamad dapat dimaksimumkan melebihi 19.52 N/mm² pada suhu teras 129.9 °C dan masa penyejukan 12.5 s; Modulus Young meningkat melebihi 4.91 N/mm² pada suhu teras 15 °C dan masa penyejukan 17.55 s; dan peratus pemanjangan dapat ditingkatkan melebihi 91.79 mm pada suhu teras dan rongga masing-masing 15 °C. Proses pengesahan menunjukkan ralat peratusan minimum antara nilai eksperimen dan ramalan model iaitu 2.40% (ledingan), 0.02% (pengecutan), 0.85% (kekuatan tegangan muktamad), 0.48% (Modulus Young), dan 1.34% (pemanjangan), sekali gus mengesahkan kekukuhan model regresi yang dibangunkan. Pengesahan eksperimen dunia sebenar menggantikan nilai ramalan optimal 44°C, 15°C dan 37.5s, menunjukkan kesepakatan yang kukuh antara nilai ramalan dan hasil eksperimen, mengesahkan bahawa model regresi kuadratik yang dibangunkan adalah signifikan secara statistik dan mampu mewakili dengan tepat hubungan antara parameter proses dan tindak balas. Perbezaan kecil yang diperhatikan boleh dikaitkan dengan variasi semula jadi dalam prestasi mesin, tingkah laku bahan, atau keadaan persekitaran semasa proses acuan suntikan. Kepentingan kajian ini terletak pada keupayaannya menangani dua kecacatan utama dalam proses acuan suntikan iaitu ledingan dan pengecutan, pada masa yang sama meningkatkan prestasi mekanikal komponen HDPE. Di samping mengatasi cabaran ini, kajian ini menyumbang kepada pengetahuan dengan mewujudkan satu kerangka pengoptimuman multi-tindak balas yang mantap, yang menekankan bukan sahaja kesan utama tetapi juga interaksi antara suhu teras, suhu rongga, dan masa penyejukan. Kerangka ini menyediakan pengeluar dengan alat praktikal untuk meningkatkan ketepatan dimensi, memperkukuh kebolehpercayaan mekanikal, mengurangkan pembaziran bahan, serta meningkatkan kecekapan pengeluaran, sekali gus merapatkan jurang antara pemodelan teori dan aplikasi pembuatan dunia sebenar.

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LIST OF ABREVIATIONS

ANOVA   - Analysis of Variance

ASTM   - American Society for Testing Materials

BBD   - Box-Behnken Design

DOE   - Design of Experiment

HDPE   - High Density Polyethylene

ISO   - International Standard Organization

MSDS   - Material Safety Data Sheet

MTC   - Mould Temperature Controller

RSM   - Response Surface Methodology

UTM   - Universal Testing Machine

UTS   - Ultimate Tensile Strength

CHAPTER 1

INTRODUCTION

1.0   Introduction

Injection moulding is one of the most widely adopted technologies for high-speed processing of thermoplastic materials. The process involves injecting molten polymer into a mould cavity under high pressure through a plunger or reciprocating screw mechanism, ensuring complete filling and accurate replication of the desired geometry (Czepiel, 2023). This method offers advantages such as rapid filling compared to alternative moulding processes, recyclability of materials, and suitability for mass production of intricate components. However, it requires high initial investment in tooling, making it economically viable primarily for large-scale production.

Among the stages of injection moulding, cooling is the most time-consuming, often accounting for 50–80% of the total cycle time (Gaspar-Cunha et al., 2025). This stage is also the most influential in determining dimensional stability, residual stress, and overall part quality. As global manufacturing shifts toward greater sustainability, the ability to shorten cooling time without sacrificing quality is vital to reducing energy consumption, material waste, and production costs.

Cooling system is very important as it largely determines the part quality and cycle time as stated by He et al., (2023). A good cooling system can reduce cycle time and achieve dimensional stability of the part. However, some of cooling system are not appropriate and lead to defective plastic product. That's why, various quality characterisation that appears in plastic product always appear because of unbalanced cooling system.

Although statistical optimization methods such as Response Surface Methodology (RSM) and Analysis of Variance (ANOVA) have been extensively applied to injection moulding, many studies remain largely simulation-based and lack rigorous validation through experimental testing of mechanical properties, including tensile strength, Young's modulus, and percentage elongation (Gaspar-Cunha et al., 2025). Similarly, the optimization of cooling mediums is still underexplored, despite findings that water generally provides superior cooling efficiency compared to oil under equivalent operating conditions (He et al., 2023).

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Another limitation in the literature concerns the issue of unbalanced cooling between the core and cavity sides of the mould. While prior research has focused on overall cooling performance, limited attention has been given to thermal imbalance, which is known to cause shrinkage differences, warpage, and residual stresses, all of which negatively affect part stability and dimensional accuracy. In addition, although novel methods such as configuration-space-based cooling layout designs have been proposed to improve cooling system feasibility, their integration into statistical design frameworks and validation through experimental work remains scarce (Chang et al., 2024).

Statistical software was employed to analyze the results using the Design of Experiments (DOE) with the Response Surface Method (RSM) for both single and multi-response optimization to evaluate the significant effect of temperature variations on product quality. Further, simulatio Although statistical optimization methods such as Response Surface Methodology (RSM) and Analysis of Variance (ANOVA) have been extensively applied to injection moulding, many studies remain largely simulation-based and lack rigorous validation through experimental testing of mechanical properties, including tensile strength, Young's modulus, and percentage elongation (Gaspar-Cunha et al., 2025). Similarly, the optimization of cooling mediums is still underexplored, despite findings that water generally provides superior cooling efficiency compared to oil under equivalent operating conditions (He et al., 2023).

Design of Experiments (DOE) is beneficial to many manufacturing processes, including injection moulding. It helps reduce material costs by minimizing the need for trial and error. As a result, it shortens the experiment cycle time and improves efficiency, making it easier and faster to identify optimal processing conditions.

Recent research shows that the difference in temperature between the core and cavity of a mould can strongly influence the quality of injection-moulded parts. When one side cools faster than the other, the part tends to shrink unevenly, which often results in distortion and warpage (Massah et al., 2022; Trinh et al., 2023). Parts moulded at higher temperatures usually shrink more, because the polymer chains remain mobile for longer during cooling, while lower mould temperatures reduce shrinkage but may create extra internal stresses (Zhang et al., 2019). The look and feel of the surface is also affected: a hotter mould surface produces smoother finishes, while cooler moulds often leave the part with a slightly rougher texture (Kuo et al., 2020). On the mechanical side, studies have shown that the percentage elongation (%EL) improves when higher mould temperatures are used, as the material becomes more ductile, while lower mould temperatures often lead to lighter but stiffer parts (Liang et al., 2021). In

short, managing mould temperature is not just a technical step—it plays a central role in balancing appearance, strength, and stability of HDPE components.

A structured Design of Experiments (DOE) approach is adopted using Response Surface Methodology (RSM) and ANOVA via Minitab software to optimize parameters for both single and multi-response conditions. Key quality responses include warpage, shrinkage, ultimate tensile strength (UTS), Young's modulus, and percentage elongation (%EL). Simulation is further employed to validate experimental results and ensure robustness of the optimized model.

The findings of this research are expected to provide a validated optimization framework for controlling mould temperature and cooling time in injection moulding, ensuring improved process efficiency and product quality. Strong correlations between predictive models and actual results, in terms of both mechanical and dimensional performance, were established by integrating statistical modelling techniques such as RSM and ANOVA with experimental outcomes. Practical insights into the comparative effectiveness of water and oil as cooling mediums were also provided, supporting more informed decisions in industrial applications. In addition, the research contributed to the body of knowledge on balancing core and cavity cooling an aspect that had been relatively underexplored with the aim of enhancing part stability and reducing common defects such as warpage and shrinkage

This study is motivated by the need to improve efficiency and product quality in injection moulding by focusing on the cooling system, particularly the core and cavity temperature balance and cooling time. By combining statistical modelling and experimental validation, this research aims to bridge the current knowledge gap and provide a comprehensive optimization framework for both academic and industrial applications.

1.1   Problem Statements

In the plastic injection moulding industry, ensuring that parts consistently meet both dimensional accuracy and mechanical performance standards remains an ongoing challenge. Common defects such as shrinkage, warpage, burn marks, short shots, and deviations from dimensional tolerances often compromise product quality (Md Ali et al., 2021). Among these, shrinkage and warpage are particularly critical, as they directly affect both the dimensional stability and the structural integrity of the final product. Shrinkage results from uneven cooling and volumetric contraction of the polymer, while warpage occurs when differential cooling between the core and cavity induces internal stresses that distort the part geometry. These dimensional instabilities not only reduce product reliability but also contribute to poor mechanical properties such as reduced tensile strength, lower modulus, and limited elongation.

The root cause is often traced back to inadequate control of processing parameters, particularly the cooling system design and mould temperature settings. Variations in cooling time, cavity temperature, and core temperature are strongly correlated with the extent of shrinkage and warpage, yet many moulding practices still rely on trial-and-error approaches. Such methods are highly time-consuming, costly, and insufficient for meeting the increasing complexity and precision demanded by modern applications (Tran & Lo, 2019). The cooling rate of moulded parts within the cavity significantly governs the extent of polymer chain relaxation and structural reorganization, thereby resulting in an asymmetric distribution of mechanical properties as mentioned by Cheng at. el (2022) in his study. Furthermore, inconsistencies caused by differences in machine tonnage, polymer type, or operating conditions exacerbate these defects, undermining both dimensional accuracy and mechanical stability of the moulded components.

Therefore, it is crucial to establish an optimized cooling strategy that balances core and cavity temperature and determines the appropriate cooling time, in order to minimize shrinkage and warpage while improving mechanical performance. By employing statistical methods such as Design of Experiments (DoE), Response Surface Methodology (RSM), and Analysis of Variance (ANOVA), along with experimental validation, a systematic optimization framework can be developed. This approach not only reduces process variability but also ensures that dimensional tolerances and mechanical properties such as tensile strength, modulus, and elongation are achieved consistently. As Gotlih et al. (2022) emphasized, understanding the effect of cooling systems on part characterization is essential for resolving these quality issues and enhancing the overall reliability of injection-moulded products.

1.2   Research Objectives

The main aim of this research is to identify the optimal settings for core temperature, cavity temperature, and cooling time in order to improve the quality of injection-moulded parts, focusing on both their mechanical and physical properties. Specifically, the objectives are as follows:

i.   To investigate the effect of cooling temperature variation between core and cavity, including the cooling time that affected the quality part of the injection moulding process.

ii.   To optimize the effects of cooling variation on HDPE plastic parts characterization by performing the design of experiment (DOE) process.

iii.   To validate the quality by comparing the experimental work and mathematical model.

1.3   Research Scopes

The focusing scopes for this study are:

i.   Injection Moulding Machine – The experimental study is conducted using a 100-ton Sumitomo Demag machine.

ii.   Mould Temperature Controller (oil for hot temperature and water for cooling) used to control the mould temperature

iii.   Tensile test using the universal tensile machine. – Shimadzu AGS-X

iv.   Horizontal Optical Comparator used to measure the warpage – ST-Industries

v.   The material used is HDPE.

vi.   The injection moulding process parameters examined in this study include the cooling time, core and cavity temperature.

vii.   Design of experiment (DoE) to optimise the input parameters. Using Response Surface Methodology (RSM)

viii.   Aanalysis of Variance (ANOVA) to validate the experimental result.

1.4   Report Organization

This thesis is structured into five chapters. Chapter 1 introduces the study by presenting the background and significance of injection moulding, with particular emphasis on the role of cooling variations in influencing product quality. The chapter defines the problem statement, outlines the research objectives, specifies the scope and limitations, and establishes the relevance of investigating core temperature, cavity temperature, and cooling time as the main process parameters. Chapter 2 provides a comprehensive literature review covering fundamental aspects of injection moulding, the influence of thermal control on polymer behavior, and prior applications of optimization techniques. It critically evaluates research gaps related to shrinkage, warpage, and mechanical properties such as ultimate tensile strength, Young's Modulus, and percentage elongation, thereby justifying the focus of the present study. Chapter 3 details the research methodology, including the use of Response Surface Methodology (RSM) to design experiments, the application of Minitab software for statistical analysis, and the procedures employed for ANOVA, regression modelling, and surface optimization. The chapter also explains the experimental setup, materials used, and methods for measuring the targeted responses to ensure reliability and reproducibility. Chapter 4 presents and discusses the results obtained from the experimental work and statistical modelling. The findings are interpreted to determine the significance of each parameter on the multiple responses, with graphical and numerical evidence supporting the analysis. Comparisons with previous studies are also included to highlight consistencies, deviations, and the novel contributions of this research. Finally, Chapter 5 concludes the thesis by summarizing the main findings, emphasizing the successful optimization of process parameters for multiple responses, and highlighting the contribution of this work to both academic knowledge and industrial practice. The chapter further provides recommendations for future research, including extending optimization studies to other polymer materials, mould geometries, and advanced statistical techniques.

CHAPTER 2

LITERATURE REVIEW

2.0   Injection Moulding Process

Injection moulding is one of the most widely utilized manufacturing processes for producing plastic components. It enables the fabrication of a broad range of products that differ significantly in size, geometry, and functional application. Saradva (2025) highlights the importance of injection moulding in modern manufacturing because of its efficiency, versatility, and ability to create complex shapes with high precision. The process involves melting plastic and injecting it into a mould, where it cools down and hardens into the finished shape. This method is crucial for mass production of plastic items as it ensures high repeatability and consistency. Figure 2.1 presents the standard configuration of an injection moulding machine.
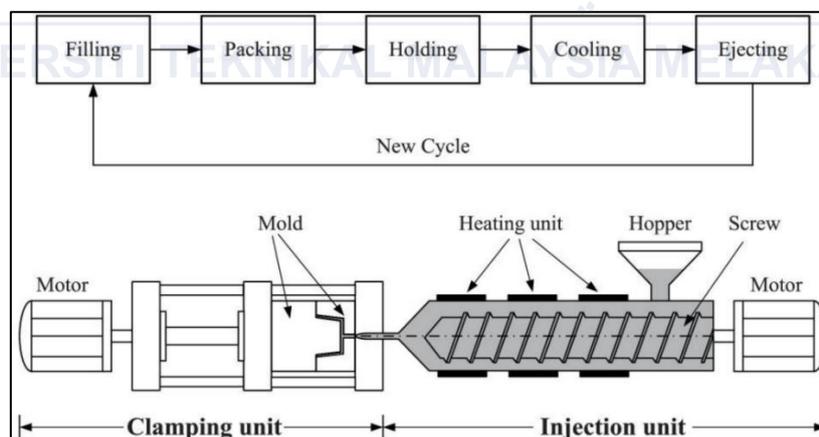
Figure 2.1: Standard injection moulding machine (Zhao et. al, (2022)

The injection moulding process is one of the most widely used manufacturing techniques for producing plastic components due to its ability to generate high-quality parts with consistent accuracy. The process is primarily carried out through two main functional units: the injection unit and the clamping unit. The injection unit is responsible for plasticizing the polymer resin, melting it into a homogeneous state, and delivering the molten polymer into

the mould cavity. Meanwhile, the clamping unit ensures that the mould remains tightly closed during injection, providing sufficient force to counteract the injection pressure.

The process can generally be divided into three essential stages: filling, packing (or holding), and cooling. In the filling stage, the reciprocating screw advances within a heated barrel to inject the molten resin into the mould cavity. This stage is critical, as insufficient or uneven filling can result in voids, incomplete parts, or visible defects. Once the cavity is filled, the process transitions into the packing or holding phase. At this point, sustained pressure is applied to compensate for volumetric shrinkage that naturally occurs as the polymer begins to solidify. This step ensures dimensional accuracy and prevents sink marks by maintaining material flow into the cavity until the gate region solidifies.

The final stage, cooling, is equally critical because it determines the solidification rate of the polymer, influencing both dimensional accuracy and mechanical properties. During cooling, heat is extracted through the mould walls, and the part gradually stabilizes in its final geometry. Cooling conditions, particularly mould temperatures and cooling time, play a significant role in minimizing warpage, shrinkage, and residual stresses (Zhao et al., 2022; He et al., 2023).

In the context of this study, the injection moulding process is tailored for High-Density Polyethylene (HDPE) dumbell-shaped specimens, which serve as standardized test samples for mechanical and dimensional analysis. The selected parameters; core temperature, cavity temperature, and cooling time were varied systematically to examine their effects on warpage, shrinkage, tensile strength, Young's modulus, and elongation at break. By controlling these stages of the injection moulding process, the study seeks to establish an optimized balance between dimensional stability and mechanical performance of HDPE components

2.1 Injection Moulding Machine

The injection moulding process is carried out using two main functional units: the injection unit and the clamping unit. The injection unit is designed to melt the polymer resin, homogenize it, and deliver the molten material into the mould cavity under controlled temperature and pressure. The clamping unit, on the other hand, holds the mould in place and applies sufficient clamping force to resist the high injection pressure, ensuring dimensional consistency and preventing material leakage during processing.

The moulding process generally consists of three sequential stages: filling, packing (or holding), and cooling. During the filling phase, a reciprocating screw within a heated barrel plasticizes the resin and injects it into the mould cavity. Proper filling is essential to avoid short shots, voids, or incomplete parts. Once the cavity is filled, the process transitions into the packing or holding phase, where additional molten polymer is injected under sustained pressure to compensate for volumetric shrinkage that naturally occurs as the material cools. This ensures that the cavity is completely filled and that surface defects such as sink marks are minimized.

Finally, in the cooling phase, heat is extracted through the mould walls using temperature control systems such as water or oil channels. This phase is critical, as cooling not only dictates the cycle time but also influences the dimensional accuracy and mechanical performance of the moulded part. Uneven or insufficient cooling can lead to warpage, shrinkage, and residual stresses, which compromise both geometry and strength (Zhao et al., 2022; He et al., 2023).

In this study, the injection moulding machine (SE100V model) was employed to fabricate dumbbell shaped HDPE specimens in compliance with ASTM D638 Type I standards. The machine was set to operate with varying core temperature, cavity temperature, and cooling time, as determined by the experimental design. These parameters were specifically selected for their direct influence on the dimensional stability (shrinkage and warpage) and mechanical behaviour (ultimate tensile strength, Young's modulus, and elongation at break) of the moulded specimens.

2.2   Common Defects in Injection Moulding

Table 2.1 summarizes the most common injection moulding defects identified in previous research, together with their causes and possible solutions. These findings highlight the critical influence of parameters such as mould temperature, cooling rate, injection pressure, and clamping force on part quality. By understanding these relationships, researchers have demonstrated that defects like warpage, shrinkage, bubbles, and flash can be minimized through proper process optimization, which directly relates to the dimensional accuracy and mechanical properties (UTS, Young's modulus, and elongation) examined in this study.

Table 2.1: Injection moulding defects, parameters, solutions and previous key findings

Defect	Parameter	Solution	Key Findings from Authors
Warping, Shrinkage	Core & Cavity Temperature	Maintain balanced temperature; optimize cooling channel design	Zhao et al. (2022) highlighted that uneven mould wall temperature leads to residual stresses and dimensional inaccuracy. Cheng et al. (2022) showed higher cavity temperatures improve surface quality but increase risk of deformation.
Warping, Incomplete crystallization, Dimensional instability	Cooling Time	Optimize cycle time; avoid undercooling or excessive cooling	He et al. (2023) found optimized cooling improves dimensional accuracy and mechanical properties by ensuring uniform crystallinity.
Flash, Short shots, Burn marks	Clamping Force	Set appropriate clamping force; avoid too low or excessive settings	Chen et al. (2020) emphasized that improper clamping force reduces stability of product weight. Huang et al. (2017) reported too low force causes flashing, while too high force causes venting problems.
Flash, Sink marks	Injection Pressure & Speed	Optimize injection pressure and melt temperature; balance material flow	Olmsted et al. (2019) noted flash occurs when injection pressure is too high or clamping force is insufficient.
Bubbles, Voids	Moisture & Melt Temperature	Dry material properly; control melt temperature	Olmsted et al. (2019) found excessive injection temperature and material moisture cause bubbles and uneven cooling defects.

Most defects in injection moulding, such as flash, warpage, bubbles, sink marks, unfilled sections, and ejector marks, are closely related to improper control of process parameters particularly are mould temperature, cooling rate, injection pressure, and clamping force. Uneven cooling between the core and cavity often leads to dimensional issues like shrinkage and warpage, while insufficient pressure or moisture in the material can reduce mechanical properties such as tensile strength, Young's modulus, and elongation. Previous studies (Chen et al., 2020; Massah et al., 2022) have consistently shown that careful optimization of cooling and pressure conditions is critical not only to minimize visible defects but also to ensure stable part performance. This highlights the direct connection between processing conditions, defect formation, and the mechanical outcomes investigated in this thesis.

2.2.1 Warpage

Recent research shows that the difference in temperature between the core and cavity of a mould can strongly influence the quality of injection-moulded parts. When one side cools faster than the other, the part tends to shrink unevenly, which often results in distortion and warpage (Massah et al., 2022; Trinh et al., 2023). A recent review by Coca-Gonzalez and Jimenez-Martinez (2024) also emphasized that warpage remains one of the most critical challenges in injection moulding, mainly driven by thermal gradients and non-uniform shrinkage during cooling. Parts moulded at higher temperatures usually shrink more, because the polymer chains remain mobile for longer, while lower mould temperatures reduce shrinkage but may create extra internal stresses (Zhang et al., 2019). Figure 2.2 exhibits the examples of warpage defect in multiple application.

The look and feel of the surface is also affected: a hotter mould surface produces smoother finishes, while cooler moulds often leave the part with a slightly rougher texture (Kuo et al., 2020; Mahmoodi et al., 2021). On the mechanical side, studies have shown that the percentage elongation (%EL) improves when higher mould temperatures are used, as the material becomes more ductile, while lower mould temperatures often lead to lighter but stiffer parts (Liang et al., 2021). In short, managing mould temperature is not just a technical step but it plays a central role in balancing appearance, strength, and stability of HDPE components. Due to the cooling of the part, a residual stress gradient is shown in Figure 2.3.
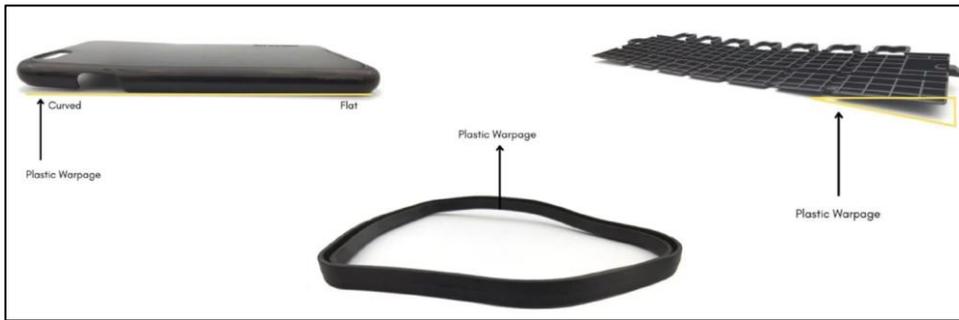
Figure 2.2: Examples of warpage occurring in different components (Coca-Gonzalez and Jimenez-Martinez, 2024)
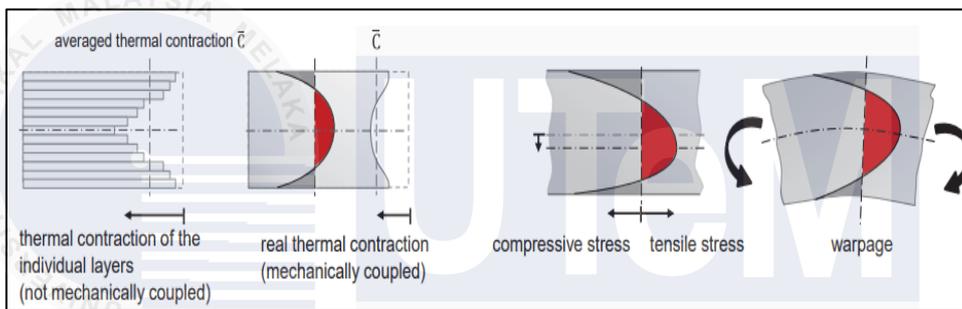
Figure 2.3: Residual stresses due to cooling effects. (Koslowski and Bonten, 2019)

Table 2.2 presents the key findings from previous researchers on the causes of warpage, with particular emphasis on the influence of mould temperature in HDPE materials during the injection moulding process.

Table 2.2: The warpage findings by other researchers on HDPE and mould temperature

Researcher(s) & Year	Focus Area	Key Findings	Relevance to HDPE & Mould Temperature
Coca-Gonzalez & Jimenez-Martinez, 2024	Warpage review	Identified causes, manufacturing influences, and future challenges of warpage.	Highlighted temperature variation as a main factor for distortion in injection moulding.
Kuo et al., 2020	Mould temperature and surface replication	Found that higher mould temperatures improve surface replication and mechanical properties.	Directly links mould temperature to surface quality outcomes.
Mahmoodi et al., 2021	Surface quality under varying mould temperatures	Reported better surface finish and strength with optimized mould temperatures.	Supports evidence that mould temperature impacts both appearance and structural integrity.
Massah et al., 2022	Warpage and shrinkage using RSM	Applied statistical modeling to show mould temperature's significant effect on warpage/shrinkage.	Provides optimization approach for reducing HDPE defects.
Trinh et al., 2023	Optimization of mould temperature distribution	Demonstrated minimizing warpage by controlling temperature gradients.	Confirms that managing temperature difference between core and cavity reduces defects.
Zhang et al., 2019	Shrinkage and mechanical properties of PP & PE	Mould temperature influences shrinkage and mechanical strength.	Important reference showing polyethylene's (including HDPE) sensitivity to mould temperature.

2.2.2 Shrinkage

Shrinkage is one of the common defects found on the injection moulding parts. Shrinkage leads to many problems in the application fields, such as process-induced distortions of angled fiber reinforced plastics. Besides, it also can cause uneven surfaces due to shrinkage marks (Jozwik et. al., 2019). Based on the study of Jorgensen (2024), thermal shrinkage, on the one hand, is relevant whenever the curing temperature is changed and, therefore, mainly in heating up and cooling down processes. Temperature changes thus cause thermal shrinkage. The amount of volumetric change is determined by the temperature change and the coefficient of thermal expansion.

Zhao et al. (2022) explain in their study that shrinkage is used to measure the decline in part volume as the polymer cools from its melt state to room temperature. Volumetric shrinkage reflects the difference between the actual volume and the volume of the product after being ejected from the mould cavity (Figure 2.4). The final volume can be calculated using the product's density and mass. Shrinkage is classified into three types: (a) in-mould shrinkage, which occurs while the part is still in the mould and is very rare, (b) mould shrinkage, which happens after the mould is opened, and (c) post-shrinkage, which occurs during the storage of the mat'rial. All the research findings are presented in Table 2.3.
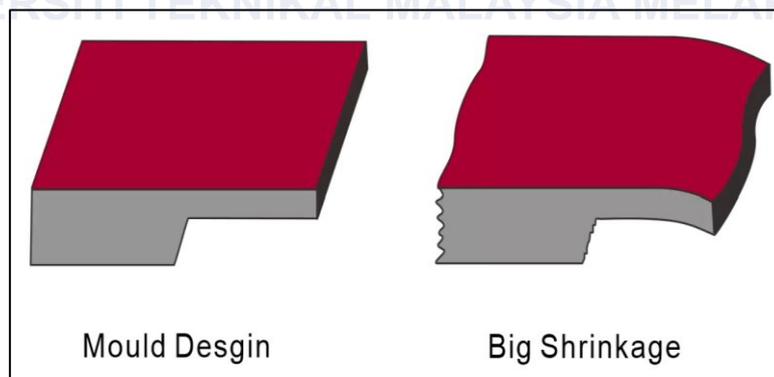
Figure 2.4: The shrinkage in plastic moulded part (Leo, 2021)

Table 2.3: The shrinkage findings by other researchers on HDPE and mould temperature

Researcher(s) & Year	Focus Area	Key Findings	Relevance to HDPE & Mould Temperature
Jóźwik et al., 2019	Surface quality issues from shrinkage	Shrinkage causes uneven surfaces and shrinkage marks, affecting part aesthetics.	Relevant for HDPE where surface finish is sensitive to mould cooling rates and temperature variations.
Jørgensen, 2024	Thermal shrinkage and temperature influence	Shrinkage occurs due to heating/cooling cycles; volumetric change depends on temperature difference and coefficient of thermal expansion.	Directly linked to HDPE processing since mould temperature strongly governs thermal shrinkage and final dimensions.
Zhao et al., 2022	Volumetric shrinkage classification	Shrinkage reflects volume reduction as polymer cools; classified into in-mould, mould, and post-shrinkage.	Supports analysis of HDPE where mould temperature and cooling conditions dictate shrinkage type and severity.

2.3 Thermoplastic materials

Large quantities of thermoplastics are chemically produced from plant-based materials. Some of the most significant thermoplastics include polypropylene (PP), polyvinyl chloride (PVC), polystyrene, low-density polyethylene (LDPE), and high-density polyethylene (HDPE). These polymers are widely used in various structural applications, such as wiring and lightweight utilities. Additionally, thermoplastic polymers serve as a matrix for both synthetic and natural fibres. At specific temperatures, thermoplastic polymers can melt and be moulded or reformed by heating to fit a mould. However, polymeric chain breakage during reprocessing can cause the physical properties of thermoplastic polymers to degrade (Kwon et al., 2021).

2.3.1 High-Density Polyethylene (HDPE)

High-Density Polyethylene (HDPE) is one of the most widely used thermoplastics because of its affordability, versatility, and excellent processing characteristics. Its applications range from packaging products such as bottles and films, to industrial goods like pipes, furniture, and medical devices, owing to its high chemical resistance, toughness, and bio-neutrality (Olesik et al., 2020). These same characteristics make HDPE an ideal candidate for injection moulding, where its lightweight nature and ease of processing allow for efficient batch and continuous production.

In the context of injection moulding, the performance of HDPE parts is strongly affected by processing conditions, particularly cooling variations and mould temperature. Studies have shown that improper cooling can lead to dimensional defects such as warpage and shrinkage, which reduce product accuracy and increase rejection rates (Bianchi et al., 2019). For example, Trish et al. (2022) demonstrated that shrinkage and warpage in HDPE mouldings are directly influenced by the balance between cavity and core temperatures, where uneven cooling accelerates distortion. Similarly, Fletcher et al. (2023) reported that higher mould temperatures slow down cooling, increasing crystallinity and altering the mechanical behaviour of HDPE by affecting Ultimate Tensile Strength (UTS), Young's modulus, and elongation at break.

These findings underline the dual role of HDPE's favourable processing properties: while it is easy to mould into complex shapes, its sensitivity to thermal gradients makes it highly dependent on careful process optimization. In this study, focusing on core and cavity cooling variations helps to better understand the link between mould temperature control and the resulting dimensional stability and mechanical properties of HDPE. This approach ensures not only compliance with international testing standards but also provides valuable insights into minimizing defects and improving the overall quality of injection-moulded products.

The material specifications of HDPE reported by previous researchers are summarized in Table 2.4. These specifications provide essential reference data for this study and establish a foundation for comparing and validating the experimental findings.

Table 2.4: HDPE Material specifications reported by previous studies

Property	Typical Value Range	Testing Standard / Condition	Supporting References
Density	0.94 – 0.97 g/cm³	ASTM D792	Rahman et al. (2019); Zhao et al. (2022)
Melt Flow Index (MFI)	0.2 – 20 g/10 min (190 °C / 2.16 kg)	ASTM D1238	Chen et al. (2020)
Tensile Strength at Yield	20 – 35 MPa	ASTM D638 / ISO 527	Trish et al. (2022); Fletcher et al. (2023)
Young's Modulus	800 – 1400 MPa	ASTM D638 / ISO 527	Zhao et al. (2022)
Elongation at Break	100 – 1000 %	ASTM D638 / ISO 527	Trish et al. (2022)
Flexural Modulus	800 – 1200 MPa	ASTM D790	Rahman et al. (2019)
Izod Impact Strength	50 – 150 J/m	ASTM D256	Chen et al. (2020)
Shore Hardness (D)	55 – 70	ASTM D2240	Fletcher et al. (2023)
Melting Temperature (Tm)	125 – 137 °C	DSC Analysis	Zhao et al. (2022)
Crystallinity	60 – 80 %	XRD / DSC	Trish et al. (2022)
Heat Deflection Temperature (HDT)	50 – 75 °C	ASTM D648	Rahman et al. (2019)

2.4 Two Plate Mould

The two-plate mould is one of the simplest and most widely used designs in injection moulding, consisting of two main halves: the stationary side (Plate A), which houses the cavities, and the moving side (Plate B), which contains the cores. Plate A is also where the sprue bushing is mounted, allowing molten polymer to flow into the cavity through a central

gate. Depending on the design, the polymer can either be delivered via a cold runner system or through a hot runner system that employs nozzle drops to distribute the melt directly into the cavity area.

In this study, a two-plate mould design was selected to produce dumbbell-shaped (dog-bone) specimens in accordance with ASTM D638 and ISO 527-2 standards. The simplicity and reliability of this mould type made it ideal for generating consistent tensile test specimens while enabling precise control of parameters such as core temperature, cavity temperature, and cooling time. The ability of the two-plate mould to provide uniform melt flow and straightforward demoulding is especially important when investigating how thermal variations influence shrinkage, warpage, and mechanical properties of HDPE parts.

Researchers have highlighted the critical role of mould temperature in ensuring dimensional accuracy and mechanical integrity. For instance, Zhao et al. (2022) demonstrated that uneven thermal conditions across mould walls result in residual stresses and geometric distortion, while Cheng et al. (2022) showed that higher cavity temperatures improved surface quality but increased the risk of warpage in HDPE parts. Likewise, Fletcher et al. (2023) observed that changes in mould temperature affected crystallinity, thereby influencing tensile behaviour. The use of a two-plate mould in this research ensures that such effects can be systematically studied, since its straightforward construction reduces additional process variability.

By integrating the two-plate mould design with carefully controlled parameter settings, this research establishes a direct link between mould thermal conditions, specimen quality, and final mechanical performance. This approach not only strengthens the reliability of the experimental results but also makes the findings more applicable to real-world injection moulding practices where two-plate moulds remain a dominant choice. Figure 2.5 illustrates the structure of a two-plate mould, which is the mould design employed in this study for producing the test specimens.
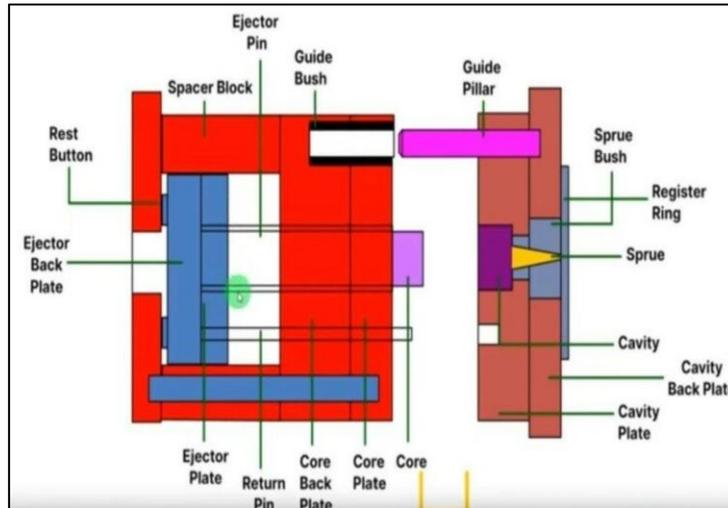
Figure 2.5: Mould components of a 2 plate mould (Achary, 2021)

2.4.1 Mould Components

The performance of the flow system is closely related to the core and cavity plates, as these plates determine how the molten polymer is distributed, cooled, and solidified. The material typically used for mould plates is tool steel due to its high strength, wear resistance, and good thermal conductivity, which ensures consistent temperature distribution. Precise temperature control of the core and cavity plates is critical, since uneven thermal conditions result in non-uniform shrinkage and residual stresses that manifest as warpage. Zhao et al. (2022) further supported this by showing that imbalances in thermal behaviour across the cavity walls increase dimensional deformation, while Gotlih et al. (2022) confirmed that cooling system design in the plates significantly affects residual stress and shrinkage.

Fletcher et al. (2023) demonstrated that mould temperature distribution influenced the crystallinity of HDPE specimens, where higher crystallinity increased stiffness (Young's modulus) but reduced ductility (percentage elongation). Similarly, He et al. (2023) observed that optimised cooling, governed by cavity and core temperature balance, improved the ultimate tensile strength (UTS) by promoting uniform stress distribution during solidification.

The choice of mould material is closely linked to the thermal behaviour of the core and cavity plates, which directly impacts cooling uniformity and thus the dimensional and mechanical performance of injection-moulded HDPE parts. Tool steels, while strong and durable, have moderate thermal conductivity, meaning that without optimized cooling channel design, they can induce residual stresses leading to shrinkage and warpage (Zhao et al., 2022; Gotlih et al., 2022). Stainless steels offer corrosion resistance but suffer from poor heat transfer,

which further increases the risk of dimensional deformation (Cheng et al., 2022). In contrast, beryllium–copper alloys allow faster and more uniform cooling, which has been shown to reduce shrinkage and warpage while improving crystallinity and enhancing tensile performance, such as UTS and stiffness, though sometimes at the expense of ductility (Gotlih et al., 2022; Fletcher et al., 2023; He et al., 2023). In this study, the relevance of mould material lies in its role in controlling thermal gradients across the core and cavity plates, which directly affect the cooling rate, crystallization behaviour, and therefore the shrinkage, warpage, and mechanical properties (Young's modulus, UTS, and percentage elongation) of HDPE dumbbell shaped.

2.5   Injection Moulding Parameters

Injection moulding is a delicate balance of parameters that ultimately decide the quality, efficiency, and cost of the final product. These parameters function like the "control knobs" of the process—small changes can dramatically affect how molten plastic flows, cools, and solidifies into the desired shape. Determining the right settings is therefore critical: improper adjustment often leads to defects such as warpage, shrinkage, and poor mechanical performance, which not only increase scrap rates and cycle time but also raise production costs and reduce competitiveness.

Previous studies have shown that parameters such as melt temperature, mould temperature, injection pressure, injection velocity, holding/packing pressure, packing time, cooling temperature, and cooling time all play a vital role in defining product quality (Gao et al., 2018). Mould temperature directly influences crystallization behaviour, which in turn affects dimensional stability. Zhao et al. (2022) further explained that uneven temperature control across the mould leads to residual stresses, resulting in shrinkage and warpage. Similarly, Fletcher et al. (2023) showed that mould temperature changes significantly alter mechanical responses—higher temperatures increased stiffness (Young's modulus) but reduced elongation at break, while faster cooling at lower temperatures improved toughness but increased shrinkage.

Cooling time and heat management are equally critical. Hassan et al. (2024) demonstrated that optimizing cooling time, melt temperature, and holding pressure significantly minimized warpage and shrinkage, while also improving tensile strength. Gotlih et al. (2022) reinforced this by showing that cooling system design and timing directly

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influenced residual stress distribution within HDPE parts. These findings align closely with this study, where the systematic variation of core temperature, cavity temperature, and cooling time is used to investigate their influence on dimensional defects (warpage and shrinkage) and mechanical responses (UTS, Young's modulus, and percentage elongation) of HDPE specimens.

In essence, the injection moulding parameters act as an interconnected system for adjusting one parameter often requires fine-tuning others to maintain balance. Through controlled experimentation and statistical optimization using RSM in Minitab, this study builds upon existing literature to identify optimal parameter settings for HDPE that reduce defects and enhance mechanical performance. Table 2.5 presents the findings of the researchers regarding the parameters involved in this study.

Table 2.5: Previous study on the injection moulding parameter.

Source	Core Temp. (°C)	Cavity Temp. (°C)	Cooling Time (s)	Key Findings
Wang et al. (2019)	60-80	30-50	40-60	Showed that higher mould/core temperatures improved creep resistance and mechanical strength of polypropylene composites.
Jamaluddin et al. (2018)	40-60	25-35	50-70	Identified that lower cavity temperatures and optimized cooling reduced shrinkage defects in polypropylene gears.
Huang et al. (2020)	30-70	15-25	10-15	Demonstrated that proper machine calibration combined with DOE significantly improved part quality and reduced variability.
Ravikiran et al. (2022)	50-70	20-40	15-25	Found that optimized parameters for PMMA improved dimensional accuracy and minimized warpage for FMCG components.

2.5.1 Cooling Time

Cooling time is one of the most critical stages in the injection moulding process because it directly influences both production efficiency and part quality. It refers to the period needed for molten polymer to solidify inside the mould and gain enough rigidity for safe ejection. As highlighted by Kuo and Xu (2022), the efficiency of cooling dictates overall cycle time while also determining whether the moulded component meets dimensional and mechanical performance requirements.

If cooling is too short, parts may be ejected prematurely, leading to warpage, sink marks, incomplete crystallization, or residual stresses that compromise structural integrity. Conversely, excessively long cooling times extend the production cycle and reduce efficiency without guaranteeing proportional improvements in quality. The thermal balance within cooling channels is also essential. When coolant is too hot, the polymer cools slowly, increasing the risk of dimensional inaccuracy and shrinkage. If it is too cold, rapid cooling generates steep thermal gradients, which introduce internal stresses and weaken ductility.

This relationship is especially relevant for HDPE specimens in this study. Previous findings reinforce the significance of optimized cooling (Table 2.6). Zhao et al. (2022) showed that thermal imbalances during cooling are a key driver of residual stresses and warpage, while Gotlih et al. (2022) demonstrated that poor cooling system design amplifies volumetric shrinkage. Fletcher et al. (2023) further observed that slower cooling at higher mould wall temperatures increased crystallinity, raising stiffness (Young's modulus) but lowering elongation at break. Similarly, He et al. (2023) found that synchronizing cooling time with mould wall temperature improved ultimate tensile strength (UTS) by promoting more uniform stress distribution.

In this thesis, cooling time is systematically varied alongside core and cavity temperatures to evaluate its effect on warpage, shrinkage, UTS, Young's modulus, and percentage elongation in HDPE dumbbell shaped specimens. This integrated approach enables a clearer understanding of how cooling duration, when combined with thermal conditions, governs both dimensional accuracy and mechanical performance.

Table 2.6: Effects of cooling time on warpage, shrinkage, and mechanical properties

Author(s) & Year	Focus of Study	Key Findings	Relation to This Thesis
Kuo & Xu (2022)	Cooling time in injection moulding	Cooling time strongly affects cycle efficiency and part quality. Too short causes warpage, sink marks, and dimensional inaccuracy; too long reduces efficiency.	Highlights the need to optimize cooling duration for HDPE to balance efficiency with warpage and shrinkage control.
Zhao et al. (2022)	Thermal imbalance in mould cooling	Uneven cooling generates residual stresses, leading to warpage and dimensional deformation.	Supports thesis objective of evaluating how core/cavity temperature and cooling time affect warpage.
Gotlih et al. (2022)	Cooling system design and residual stress	Poor cooling system design intensifies volumetric shrinkage and stress concentration.	Relevant for assessing shrinkage behaviour in HDPE dumbbell sahped specimens under different cooling times.
Fletcher et al. (2023)	Cooling rate and crystallinity in HDPE	Slower cooling (higher mould temperature) increased crystallinity, raising stiffness but reducing elongation at break.	Directly relates cooling to mechanical responses (Young's modulus and % elongation).
He et al. (2023)	Optimisation of cooling cycle	Synchronizing cooling time with mould wall temperature improved UTS by enabling uniform stress distribution.	Reinforces the combined effect of cooling duration and mould thermal control on UTS in HDPE specimens.

2.5.2 Mould Temperature (Core and Cavity Temperature)

Mould temperature is widely recognized as one of the most critical parameters in the injection moulding of thermoplastic polymers, particularly semi-crystalline materials such as HDPE. Traditional contact measurement methods, such as thermocouples, often introduce errors because they rely on heat transfer between the probe and the mould surface, which may not reflect the true thermal conditions within the mould.

The significance of mould temperature lies in its strong influence on the cooling rate, crystallization behaviour, and residual stress distribution, which directly affect both dimensional accuracy and mechanical performance. In particular, differences between core and cavity temperatures create uneven cooling conditions that lead to non-uniform shrinkage and, ultimately, warpage of the part. Zhao et al. (2022) reported that thermal imbalances across mould walls are a key factor contributing to residual stresses, which not only distort the geometry of injection-moulded parts but also reduce their mechanical stability. Similarly, Cheng et al. (2022) demonstrated in their study on HDPE pallets that higher cavity temperatures improved surface quality but increased the likelihood of dimensional deformation due to slower, uneven cooling.

The link between mould temperature and mechanical properties has also been documented. Fletcher et al. (2023) found that higher mould temperatures promoted slower cooling, which increased crystallinity in HDPE specimens. While this led to improved stiffness (higher Young's modulus), it also reduced ductility, lowering the percentage elongation at break. Conversely, lower mould temperatures accelerated cooling, reducing crystallinity and yielding parts with higher toughness but greater shrinkage. Similarly, He et al. (2023) observed that optimizing cooling time and mould wall temperature together improved ultimate tensile strength (UTS) by achieving more uniform stress distribution and controlled crystal growth.

For shrinkage, Gotlih et al. (2022) noted that uneven heat transfer between the core and cavity surfaces exacerbated volumetric shrinkage, which strongly correlates with mould temperature distribution. Their findings underscore that dimensional stability cannot be achieved by adjusting a single parameter in isolation but instead requires balanced control of both core and cavity thermal conditions.

In the context of this study, these findings are especially relevant. By systematically varying the core temperature, cavity temperature, and cooling time, this research investigates how these parameters influence dimensional defects (warpage and shrinkage) and mechanical responses (UTS, Young's modulus, and elongation) in HDPE dumbbell-shaped specimens

(Table 2.7). The results are expected to highlight the importance of precise mould temperature control in minimizing defects while optimizing the balance between stiffness and ductility in injection-moulded parts.

Table 2.7: Effects of mould temperature on shrinkage, warpage, and mechanical properties

Author(s) & Year	Mould Temperature Aspect	Effects on Shrinkage / Warpage	Effects on Mechanical Properties (UTS, Young's Modulus, % Elongation)
Zhao et al. (2022)	Uneven core and cavity temperature	Creates thermal imbalance → uneven cooling → non-uniform shrinkage → warpage and dimensional distortion	Reduces mechanical stability due to residual stresses
Cheng et al. (2022)	Higher cavity temperature	Improves surface quality, but increases risk of warpage and deformation due to slower cooling	Alters stress distribution, lowering toughness
Fletcher et al. (2023)	Higher mould temperature (slower cooling)	Increases crystallinity → dimensional changes; higher shrinkage risk	Improves stiffness (higher Young's modulus), reduces ductility (lower % elongation)
Fletcher et al. (2023)	Lower mould temperature (faster cooling)	Reduces crystallinity → higher volumetric shrinkage and potential warpage	Produces tougher parts, but with reduced stiffness
Gotlih et al. (2022)	Uneven heat transfer between core and cavity surfaces	Exacerbates volumetric shrinkage, leads to dimensional instability	Strong correlation between cooling design and mechanical uniformity

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He et al. (2023)	Optimised cooling cycle (balanced mould wall temp. + time)	More uniform cooling → reduces shrinkage and warpage	Improves UTS by controlling stress distribution and crystal growth

2.6   Mould Temperature Controller (MTC)

The mould temperature controller (MTC) plays a crucial role in regulating the mould temperature during the injection moulding process, which directly influences the quality of the final product. Its main functions are: (i) heating the mould to the desired temperature, and (ii) maintaining that temperature consistently throughout the cycle. The success of these two functions ensures cycle time optimization and the production of stable, high-quality moulded parts.

Mould temperature strongly affects the surface quality, flowability of the melt, shrinkage behaviour, dimensional deformation, and overall cycle time. For thermoplastics such as HDPE, maintaining slightly higher mould temperatures improves surface finish and enhances melt flow, but it can also prolong cooling and cycle time. Conversely, lower mould temperatures can reduce in-mould shrinkage but may lead to greater post-mould shrinkage and warpage as the part cools unevenly. Zhao et al. (2022) emphasized that inadequate thermal balance in the mould can create residual stresses, resulting in warpage and reduced dimensional stability, while Fletcher et al. (2023) found that higher mould temperatures increase crystallinity in HDPE, improving stiffness (Young's modulus) but reducing ductility (percentage elongation).

In the context of this study, the use of an MTC is essential for systematically varying and controlling the core and cavity temperatures, enabling the analysis of how thermal regulation affects shrinkage, warpage, and mechanical performance (UTS, Young's modulus, and elongation) of HDPE dumbbell shaped specimens. This precision in mould temperature control provides a practical pathway to balance dimensional stability with mechanical performance. Controlling mould temperature is widely recognised as a key parameter in injection moulding for minimizing defects such as warpage and shrinkage, and in stabilizing dimensional accuracy and mechanical properties (Zhao et al., 2022).

2.7 Mechanical Properties

Mechanical properties describe how materials behave when subjected to forces or stresses, and they are essential for evaluating a material's performance in manufacturing and structural applications. Key properties include tensile strength (the maximum stress before fracture), yield strength (the stress at which permanent deformation begins), Young's modulus (stiffness), ductility (ability to stretch before breaking), brittleness (tendency to fracture with little deformation), impact strength, fatigue strength, and fracture toughness (resistance to crack propagation).

In the context of injection moulding, these properties are strongly influenced by processing parameters such as melt temperature, mould temperature, packing pressure, and cooling time. These parameters affect the alignment of polymer chains, crystallinity, and residual stresses within the part. For instance, faster cooling rates can reduce crystallinity, leading to improved ductility but lower stiffness, while slower cooling allows for higher crystallinity, enhancing stiffness but often at the cost of reduced elongation. This directional dependence of properties is known as anisotropy (Callister, 2018).

Farotti and Natalini (2017) demonstrated that mould temperature and holding pressure were particularly significant in determining tensile strength and overall mechanical behaviour. More recently, Fletcher et al. (2023) reported that higher mould temperatures in HDPE promote increased crystallinity, which enhances Young's modulus but reduces elongation at break. He et al. (2023) further showed that optimizing cooling conditions can balance tensile strength (UTS) and ductility by controlling crystal growth and stress distribution. These findings are consistent with Zhao et al. (2022) and Gotlih et al. (2022), who highlighted that uneven thermal distribution between core and cavity surfaces increases residual stresses, contributing to warpage, shrinkage, and compromised mechanical stability.

For this study, these insights are particularly relevant. By systematically varying core temperature, cavity temperature, and cooling time, the relationship between processing parameters and the resulting mechanical properties (UTS, Young's modulus, and elongation) of HDPE dumbbell shaped specimens will be clarified. This analysis not only connects dimensional stability issues such as shrinkage and warpage to thermal management but also provides an understanding of how to optimize the balance between stiffness and ductility in injection-moulded HDPE parts. Table 2.8 presents the studies on mechanical properties that integrated with parameters that involved in this study.

Table 2.8: Previous studies on mechanical properties

Author(s)	Contribution	Limitation / Gap
Farotti & Natalini (2017)	Identified mould temperature and holding pressure as key parameters influencing tensile strength and overall mechanical behaviour.	Did not explore interactions with cooling time or effects on ductility.
Fletcher et al. (2023)	Showed that higher mould temperatures in HDPE increase crystallinity, enhancing stiffness (Young's modulus) but reducing elongation.	Focuses mainly on crystallinity; less emphasis on shrinkage and warpage implications.
He et al. (2023)	Highlighted that optimizing cooling conditions can balance tensile strength and ductility by controlling crystal growth and stress distribution.	Limited material scope; specific to cooling optimization without broader parameter interaction.
Zhao et al. (2022)	Demonstrated that uneven thermal distribution increases residual stresses, contributing to warpage and shrinkage.	Emphasis on residual stress; lacks integration with mechanical strength outcomes.
Gotlih et al. (2022)	Confirmed that uneven cooling intensifies volumetric shrinkage, reducing tensile strength and modulus.	Focused on shrinkage; did not fully address optimization of thermal management strategies.
Ismail et al. (2019)	Described tensile testing methodology as a tool to evaluate key mechanical properties in injection-moulded polymers.	General testing description; does not address specific parameter–property relationships.

2.7.1 Tensile Testing

Tensile testing is one of the most widely used destructive methods for evaluating the mechanical properties of polymers, including tensile strength, yield strength, Young's modulus, and percentage elongation. In this test, a dog-bone specimen is subjected to a controlled pulling force until fracture, while the stress–strain curve generated provides critical information on stiffness, ductility, and ultimate tensile strength (Ismail et al., 2019).

In injection-moulded components, tensile behaviour is strongly influenced by processing conditions, particularly core and cavity temperatures, which govern the cooling rate and crystallization of the polymer. Uneven thermal gradients between the mould plates can cause residual stresses and anisotropic chain orientation, leading to non-uniform shrinkage and warpage. These dimensional instabilities not only distort the part geometry but also reduce its mechanical performance. Zhao et al. (2022) showed that thermal imbalances increase residual stresses, lowering the stability of injection-moulded parts, while Gotlih et al. (2022) confirmed that uneven cooling intensifies volumetric shrinkage, directly affecting tensile strength and modulus.

For HDPE, Fletcher et al. (2023) reported that higher cavity temperatures slow cooling and increase crystallinity, improving stiffness (Young's modulus) but reducing ductility (percentage elongation). Conversely, lower mould temperatures accelerate cooling, resulting in lower stiffness but higher toughness. He et al. (2023) highlighted that optimizing cooling time together with mould wall temperatures improves tensile strength (UTS) by balancing crystallinity development and stress distribution.

In this study, tensile testing of HDPE dumbell shaped specimens is used to correlate core and cavity temperature differences and cooling time with mechanical properties. The results provide direct evidence of how thermal control strategies influence shrinkage, warpage, and the balance between stiffness and ductility, which are crucial for ensuring dimensional accuracy and reliable mechanical performance in injection-moulded products. Tensile testing machine is shown in Figure 2.6.

Figure 2.6: Tensile testing machine (Ismail et al., 2019)

2.8   Design of Experiment (DOE)

The Design of Experiment (DOE) is a structured and systematic approach used to investigate the influence of process parameters on output responses under controlled conditions. According to Jankovic et al. (2021), well-established guidelines and procedures are available to support DOE implementation, which typically involve defining research objectives, identifying response variables, selecting factors and their levels, and determining the appropriate experimental design type before executing the experiments. The choice of factors and design type generally depends on the purpose of the study whether it is for screening, characterization, or optimization as well as the available resources. While several DOE strategies can theoretically fit a given investigation, the quality of the design is determined by how efficiently it provides meaningful insight with minimal resource usage.

In this research, DOE is applied to analyze the effects of cooling variation between the core and cavity of the mould in the injection moulding process. The selected factors are core temperature, cavity temperature, and cooling time, as these parameters are known to directly influence both dimensional quality (shrinkage and warpage) and mechanical properties (ultimate tensile strength, Young's modulus, and percentage elongation) of HDPE dumbbell shaped specimens. The use of DOE ensures that the relationships between these parameters and the responses can be systematically studied, while minimizing experimental runs and avoiding the inefficiency of trial-and-error approaches.

Previous studies support this approach. For instance, Bhalerao et al. (2017) demonstrated that DOE combined with numerical analysis significantly improves both product quality and productivity in injection moulding by optimizing mould parameters such as runner dimensions and cooling channel configurations. Similarly, Zhao et al. (2022) highlighted that DOE methods are easier to apply and less computationally expensive compared to conventional trial-and-error techniques, which explains their widespread adoption across fields like materials science, medicine, and manufacturing.

For this study, the Response Surface Methodology (RSM) with a Box–Behnken Design (BBD) is selected as the DOE approach. RSM is particularly well suited for optimization problems involving curvature in the response surface and interactions among multiple parameters. The Box–Behnken design is efficient in terms of the number of experimental runs required, making it ideal for studies with three or more factors. By employing this method, the research not only identifies the main and interaction effects of the selected factors but also determines the optimal combination of parameters to minimize dimensional defects while maximizing mechanical performance.

Overall, the application of DOE in this research provides a systematic and statistically valid framework to explore the impact of cooling variations in HDPE injection moulding. It ensures that the findings are both reliable and applicable to industrial practice, particularly in reducing defects such as shrinkage and warpage while maintaining the required tensile properties.

2.8.1 Full Factorial

A full factorial Design of Experiments (DOE) is the most comprehensive and systematic way to study a process because it investigates all possible combinations of factor levels. This approach allows researchers to evaluate not only the main effects of each parameter but also the interaction effects between them. Interaction effects are particularly important in injection moulding because parameters such as mould temperature, core–cavity imbalance, packing pressure, and cooling time rarely act independently (Bianchi et al., 2019).

For example, a higher mould temperature may improve part surface quality but also extend cooling time, while excessive packing pressure can reduce shrinkage but increase residual stresses (Cheng et al., 2022; Zhao et al., 2022). A full factorial design captures such interactions by systematically varying every parameter at each level, ensuring no potential

combination is overlooked. This makes it an excellent tool for screening studies or when dealing with a small number of factors, as it provides a complete understanding of the process behavior.

However, the method becomes increasingly impractical as the number of factors grows. The number of runs increases exponentially with each additional factor. For instance, a two-level full factorial design with 3 factors requires only 8 runs, but with 6 factors, it jumps to 64 runs, and with 9 factors, it skyrockets to 512 runs. In injection moulding, where multiple variables such as, melt temperature, mould temperature, cooling time, holding pressure, and injection speed can all influence shrinkage, warpage, and mechanical properties, running such a large experimental plan would demand excessive time, cost, and material resources.

Moreover, full factorial designs are less effective in modeling non-linear relationships and curvature effects, which are common in polymer processing. Cooling rate differences between the core and cavity surfaces, for instance, can create anisotropy and residual stresses that influence both dimensional stability and tensile properties (Gotlih et al., 2022; Zhao et al., 2022; Hassan et al., 2024). These curvature effects are better captured by quadratic models, which full factorial designs cannot efficiently provide without extremely high run counts.

Because of these limitations, researchers increasingly turn to Response Surface Methodology (RSM). Unlike full factorial designs, RSM employs efficient designs such as Central Composite Design (CCD) or Box–Behnken Design to approximate the true response surface with far fewer runs. Gao et al. (2018) and Hassan et al. (2024) showed that RSM can successfully optimize injection moulding parameters such as mould temperature and cooling time—while significantly reducing the number of experiments required. Fletcher et al. (2023) and He et al. (2023) further demonstrated that RSM is highly effective for simultaneously analyzing dimensional responses (shrinkage, warpage) and mechanical responses (tensile strength, modulus, elongation), capturing the curvature that emerges from thermal and pressure variations.

In this thesis, while a full factorial design would theoretically provide exhaustive detail, it is not feasible due to the large number of factors and the need to model non-linear effects. Therefore, RSM is chosen as the more practical and powerful tool, enabling systematic optimization of core temperature, cavity temperature, and cooling time with manageable experimental runs, while still capturing curvature, interactions, and multi-response trade-offs.

2.8.2   Response Surface Methodology (RSM)

Response Surface Methodology (RSM) is a collection of mathematical and statistical methods developed to analyze, model, and optimize complex processes where multiple variables influence one or more responses. The strength of RSM lies in its ability to capture not only the main effects of process parameters but also their interactions and curvature effects, which are highly relevant in injection moulding where thermal and pressure variations strongly affect product performance (Gao et al., 2018; Hassan et al., 2024).

In injection moulding research, RSM is particularly valuable because parameters such as mould temperature, core temperature, cooling time, and packing pressure are interdependent. Adjusting one parameter often impacts others, and these changes manifest in critical responses such as warpage, shrinkage, tensile strength, and modulus (Farotti & Natalini, 2017; Zhao et al., 2022; Gotlih et al., 2022). By using RSM, it is possible to model these interactions and identify the optimal parameter window where multiple responses can be balanced simultaneously.

In the context of this thesis, which investigates the effect of core temperature, cavity temperature, and cooling time on HDPE tensile specimens, RSM is chosen over other DOE approaches because it provides a systematic yet efficient framework for understanding and optimizing thermal conditions. Mould temperature is a dominant factor in thermal control, while Zhao et al. (2022) showed that imbalances in thermal behavior across cavity walls amplify warpage and dimensional deformation. Gotlih et al. (2022) further demonstrated that cooling system design directly influences shrinkage and residual stress.

By applying RSM, these findings can be extended into a multi-response optimization strategy, allowing the thesis to propose an optimal balance of cooling and thermal settings that improve both dimensional stability and mechanical properties of injection-moulded HDPE parts. Thus, RSM serves as the bridge between experimental data and practical process optimization, making it highly suitable for solving the complex thermal challenges in injection moulding addressed in this study.

Table 2.9 provides a summary of selected studies that applied Response Surface Methodology (RSM) to minimize warpage in injection-moulded parts. The table highlights the materials investigated, optimized process parameters, key findings, and the reported improvements in warpage reduction.

Table 2.9: Warpage reduction using Response Surface Methodology (RSM)

Researcher (s) & Year	Material / Part	RSM Design / Variables	Key finding	Significant parameters
Godec et. al., 2024	PBT + 30% GF (side-panel housing)	RSM (Autodesk Moldflow + RSM) — optimized melt temp, mould temp, coolant temp	Warpage reduced from 1.85 mm to 0.73 mm (~61%) after RSM; further reduced to ±0.30 mm (~82%) after inverse contouring.	Melt temperature, target mould temperature, coolant temperature (also cooling channel geometry)
Mohd Hanid et al., 2021	ABS front panel housing (straight-drilled & MGSS conformal cooling channels)	Face-centered CCD / RSM (30 simulation runs); RSM model used as objective for GSO/GA	RSM reduced maximal warpage (simulation) by ~38.3% (straight drilled) and ~27.7% (MGSS); experimental RSM reductions ≈30.7% and 22% respectively.	Coolant temperature, melt temperature, packing pressure, cooling time
Sudsawat and Sriseubsai, 2018	Injection-moulded plastic part (simulation + experiments)	Box–Behnken / RSM combined with Firefly Algorithm (FA) and annealing	RSM-based optimization significantly decreased warpage; annealing further reduced warpage dramatically (authors report notable improvement vs. standard optimized parameters).	Packing time, cooling time, melt temperature; annealing post-process
Zhao et al., 2022; Coca-Gonzalez &	Multiple polymers / geometries	RSM used alongside CAE	Reported RSM-driven warpage reductions typically range from	Mould temperature, melt temp, cooling

Jimenez-Martinez, 2024		(Moldflow), GA, inverse contouring and cooling optimization	~20% up to >60% (case dependent); combining RSM with geometry/mould design gives the largest improvements.	setup, packing/holding profile, cooling channel design

2.8.2.1 Central Composite Design

The Central Composite Design (CCD) is one of the most widely used designs under Response Surface Methodology (RSM) to fit a second-order (quadratic) model. It combines three types of points: factorial (or cube) points, which capture the main effects and interactions; axial (star) points, which extend the design space beyond the factorial region to detect curvature; and center points, which provide replication to estimate experimental error and check model adequacy (Montgomery, 2017). The inclusion of axial points makes CCD highly flexible, enabling the modelling of curvature effects with fewer runs than a full factorial design, while still offering precise estimation of quadratic terms.

However, CCD does present some challenges. The axial (α) points are often positioned outside the practical operating range, which can be problematic in injection moulding experiments where exceeding certain temperature or time limits may lead to polymer degradation, machine constraints, or unrealistic production conditions (Gao et al., 2018). For example, very high core or cavity temperatures in HDPE moulding may induce excessive shrinkage or cause difficulties in cooling and part ejection.

When compared with Box–Behnken Design (BBD), CCD typically requires more runs and covers a wider design space, including extreme settings. In contrast, BBD avoids star points and instead positions experimental runs at the midpoints of the factor levels, making it safer and more efficient when the process window is well-defined (Aziz & Aziz, 2018; Polat & Sayan, 2019). For this thesis, which investigates three key factors (core temperature, cavity temperature, cooling time) and five responses (shrinkage, warpage, tensile strength, Young's modulus, and elongation), BBD is more suitable. It provides sufficient ability to detect curvature and optimize multiple responses while limiting the number of runs and avoiding impractical experimental conditions.

Thus, while CCD is powerful for exploring wide ranges and potential nonlinear effects, the BBD design aligns better with the objectives and constraints of this research by balancing efficiency, safety, and the need for accurate modelling of warpage, shrinkage, and mechanical properties in HDPE injection moulding. The 3-factor design of the CCD and α star point was illustrated in Figure 2.7.
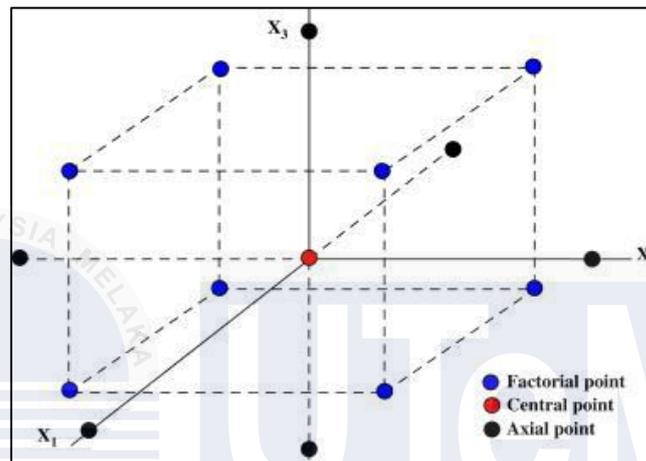
Figure 2.7: The composite central design with three factors (Hartono and Practikto, 2020)

2.8.2.2 Box- Behnken Design (BBD)

The Box–Behnken Design (BBD) is one of the most practical response surface methodology (RSM) design, requiring only three levels for each factor, usually coded as –1, 0, and +1 as shown in Figure 2.8. Unlike full factorial designs, which quickly become costly and time-consuming as the number of parameters increases, BBD achieves reliable modelling of quadratic responses with significantly fewer experimental runs (Aziz & Aziz, 2018). This makes it highly relevant to injection moulding studies, where factors such as core temperature, cavity temperature, and cooling time interact in nonlinear ways to influence critical quality responses like shrinkage, warpage, and mechanical properties.

One of the strengths of BBD is that its experimental points are located at the midpoints of the edges of the design space and at the center. This avoids extreme process settings that might cause polymer degradation, mould damage, or impractical cooling conditions, while still capturing the curvature of the response surface (Polat & Sayan, 2019). In the case of HDPE injection moulding, this is particularly important since uneven heating and cooling in the core and cavity plates directly lead to anisotropic shrinkage and warpage, ultimately affecting tensile strength and modulus of the specimen (Gao et al., 2018; Hassan et al., 2024).

In line with the present study, BBD provides a systematic and resource-efficient framework for exploring the effects of mould temperature, core–cavity balance, and cooling time on multiple responses. By estimating linear, quadratic, and interaction effects, the design supports not only prediction of warpage and shrinkage but also optimization of mechanical properties such as tensile strength and percentage elongation (Farotti & Natalini, 2017). Compared to designs like Central Composite Design (CCD), BBD is more efficient when studying three or four factors, making it an ideal choice for this thesis.
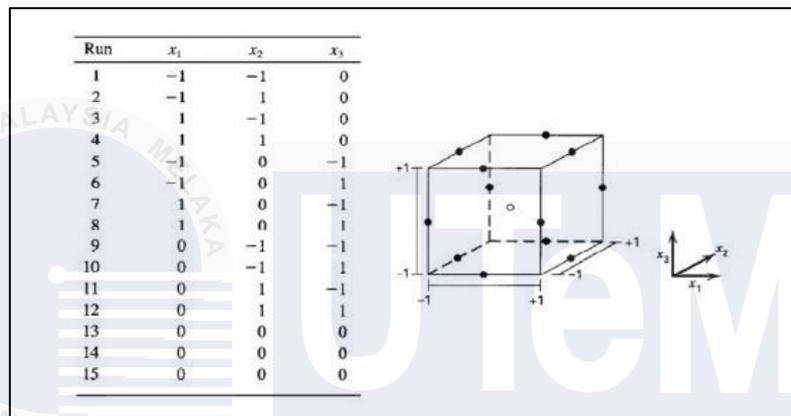
Figure 2.8: The BBD three factors (Aziz and Aziz, 2018)

2.9 Analysis of Variance (ANOVA)

The Analysis of Variance (ANOVA) is a powerful statistical method used to determine whether differences in data are due to systematic effects of independent variables or random variation. In essence, ANOVA separates the total variability observed in a dataset into two components: variability caused by the experimental factors (systematic) and variability arising from random error. This distinction enables researchers to assess the relative contribution of each input parameter to the variation observed in the output responses.

In regression-based studies, ANOVA is commonly employed to evaluate the influence of independent variables (factors) on dependent variables (responses). Dependent variables reflect the process outcomes—such as warpage, shrinkage, ultimate tensile strength (UTS), Young's modulus, and elongation—while independent variables represent the controllable process parameters, such as core temperature, cavity temperature, and cooling time in injection moulding. By quantifying the statistical significance of these relationships, ANOVA provides a robust framework for understanding how process conditions affect product quality.

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Sawyer (2019) explains that ANOVA is most effective when analyzing variations in group means where there is one continuous dependent variable and one or more independent variables. The method assumes that data are normally distributed, variances are homogenous across groups, and that observations are independent. While minor violations of these assumptions may not severely affect results particularly with larger sample sizes and balanced designs it is important to validate these assumptions to ensure reliable conclusions.

For this study, ANOVA is applied to identify the most significant factors influencing the dimensional (shrinkage and warpage) and mechanical (UTS, Young's modulus, percentage elongation) properties of HDPE dumbbell shaped specimens. The method helps determine not only whether a factor has a statistically significant effect but also the extent of its contribution to the total variation in responses. Statistically significant results are further examined using multiple comparison procedures to pinpoint which parameter levels or combinations differ meaningfully from others.

By integrating ANOVA within the DOE and Response Surface Methodology framework, this research ensures a rigorous statistical evaluation of the parameter-response relationships. This strengthens the optimization process by distinguishing meaningful effects from random noise, thereby providing confidence that the recommended parameter settings are both statistically valid and practically relevant for minimizing warpage and shrinkage while maintaining mechanical integrity.

2.10   Minitab Software

In injection-moulding research and practice, Minitab is widely used as the statistical workhorse for designing experiments, fitting response-surface regression models, testing factor significance with ANOVA, and visualising interactions via contour and 3-D surface plots. Response Surface Methodology (RSM) in Minitab (central-composite, Box–Behnken and related designs) is typically used to build second-order (quadratic) regression equations that model responses such as warpage, shrinkage or cycle time; those regression models are then analysed with ANOVA to identify significant main effects and interactions and to test model adequacy (e.g., F-tests, R^2, lack-of-fit).

Recent methodological reviews emphasise that careful regression practice, e.g., variable selection (backward elimination), diagnostic checking of residuals and predictive metrics such as PRESS and predicted R^2 which is essential to avoid over-fitting and to obtain reliable RSM optima. In applied injection-moulding studies, this Minitab

RSM→regression→ANOVA workflow has repeatedly produced practically useful optimizations: for example, central-composite RSM and ANOVA were used to screen and then model the effect of mould temperature, melt temperature, cooling time and packing parameters on warpage and shrinkage, allowing authors to reduce predicted warpage substantially and to identify mould-temperature and coolant settings as primary drivers of deformation (Mohd Hanid et al., 2021; Zhao et al., 2022).

In industrially-focused work, researchers have combined screening (fractional factorials), CCD RSM and ANOVA to prune insignificant variables and focus experiments on the most influential parameters (Kariminejad et al. (2024), while comparative studies show that Minitab's DOE and regression modules can produce results comparable to other DOE packages and optimization methods when modern regression diagnostics are applied. Practically, researchers use Minitab not only to generate optimal set-points but also to produce contour and response-surface plots and desirability analyses that translate statistical optima into actionable machine settings (mould temperature, melt temperature, cooling time, packing/holding), streamlining transfer from design of experiments to process validation on the shop-floor.

Finally, Minitab's built-in model diagnostic tools (residual plots, normality tests, leverage/influence statistics) are particularly valuable for validating RSM models before using them in optimization or control applications, a point repeatedly stressed in both the RSM methodology literature and injection-moulding applications. Table 2.10 presents the application of Minitab software in optimizing injection moulding parameters, highlighting how researchers have employed RSM, ANOVA, and regression analysis to identify significant factors, reduce defects, and enhance product quality.

Table 2.10: Minitab application in injection moulding optimization process

Author(s) & Year	Material/Focus	Method (Minitab Tools)	Key Findings
Mohd Hanid et al. (2021)	Injection-moulded parts with drilled vs. conformal cooling channels	Minitab RSM, ANOVA, Regression	RSM + ANOVA showed mould temperature and cooling design strongly influence warpage; optimization reduced warpage significantly.
Zhao et al. (2022)	Review of polymer injection moulding (various materials, focus on shrinkage/warpage)	Minitab DOE, RSM regression, ANOVA	Highlighted that shrinkage/warpage reduction requires careful control of mould temperature, cooling time, and melt temperature; regression models widely used.
Kariminejad et al. (2024)	Industrial injection moulding process (real-time optimization)	Minitab DOE, RSM, ANOVA, Bayesian adaptive design	Reduced number of required experiments by 50%; optimised temperature stability and cycle time; showed advantage of combining RSM regression with adaptive DOE.
Chen (2025)	Methodological review on regression in RSM	Minitab regression, ANOVA, diagnostics	Emphasized importance of regression diagnostics (PRESS, predicted R^2, residual plots) in validating RSM models to avoid overfitting.

CHAPTER 3

METHODOLOGY

3.0   Introduction

This research aims to analyze the effect of cooling variations between the core and cavity on the quality of parts produced through the injection moulding process. Investigating the influence of the cooling system on part characterization is essential, as it can help address dimensional accuracy issues and improve the visual quality of the final plastic product. To determine the optimal process parameters, the Design of Experiments (DOE) approach is employed using Response Surface Methodology (RSM).

A systematic and logical framework is required to obtain the best solution to the identified problems. The research is expected to ensure that part quality, particularly in terms of physical characteristics (such as geometric and volumetric shrinkage) and mechanical properties (including percentage elongation, tensile strength, and modulus of elasticity), can be achieved by analyzing and optimizing the cooling system within the mould. This is supported through validation using both experimental investigations and statistical analyses. In order to achieve the expected outcomes, a structured methodology is essential to ensure that reliable and effective solutions are derived for the problems addressed. This chapter therefore outlines the methodology and tools employed in this research.

3.1   Research Planning

This study is designed to investigate how variations in cooling between the core and cavity influence the quality of parts produced through the injection moulding process. The overall research framework is organized into three main phases. The first phase involves experimental work, where HDPE specimens are produced under systematically varied mould temperatures and cooling times to evaluate their dimensional stability and mechanical performance. The second phase focuses on statistical analysis, employing Response Surface Methodology (RSM), ANOVA, and regression modelling to determine the significance of process parameters and their interactions on shrinkage, warpage, tensile strength, Young's modulus, and percentage elongation. The final phase centers on validation of results, where optimized parameter settings are verified through comparison between experimental outcomes and statistical predictions.

By structuring the research in this systematic manner, the study ensures that both dimensional (shrinkage and warpage) and mechanical (tensile properties) aspects of HDPE injection moulded parts are thoroughly examined. This approach not only identifies the optimal balance of core and cavity cooling but also contributes a validated framework for parameter optimization, strengthening the reliability and applicability of the findings. This research is conducted to analyze the effect of cooling variations between the core and cavity on the quality of parts produced in the injection moulding process. The research design consists of three major phases, namely the experimental work process, the statistical analysis process, and the validation of results.

3.1.1 Experimental work process flow

The experimental workflow applied in this project is illustrated in Figure 3.1.
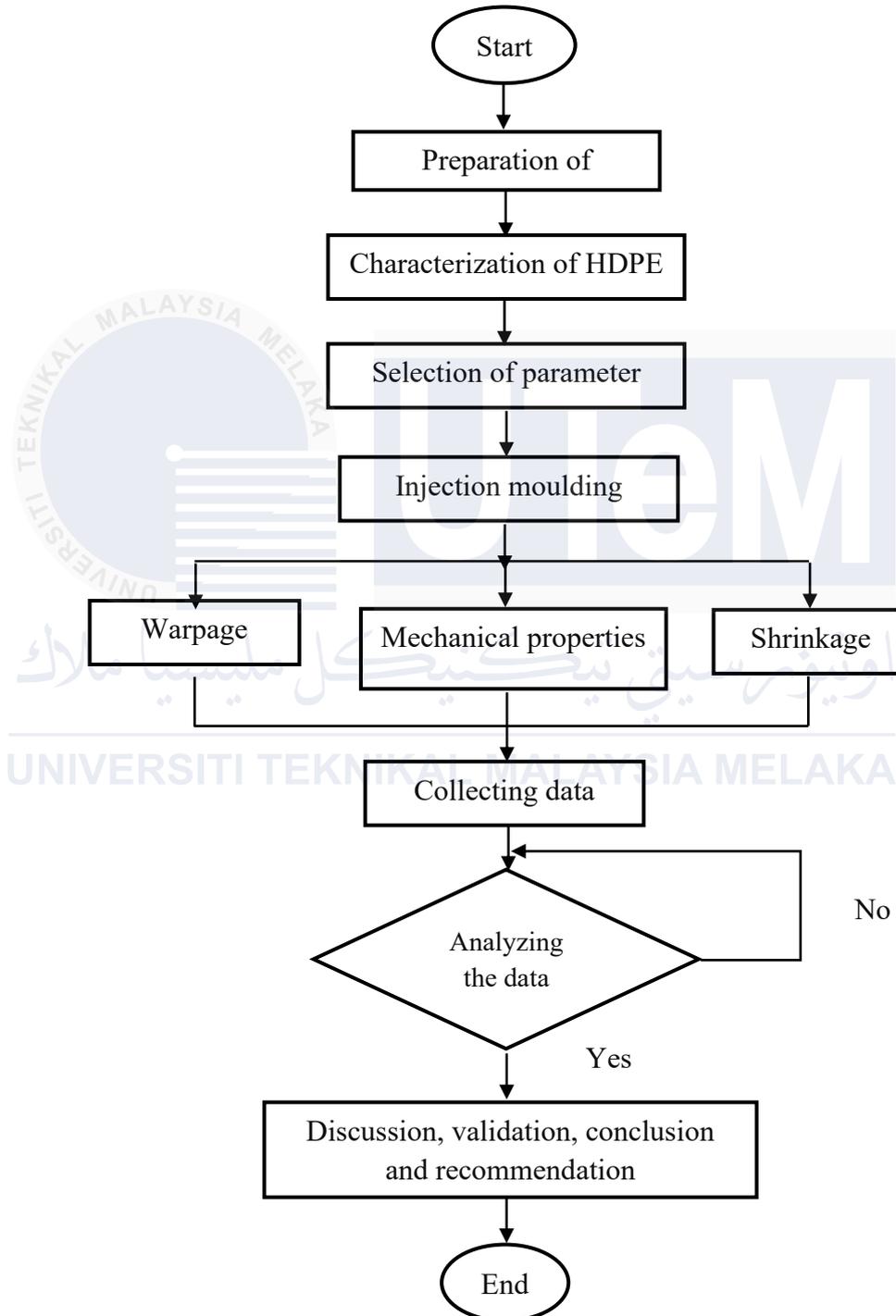
Figure 3.1: Experimental work process flow chart

From Figure 3.1, the experimental workflow adopted in this research was shown. The process begins with the preparation of materials, where High-Density Polyethylene (HDPE) was selected and characterized to ensure its suitability for injection moulding trials. Following this, the key processing parameters are identified, with particular emphasis on core and cavity temperatures as well as cooling time, since these factors are expected to influence both dimensional stability and mechanical performance.

The next stage involves conducting the injection moulding experiments using the SUMITOMO DEMAG 100T machine. During this process, HDPE dumbell shapedspecimens are produced according to standardized testing requirements (ASTM D638/ISO 527). These specimens are then assessed in terms of dimensional quality, specifically warpage and shrinkage as well as mechanical properties, including tensile strength, modulus, and percentage elongation.

Data collected from these evaluations are subsequently analyzed using statistical methods such as Response Surface Methodology (RSM) and Analysis of Variance (ANOVA) within Minitab software. If the analysis indicates insufficient accuracy or reliability, the process is repeated with revised parameters. Once satisfactory results are achieved, the final stage involves validation, interpretation, and discussion of findings, culminating in conclusions and recommendations.

This structured approach ensures a systematic pathway from material preparation to experimental validation, aligning with the overall aim of this research, which is to optimize the injection moulding process by balancing cooling variations between the core and cavity to improve both dimensional accuracy and mechanical integrity of HDPE parts.

3.2   Preparation of High Density Polyethylene (HDPE) material

The material selected for this research was High-Density Polyethylene (HDPE), a thermoplastic polymer widely utilized in injection moulding due to its excellent balance of mechanical strength, toughness, processability, and recyclability. HDPE has a relatively low density compared to other engineering polymers but provides high tensile strength, good impact resistance, and low moisture absorption. These characteristics make it suitable for applications where lightweight and durable products are required, such as packaging containers, automotive parts, and household goods. Furthermore, HDPE exhibits good melt flow properties, making it an

appropriate material for experimental investigations on the influence of cooling variation in moulding processes.

Once conditioned, the HDPE pellets were stored in sealed containers to prevent reabsorption of ambient moisture before processing. The prepared material was then fed into the SUMITOMO DEMAG 100T injection moulding machine, where experiments were conducted under varied core and cavity temperatures and cooling times. Figure 3.2 shows the HDPE material used in this study.
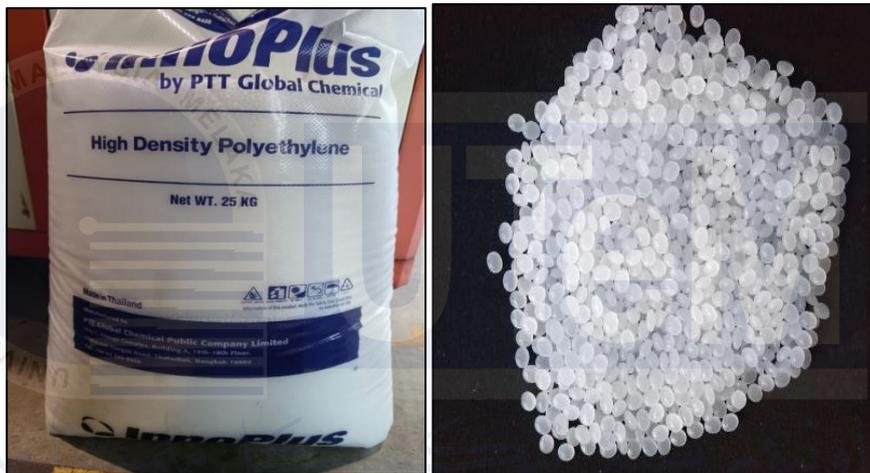
Figure 3.2: HDPE material produced by PTT Global Chemical

3.2.1 Characterization of material (HDPE)

High-Density Polyethylene (HDPE) was chosen as the material for this study because of its wide industrial use and its balance of strength, toughness, and ease of processing. To properly evaluate how process parameters influence product performance, the material needs to be characterized under standardized conditions. For this reason, dumbbell-shaped (dog-bone) specimens were produced in accordance with ASTM D638 (Type I) and ISO 527-2 standards. This specimen shape is widely used in mechanical testing because the narrow gauge section ensures that failure occurs in the middle of the specimen, away from the grips, allowing accurate measurement of tensile strength, Young's modulus, and elongation at break.

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Previous studies have shown why this approach was particularly important for HDPE. For example, Trish et al. (2022) demonstrated that changes in injection moulding parameters, such as injection temperature and cooling rate, had a direct impact on shrinkage, warpage, and tensile strength of HDPE composites. Their experiments on dumbbell specimens confirmed that both dimensional accuracy and mechanical behaviour are closely linked to the way the material cools inside the mould. Likewise, Fletcher et al. (2023) studied HDPE components produced under different mould temperatures and found that slower cooling at higher mould temperatures increased crystallinity, which in turn altered the tensile properties of the specimens. These findings highlight that even subtle changes in cooling history can be captured through standardized tensile testing.

Reviews such as the one by Zhao et al. (2022) further reinforce this connection, noting that dumbell shaped specimens play a crucial role in bridging statistical optimization methods like DOE and RSM with real-world validation of mechanical properties. By examining tensile performance in combination with dimensional outcomes such as warpage and shrinkage, researchers can better understand how process conditions shape the overall quality of injection-moulded HDPE parts.

In this study, the use of dumbbell specimens makes it possible to establish a clear correlation between core and cavity cooling variations, the resulting dimensional defects, and the mechanical performance of the moulded parts. This ensures that the findings are both reliable and comparable to international standards, while also offering practical insights for improving injection moulding processes.

3.3   Selection of parameters

The choice of parameters in this research was guided by their direct influence on both the dimensional accuracy and the mechanical properties of injection-moulded parts. Among the many factors that can be controlled during moulding, core temperature, cavity temperature, and cooling time stand out as critical variables because of their strong relationship with warpage, shrinkage, tensile strength, Young's modulus, and percentage elongation.

The temperatures of the core and cavity play a decisive role in how the material cools and solidifies within the mould. An imbalance between these two surfaces can result in uneven

shrinkage, leading to warpage and distortion of the part. Zhao et al. (2022) explained that when temperature differences exist across the mould walls, residual stresses develop, which not only compromise dimensional accuracy but also reduce the mechanical stability of the product. Similarly, Cheng et al. (2022), in their work on HDPE pallet structures, showed that higher cavity temperatures produced smoother surfaces but also increased the risk of dimensional deformation due to slower cooling. This highlights the need to carefully balance mould wall temperatures to minimize shrinkage while still achieving good surface quality.

Cooling time was identified as a critical factor, as it governed the rate of heat extraction from the polymer melt. Insufficient cooling resulted in parts being ejected prior to achieving dimensional stability, which in turn led to warpage or incomplete crystallization. On the other hand, excessively long cooling times increase cycle time and reduce production efficiency. Studies such as He et al. (2023) emphasize that an optimized cooling cycle not only improves dimensional accuracy but also enhances mechanical performance by promoting more uniform stress distribution and controlled crystallinity in the polymer matrix. This means that properties like ultimate tensile strength (UTS), modulus, and elongation at break are all influenced by how effectively the part is cooled inside the mould.

Researchers have also shown that these parameters do not act independently but interact in complex ways. For example, Gotlih et al. (2022) observed that cooling system design and temperature control together determined the extent of residual stresses and dimensional deviation in plastic parts. Their findings support the view that proper parameter selection is essential not only for minimizing defects but also for achieving reliable mechanical behaviour. The effect of key process parameters on the dimensional accuracy and mechanical properties of HDPE injection-moulded parts was analyzed, and the findings are summarized to provide a basis for identifying the most significant parameters in this study as shown in Table 3.1.

Based on these insights, this study focuses on core temperature, cavity temperature, and cooling time as the most significant and practical parameters for optimization. By investigating their individual and combined effects using Design of Experiments (DOE) and Response Surface Methodology (RSM), the research aims to identify the parameter settings that deliver the best trade-off between dimensional stability (shrinkage and warpage) and mechanical integrity (UTS, modulus, and elongation) for HDPE parts.

Table 3.1: Effect of key parameters on dimensional accuracy and mechanical properties of HDPE injection-moulded parts

Parameter	Effect on Dimensional Properties (Shrinkage/Warpage)	Effect on Mechanical Properties (UTS, Young's Modulus, % Elongation)	Authors
Core Temperature	Uneven core cooling leads to differential shrinkage and internal stresses, causing warpage and distortion.	Affects crystallinity and molecular orientation, influencing tensile strength and stiffness.	Zhao et al. (2022); Cheng et al. (2022)
Cavity Temperature	Higher cavity temperatures improve surface finish but increase risk of shrinkage variation; imbalance with core temperature promotes warpage.	Alters cooling rate and relaxation, impacting modulus and elongation properties.	He et al. (2023); Gotlih et al. (2022)
Cooling Time	Short cooling causes premature ejection → higher warpage and shrinkage; long cooling reduces defects but increases cycle time.	Optimal cooling promotes dimensional stability and mechanical integrity (balanced tensile strength and ductility).	Gotlih et al. (2022); He et al. (2023)

3.4 Injection moulding process

The injection moulding process forms the core of this research, as it enables the production of standardized HDPE dumbell shaped specimens used for evaluating both dimensional stability and mechanical performance. Injection moulding is a cyclic process that involves four primary stages: plasticization, injection, cooling, and ejection. During plasticization, HDPE pellets are heated and melted within the barrel of the machine. The molten polymer is then injected under high pressure into the mould cavity, where it fills and replicates the shape of the specimen. The

cooling stage follows, in which the polymer solidifies through heat transfer to the mould walls, before the final ejection of the part.

In this study, the experiments were carried out using a SUMITOMO DEMAG 100T injection moulding machine as shown in Figure 3.3, with core and cavity temperature precisely regulated by a Mould Temperature Controller (MTC). Water and oil were employed as cooling and heating mediums, respectively, allowing controlled temperature variations between the core and cavity surfaces. These variations are essential for investigating the effects of thermal imbalance on shrinkage, warpage, and the mechanical properties of HDPE specimens.

The importance of controlling mould temperature and cooling time has been highlighted in prior studies. Zhao et al. (2022) reported that uneven temperature distribution across mould walls leads to residual stresses, which directly influence part distortion and poor mechanical stability. Similarly, Cheng et al. (2022) demonstrated that while higher mould temperatures enhance surface quality, they can also prolong cooling and increase the risk of deformation. He et al. (2023) further emphasized that optimized cooling time is critical not only for reducing defects like shrinkage and warpage but also for improving tensile strength and modulus by ensuring controlled crystallinity.

This research builds on these findings by focusing on the role of core temperature, cavity temperature, and cooling time as the most influential process parameters. By applying Design of Experiments (DOE) and Response Surface Methodology (RSM) through Minitab software, the study systematically analyzes the impact of these variables on both dimensional (shrinkage, warpage) and mechanical outcomes (ultimate tensile strength, Young's modulus, and percentage elongation). The use of standardized dumbell shaped specimens ensures that results are both reliable and comparable with established testing protocols.

In short, the injection moulding process in this research is not only the means of producing test specimens but also the experimental platform for understanding how cooling variations between the core and cavity can affect the quality of HDPE products. The insights gained are expected to contribute toward improved parameter optimization strategies, which can reduce defects, enhance mechanical reliability, and increase overall manufacturing efficiency. Table 3.2 presents the specifications of the injection moulding machine SE100EV employed in this study.

Figure 3.3: Injection moulding machine

Table 3.2: Injection moulding machine SE100EV specification

Specifications	Unit	Figures									
Max. mold clamp force	kN{tf}	1000									
Clearance between tie-bars (LxH)	mm	460×460									
Clamp platens max. (LxH)	mm	650×650									
Mold space	mm	180~450									
Plasticizing capacity		C110			C160			C250			C360	
Screw diameter		S			S			M			M	
	mm	22	25	28	25	28	32	28	32	36	32	36	40
Maximum injection pressure	MPa	274	212	174	274	218	167	284	217	171	273	215	175
Injection mass (GPPS)	g	38	49	61	49	61	80	83	108	137	124	156	193
Plasticizing capacity	kg/h	18	26	37	26	37	53	37	53	76	53	76	101
Maximum injection speed	mm/s	500			400			350			350	
Dimensions (LxWxH)	mm	4502×1192×1772			4502×1192×1772			4502×1192×1837			4502×1192×1837	
Machine mass	t	3.7			3.8			4.0			4.1	

3.4.1 Sample of Study

The dumbbell-shaped specimen is a standardized test sample commonly employed in mechanical testing, particularly for evaluating the tensile and elongation properties of plastics and polymeric materials. Its geometry, resembling a dog bone, features a narrow-gauge section at the center and wider ends. This design ensures that fracture consistently occurs within the gauge length rather than at the grips, thereby improving the accuracy and reliability of the test results.

International standards define the dimensions and requirements for dumbbell shaped specimens as shown in Figure 3.4, with the most widely adopted being ASTM D638 and ISO 527-2. ASTM D638, specifies multiple specimen types (Types I to V) based on material thickness, with Type I being the most commonly used for injection-moulded plastics. Similarly, ISO 527-2, serves the same purpose but applies slightly different specimen dimensions and classifications. The selection of standard typically depends on regional or industrial practices, although both methods yield comparable and repeatable results.

The unique geometry of the dumbbell shaped specimen, plays a critical role in mechanical testing. The narrow-gauge section localizes stress and strain within the central region, while the wider ends provide a secure grip, minimizing slippage and grip-induced failure. Furthermore, the uniform cross-section in the middle allows precise calculation of tensile strength, Young's modulus, and percentage elongation.

In the context of this research, the use of standardized dumbbell shaped specimen mould as shown in Figure 3.5, is essential for establishing the correlation between injection moulding parameters such as cooling rate, core and cavity temperature, and cycle time and the resulting mechanical properties. By adopting internationally recognized standards, this study ensures the validity, comparability, and reliability of its findings within the broader scientific and industrial community.
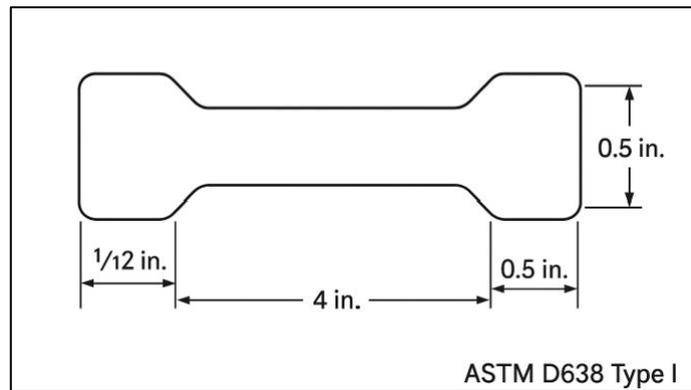
Figure 3.4: Standard dumbbell shaped specimen geometry (ASTM D638 & ISO 527-2).

Figure 3.5: Dumbbell-shaped specimen mould and moulded part

3.4.2 Mould Temperature Controller (MTC)

The mould temperature controller (MTC) plays a vital role in the injection moulding process. Its primary function is to heat the mould to the desired temperature and, more importantly, to maintain this temperature consistently throughout the production cycle. Achieving stable thermal conditions in the mould is essential because it directly influences both the cycle time and the overall quality of the moulded parts. By ensuring proper thermal control, the MTC contributes to shorter cycle times and helps maintain the stability of high-quality injection-moulded products.

Mould temperature has a strong impact on several key aspects of part quality, including surface finish, material flow, shrinkage, warpage, and the overall moulding cycle. For this reason,

controlling it precisely is critical to minimizing defects and achieving consistent results. In practice, water is the most widely used medium for cooling, as shown in Figure 3.6, because of its excellent heat transfer capability and cost-effectiveness. However, in situations requiring higher operating temperatures, oil-based MTCs are used, as shown in Figure 3.7. Oil provides better stability at elevated temperatures but behaves differently compared to water in terms of heat exchange efficiency.

The choice between water and oil as cooling media has influences on physical and mechanical properties of the final product. Differences in cooling rate can affect shrinkage, residual stresses, and even the tensile properties of the polymer. This research considers both water and oil as cooling mediums to better understand how thermal control strategies affect dimensional accuracy, visual appearance, and mechanical stability of High-Density Polyethylene (HDPE) injection-moulded specimens.

Figure 3.6: Mould temperature controller (water)

Figure 3.7: Mould temperature controller (oil)

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3.4.3 Experimental matrix

This study was designed to carefully explore how variations in cooling affect the quality of injection-moulded parts. To do this, three main process parameters were chosen: core temperature, cavity temperature, and cooling time. Each parameter was tested at three different levels, and to improve the reliability of the results, five centre points were added. Altogether, this produced 17 experimental runs, which is enough to capture the effects of the parameters while keeping the number of experiments manageable.

The design of the experiment was generated using Response Surface Methodology (RSM) with the Box–Behnken Design (BBD) in Minitab software. This approach was selected because it avoids extreme and impractical parameter settings while still providing accurate predictions of both the main effects and the interactions between factors. As illustrated in Figure 3.8, the chosen parameters (core temperature, cavity temperature, and cooling time) were adjusted according to the design, while all other machine conditions (such as injection pressure, melt temperature, and packing time) were kept constant. This ensured that any differences in the outcomes could be directly linked to the selected parameters.

For each experimental run, the resulting parts were tested for dimensional properties (warpage and volumetric shrinkage) as well as mechanical properties (ultimate tensile strength, Young's modulus, and percentage elongation). The inclusion of centre points in the design allowed the study to capture any curvature effects in the data, which improves the accuracy of the optimization process.

In the end, the findings from the experimental runs, supported by statistical analysis and validation, provide a basis for identifying the parameter settings that achieve an optimal balance between dimensional stability and mechanical performance. This provides not only a practical guideline for improving HDPE injection-moulded parts but also contributes to a better understanding of the cooling process in moulding research. Table 3.3 shows the process parameters and their levels. The experimental matrix with three factors and five responses is presented in Table 3.4.

Box-Behnken Design

Design Summary

Factors:	3	Replicates:	1
Base runs:	17	Total runs:	17
Base blocks:	1	Total blocks:	1

Center points: 5

#	C1	C2	C3	C4	C5	C6	C7
	StdOrder	RunOrder	PtType	Blocks	Core Temperature	Cavity Temperature	Cooling Time
1	1	1	2	1	15.0	15.0	25.0
2	2	2	2	1	140.0	15.0	25.0
3	3	3	2	1	15.0	140.0	25.0
4	4	4	2	1	140.0	140.0	25.0
5	5	5	2	1	15.0	77.5	12.5
6	6	6	2	1	140.0	77.5	12.5
7	7	7	2	1	15.0	77.5	37.5
8	8	8	2	1	140.0	77.5	37.5
9	9	9	2	1	77.5	15.0	12.5
10	10	10	2	1	77.5	140.0	12.5
11	11	11	2	1	77.5	15.0	37.5
12	12	12	2	1	77.5	140.0	37.5
13	13	13	0	1	77.5	77.5	25.0
14	14	14	0	1	77.5	77.5	25.0
15	15	15	0	1	77.5	77.5	25.0
16	16	16	0	1	77.5	77.5	25.0
17	17	17	0	1	77.5	77.5	25.0
18							

Figure 3.8: 17 experimental run by Box Behnken Design

Table 3.3 : Process parameters and their levels

Process Parameters	Levels	
	Low level	High level
Core temperature (^{o}C)	15	140
Cavity temperature (^{o}C)	15	140
Cooling time (s)	12.5	37.5

Table 3.4: Experimental matrix with three factors and five responses

Run no.	Core temp. (°C)	Cavity temp. (°C)	Cooling time (s)	Warpage	Shrinkage	UTS	Modulus	%EL
1	15	15	25					
2	140	15	25					
3	15	140	25					
4	140	140	25					
5	15	77.5	12.5					
6	140	77.5	12.5					
7	15	77.5	37.5					
8	140	77.5	37.5					
9	77.5	15	12.5					
10	77.5	140	12.5					
11	77.5	15	37.5					
12	77.5	140	37.5					
13	77.5	77.5	25					
14	77.5	77.5	25					
15	77.5	77.5	25					
16	77.5	77.5	25					
17	77.5	77.5	25					

3.4.4 Experimental work procedure

The experimental procedure for this study was carried out systematically to ensure accurate and repeatable results. The main steps are outlined as follows:

1. Cooling Time Setup - The cooling time parameter was established according to the experimental design generated through the Box–Behnken DOE approach as displayed in Figure 3.9
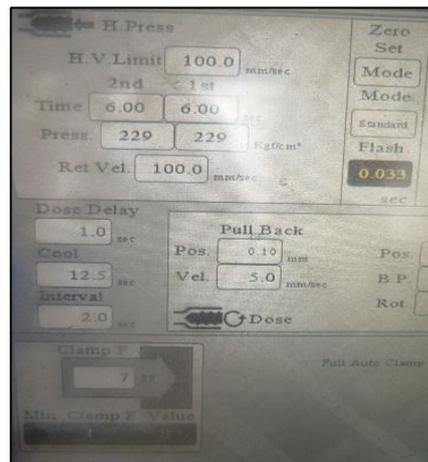
Figure 3.9: Cooling time parameter setting

2. Mould Temperature Setting (Oil Medium) - For the core and cavity temperature settings of 77.5 °C and 140 °C, oil was employed as the cooling medium. The temperatures were regulated and monitored using a mould temperature controller (MTC) connected directly to the mould as shown in Figure 3.10.

Figure 3.10: MTC (oil medium) attached to the mould

3. Mould Temperature Setting (Water Medium) – As shown in Figure 3.11, the temperature level of 15 °C, water was used as the cooling medium. The cooling system was managed and measured using a water chiller, which was also attached to the mould.

Figure 3.11: MTC (water medium) attached to the mould

4. Injection Moulding Process - Once the parameter settings were finalized, the injection moulding process was performed. For each experimental run, five dumbbell shaped specimens were produced. Figure 3.12 shows the injected parts.

Figure 3.12: The injected parts

5. Volumetric Shrinkage Measurement - The samples obtained from each run were weighed to determine volumetric shrinkage as illustrated in Figure 3.13. The average of three specimens was taken as the representative value for further analysis.

Figure 3.13: Weighing process

6. Warpage Measurement - Warpage was assessed using a vertical optical comparator as shown in Figure 3.14. A reference centerline was marked on each sample, and the deviation was measured. The average value of three specimens was calculated and considered as the final warpage measurement for DOE analysis.

Figure 3.14: Warpage measurement process

7. Mechanical Properties Testing - The mechanical properties of the specimens were evaluated through tensile testing. As shown in Figure 3.15, the samples were marked to ensure consistency, with a 30 mm section on each side allocated for gripping and a 100 mm gauge length specified for elongation measurement. The average results of three specimens were used to determine Ultimate Tensile Strength (UTS), Young's Modulus, and percentage elongation, which were then applied in the subsequent analysis.
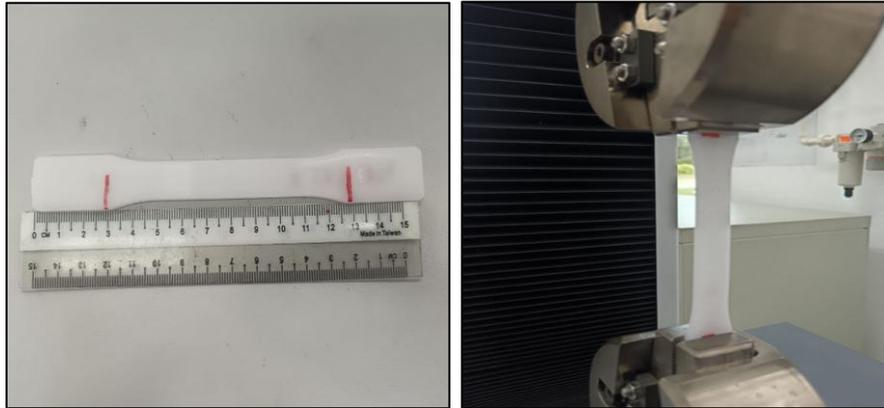
Figure 3.15: Tensile testing

3.5   Data Collection

The process of data collection in this study was designed to systematically capture all relevant information required to evaluate the effect of cooling variations on the quality of injection-moulded HDPE specimens. Data were gathered from both dimensional and mechanical perspectives to provide a comprehensive assessment of part performance.

Warpage was measured using a horizontal optical comparator with a reference centerline marked on each sample. It provides precision, repeatability, and non-contact evaluation of dimensional distortions in injection-moulded parts. The optical comparator has the capabilities as below:

- High measurement accuracy – Optical comparators allow small deviations from the reference centerline to be detected with high precision, which is critical since warpage values are often in the sub-millimeter range.

- Non-destructive and non-contact method – Unlike tactile measurement tools, the optical comparator does not apply force on the specimen, preventing further distortion or stress that could affect accuracy.

- Clear visualization of deformation – By projecting the sample profile against a magnified grid or reference line, the warpage can be directly compared to the intended geometry, ensuring reliable detection of even minor deviations.

Shrinkage was measured by measuring the weight of injected parts using the weight scale. These measurements ensured that any deviations in size, shape, or form could be directly attributed to the influence of core temperature, cavity temperature, and cooling time.

For mechanical characterization, tensile testing was performed on standardized dumbbell shaped specimens according to international testing guidelines using Universal Testing machine (Figure 16). Markings were made on each sample to define the gripping area (30 mm on each side) and the gauge length (100 mm) for elongation assessment. From this test, three primary mechanical properties were recorded: Ultimate Tensile Strength (UTS), Young's Modulus, and percentage elongation.

All measurements were conducted in triplicate for each experimental run, and average values were used to represent the final results. This approach minimized random error, improved the reliability of the data, and provided a strong basis for subsequent statistical analysis using Design of Experiments (DOE) and Response Surface Methodology (RSM.

Figure 3.16: Universal Testing machine

3.6 Data Analysis

Based on the data obtained from the experimental process, data can be analysed using the statistical method in Minitab software. The response surface method is essential to be used to analyse the most significant factor that influences the five responses of warpage, volumetric shrinkage, UTS, Young's Modulus and % Elongation. The response surface method analysis is setup from the beginning by inserting 17 runs of results obtained and further settings are done as shown in the Figure 3.17 After finishing all the required setup, the analysis of variance results can be obtained as shown in Figure 3.18. Following data analysis, the results and discussion of the quality output can be completed.
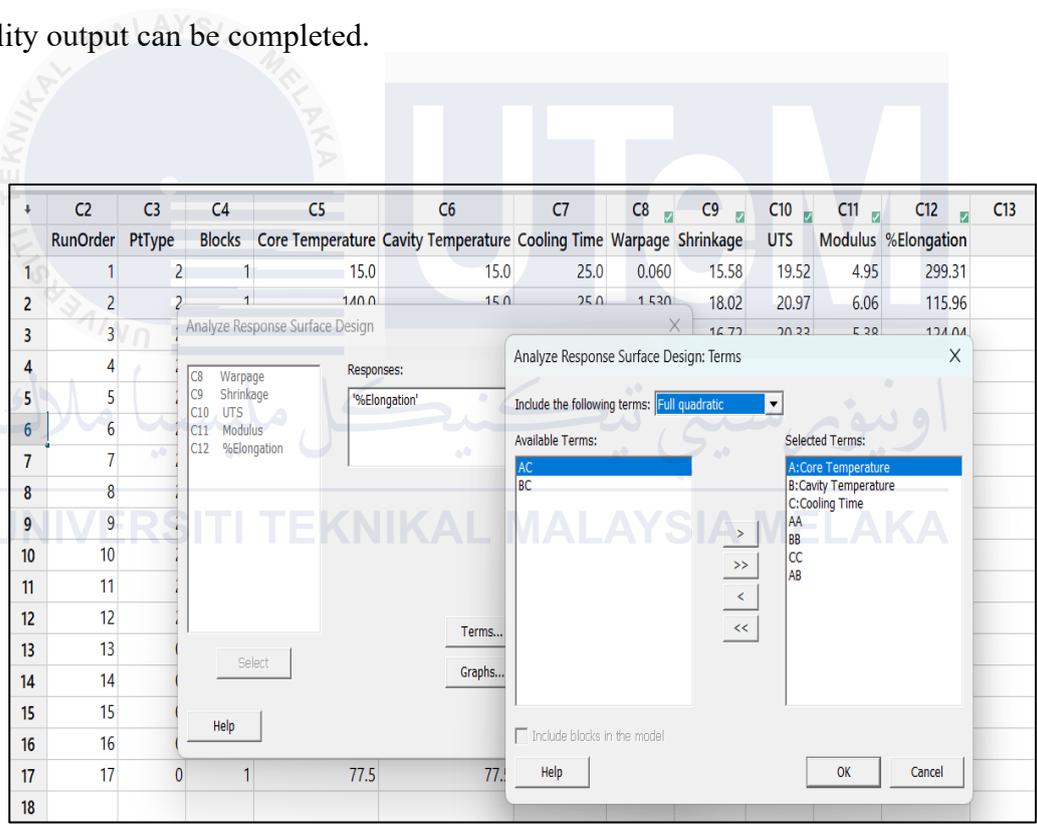
Figure 3.17: Setting in the Response Surface Methodology using Minitab Software.
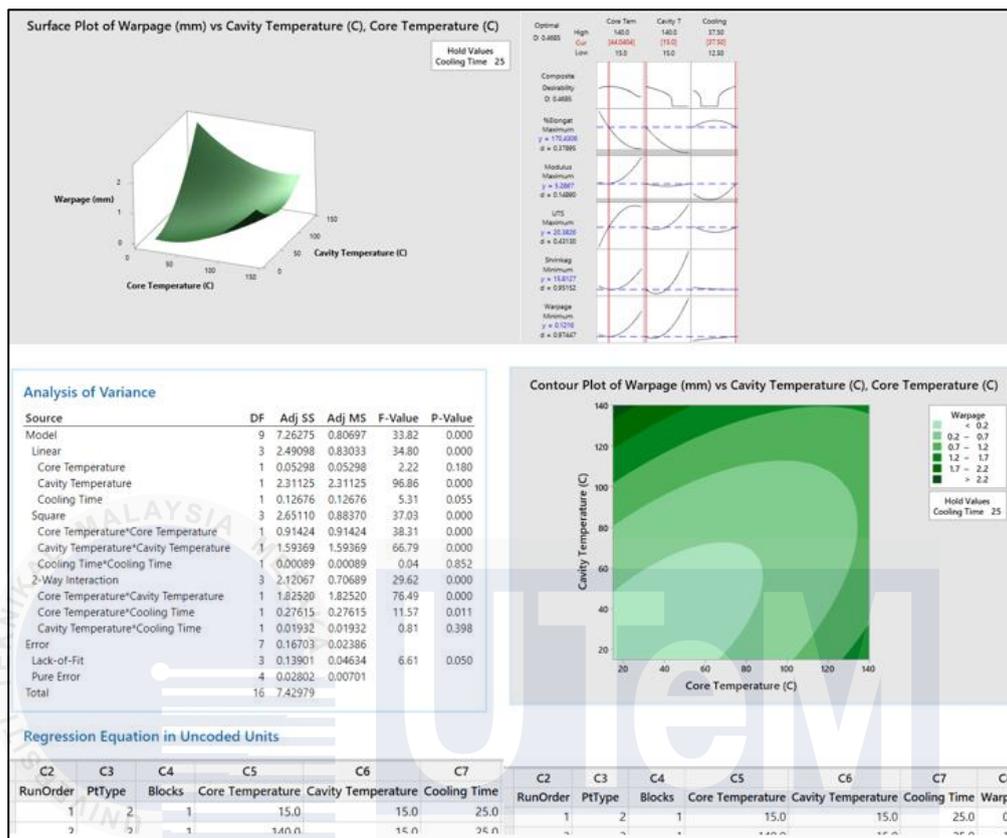
Figure 3.18: Analysis of Variance Results using Response Surface Methodology in Minitab Software.

3.7 Result Validation

Result validation constituted a critical step in this research to ensure that the outcomes derived from the experimental work and statistical analysis were accurate, reliable, and meaningful. Since this study investigates the effects of cooling variations between the core and cavity on the dimensional and mechanical properties of High-Density Polyethylene (HDPE), validation serves to confirm that the optimized parameter settings identified through Response Surface Methodology (RSM) genuinely lead to improvements in shrinkage, warpage, and mechanical performance.

The validation process was carried out by selecting the optimal parameter combination predicted by the statistical model and re-running the injection moulding process under these conditions. The HDPE dumbbell shaped specimens produced are then tested again for

dimensional accuracy (shrinkage and warpage) and mechanical properties (tensile strength, Young's modulus, and percentage elongation). These experimental results are compared against the predicted values generated by the RSM model in Minitab. A close agreement between the experimental and predicted outcomes would confirm the robustness of the model and the reliability of the optimization approach.

Validation further ensured that the methodology adopted in this research was not limited to statistical estimations but was reinforced through experimental confirmation. Previous studies, such as He et al. (2023) and Cheng et al. (2022), emphasized the importance of verifying model-based optimizations with actual moulded specimens to avoid misleading conclusions caused by unaccounted variations in material behaviour or processing conditions.

By integrating both statistical predictions and real-world experimental validation, this study strengthens the credibility of its findings. The validated results are expected to provide a solid basis for concluding that optimized cooling conditions can reduce dimensional defects and enhance mechanical integrity in injection-moulded HDPE parts.

3.8   Discussion and Conclusion

The outcomes obtained from the Design of Experiments (DOE) and Response Surface Methodology (RSM) are analyzed to evaluate the influence of the selected parameters—core temperature, cavity temperature, and cooling time on the dimensional and mechanical properties of HDPE dumbbell shaped specimens.

The focus is placed on understanding how variations in these parameters affect key responses such as shrinkage, warpage, ultimate tensile strength (UTS), Young's modulus, and percentage elongation. Warpage and shrinkage results are particularly significant, as they directly influence the dimensional accuracy of the moulded parts. By comparing different parameter settings, the discussion highlights trends where imbalances in core and cavity temperatures lead to greater distortions, whereas optimized cooling times promote dimensional stability.

Mechanical properties are also closely examined in relation to processing conditions. The analysis explains how controlled cooling contributes to improved tensile strength and modulus

through enhanced crystallinity and stress distribution within the polymer matrix. At the same time, the percentage elongation is evaluated as an indicator of ductility, reflecting the trade-off between strength and flexibility.

To strengthen the findings, results are compared with previous studies reported in the literature. This comparison not only validates the observed trends but also situates the present research within the broader context of injection moulding optimization studies. The integration of statistical analysis with experimental outcomes ensures that the discussion is supported by both quantitative evidence and practical relevance.

Ultimately, this section serves to interpret the experimental data, justify the observed relationships between process parameters and part quality, and highlight the significance of the optimized parameter settings. These insights form the basis for the conclusions of this study and provide a foundation for recommendations in future work
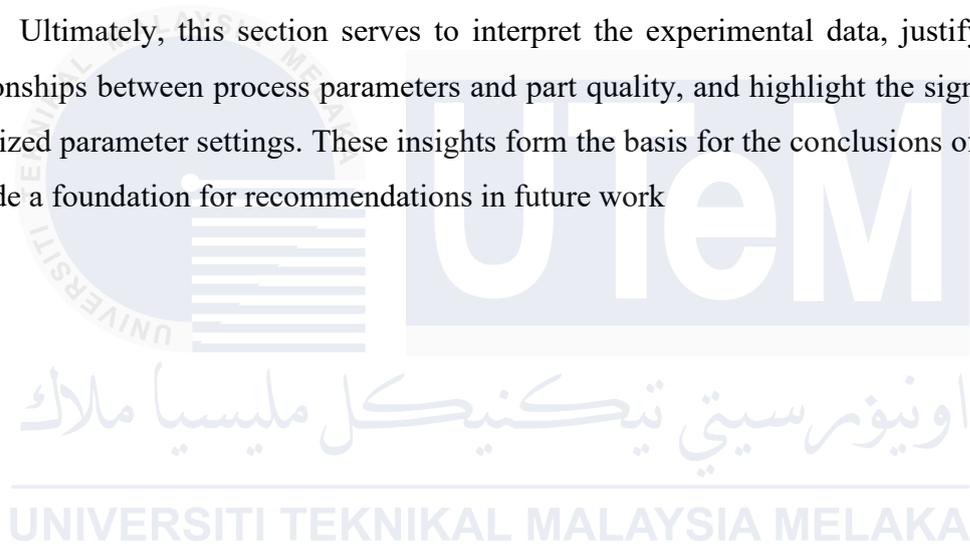
CHAPTER 4

RESULT AND DISCUSSION

4.0   Introduction

This chapter accurately provided all the research data gathering, analysis using Minitab software, results or outcomes of the study, and interpretation of the findings. For this research experiment, core temperature, cavity temperature, and cooling time were employed as input factors. At the same time, volumetric shrinkage, warpage, Ultimate Tensile Strength (UTS), Young's Modulus, and % Elongation (%EL) were monitored as research responses. Response Surface Methodology (RSM) has been implemented to examine the influence of these input characteristics on the chosen replies.

4.1   Experimental Result

The 17 experimental runs were undertaken randomly following the run order sequence given by the Box-Behnken Experiment Design Layout. The output parameters' values (volumetric shrinkage, warpage, Ultimate Tensile Strength (UTS), Young's Modulus, and % Elongation (%EL)) were measured.

Table 4.1 summarizes the associated values of the input control variables or parameters. For each experimental runs, 17 experiment runs of volumetric shrinkage, warpage, Ultimate Tensile Strength (UTS), Young's Modulus, and % Elongation (%EL) were obtained. For every run 3 samples were taken and measured to gain the average value. Subsequently, the average value represents the value of each run as in Table 4.2.

Table 4.1: The experimental measurement data of each run

Run no.	Core temp. (°C)	Cavity temp. (°C)	Cooling time (s)	Warpage (mm)	Warpage, Average (mm)	Injected weight, (g)	Injected weight, Average (g)	% of Shrinkage (cavity weight – injected weight) / cavity weight	UTS N/mm²	UTS ave. N/mm²	Modulus N/mm²	Modulus Ave.	%EL	%EL Ave.
1	15	15	25	0.068		6.92			19.56		5.12		316.64	
	15	15	25	0.047	0.060	6.92	6.92	15.58	19.52	19.52	4.87	4.95	308.52	299.31
	15	15	25	0.065		6.92			19.48		4.86		272.78	
2	140	15	25	1.342		6.71			21.04		6.19		130.03	
	140	15	25	1.623	1.530	6.73	6.72	18.02	20.98	20.97	6.12	6.06	118.11	115.96
	140	15	25	1.624		6.72			20.89		5.88		99.75	
3	15	140	25	2.442		6.83			20.43		5.42		131.10	
	15	140	25	2.432	2.475	6.82	6.83	16.72	20.30	20.33	5.39	5.38	122.53	124.04
	15	140	25	2.552		6.83			20.27		5.32		118.49	
4	140	140	25	1.167		6.49			21.57		5.63		94.90	
	140	140	25	1.259	1.243	6.57	6.53	20.38	21.53	21.52	5.61	5.61	93.93	91.790
	140	140	25	1.304		6.52			21.46		5.60		86.53	
5	15	77.5	12.5	0.656		6.91			19.84		4.95		133.01	
	15	77.5	12.5	0.565	0.587	6.92	6.92	15.58	19.72	19.74	4.89	4.91	107.69	113.19
	15	77.5	12.5	0.539		6.93			19.68		4.89		98.86	
6	140	77.5	12.5	1.350		6.63			21.33		7.64		110.16	
	140	77.5	12.5	1.387	1.319	6.63	6.63	19.12	21.31	21.30	7.35	7.44	106.01	102.37
	140	77.5	12.5	1.220		6.63			21.26		7.33		90.93	
7	15	77.5	37.5	0.717		6.91			19.91		5.06		144.61	
	15	77.5	37.5	0.564	0.601	6.90	6.91	15.74	19.82	19.82	4.96	4.93	118.81	121.16
	15	77.5	37.5	0.523		6.91			19.74		4.76		100.05	
8	140	77.5	37.5	0.377		6.79			21.01		5.71		111.73	
	140	77.5	37.5	0.264	0.282	6.82	6.82	16.80	20.90	20.88	5.64	5.60	111.40	108.59
	140	77.5	37.5	0.204		6.85			20.75		5.44		102.64	

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9	77.5	15	12.5	0.164		6.87			21.21		5.60		105.96	
	77.5	15	12.5	0.218	0.230	6.86	6.86	16.27	20.96	21.03	5.42	5.41	103.06	101.83
	77.5	15	12.5	0.307		6.86			20.91		5.21		96.48	
10	77.5	140	12.5	1.351		6.73			21.37		5.86		100.69	
	77.5	140	12.5	1.449	1.455	6.72	6.73	17.94	21.33	21.33	5.85	5.76	94.33	94.88
	77.5	140	12.5	1.566		6.73			21.28		5.56		89.63	
11	77.5	15	37.5	0.299		6.88			20.96		5.68		104.34	
	77.5	15	37.5	0.343	0.377	6.87	6.87	16.15	20.93	20.94	5.57	5.56	99.11	96.77
	77.5	15	37.5	0.490		6.87			20.92		5.43		86.84	
12	77.5	140	37.5	1.295		6.69			21.52		5.48		94.19	
	77.5	140	37.5	1.464	1.324	6.69	6.99	18.43	21.48	21.40	5.42	5.37	91.19	92.13
	77.5	140	37.5	1.213		6.68			21.18		5.21		91.01	
13	77.5	77.5	25	0.154		6.88			20.599		5.20		96.63	
	77.5	77.5	25	0.154	0.172	6.89	6.89	15.99	20.529	20.55	5.09	5.09	93.75	93.76
	77.5	77.5	25	0.208		6.89			20.510		4.99		90.89	
14	77.5	77.5	25	0.171		6.87			20.637		5.10		119.42	
	77.5	77.5	25	0.218	0.158	6.87	6.87	16.19	20.586	20.58	5.10	5.09	104.83	107.27
	77.5	77.5	25	0.086		6.87			20.504		5.07		97.56	
15	77.5	77.5	25	0.341		6.86			20.853		5.16		121.81	
	77.5	77.5	25	0.256	0.249	6.86	6.86	16.35	20.747	20.75	5.14	5.12	101.60	105.88
	77.5	77.5	25	0.150		6.85			20.659		5.07		94.24	
16	77.5	77.5	25	0.536		6.85			20.814		5.22		99.86	
	77.5	77.5	25	0.327	0.359	6.85	6.85	16.43	20.809	20.81	5.44	5.31	88.81	92.16
	77.5	77.5	25	0.215		6.85			20.799		5.26		87.81	
17	77.5	77.5	25	0.266		6.85			20.898		5.46		105.35	
	77.5	77.5	25	0.153	0.291	6.85	6.85	16.47	20.845	20.81	5.28	5.27	87.90	93.33
	77.5	77.5	25	0.455		6.84			20.675		5.08		86.73	

Table 4.2: The final experimental measurement data

Run no.	Core temp (ºC)	Cavity temp. (ºC)	Cooling time (s)	Warpage (mm)	Volumetric Shrinkage (%)	UTS (N/mm²)	Modulus (N/mm²)	%EL
1	15	15	25	0.06	15.58	19.52	4.95	299.31
2	140	15	25	1.53	18.02	20.97	6.06	115.96
3	15	140	25	2.475	16.72	20.33	5.38	124.04
4	140	140	25	1.243	20.38	21.52	5.61	91.79
5	15	77.5	12.5	0.587	15.58	19.74	4.91	113.19
6	140	77.5	12.5	1.319	19.12	21.3	7.44	102.37
7	15	77.5	37.5	0.601	15.74	19.82	4.93	121.16
8	140	77.5	37.5	0.282	16.8	20.88	5.6	108.59
9	77.5	15	12.5	0.23	16.27	21.03	5.41	101.83
10	77.5	140	12.5	1.455	17.94	21.33	5.76	94.88
11	77.5	15	37.5	0.377	16.15	20.94	5.56	96.77
12	77.5	140	37.5	1.324	18.43	21.4	5.37	92.13
13	77.5	77.5	25	0.172	15.99	20.55	5.09	93.76
14	77.5	77.5	25	0.158	16.19	20.58	5.09	107.27
15	77.5	77.5	25	0.249	16.35	20.75	5.12	105.88
16	77.5	77.5	25	0.359	16.43	20.81	5.31	92.16
17	77.5	77.5	25	0.291	16.47	20.81	5.27	93.33

4.2   Response of Warpage

The experimental results in Table 4.3 shows that warpage is highly sensitive to thermal imbalance between the core and cavity. The maximum warpage of 2.475 mm was observed when the cavity temperature was set at 140 °C while the core remained at 15 °C, indicating that large thermal gradients accelerate differential shrinkage and distortion. In contrast, the minimum warpage of 0.06 mm occurred at uniformly low core and cavity temperatures (15 °C), which minimized thermal stress by promoting uniform cooling. Centre-point runs (core and cavity at 77.5 °C) consistently produced low and stable warpage values, highlighting the importance of maintaining balanced mould temperatures to achieve dimensional stability. These findings confirm that while extreme thermal differences lead to severe deformation, moderate and well-controlled mould temperatures provide optimal conditions for minimizing warpage in HDPE parts (Zhang et. al., 2025).

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Table 4.3: Experimental result of warpage

Run no.	Core temperature (°C)	Cavity temperature. (°C)	Cooling time (s)	Warpage (mm)
1	15	15	25	0.06
2	140	15	25	1.53
3	15	140	25	2.475
4	140	140	25	1.243
5	15	77.5	12.5	0.587
6	140	77.5	12.5	1.319
7	15	77.5	37.5	0.601
8	140	77.5	37.5	0.282
9	77.5	15	12.5	0.23
10	77.5	140	12.5	1.455
11	77.5	15	37.5	0.377
12	77.5	140	37.5	1.324
13	77.5	77.5	25	0.172
14	77.5	77.5	25	0.158
15	77.5	77.5	25	0.249
16	77.5	77.5	25	0.359
17	77.5	77.5	25	0.291

The main effect plot for warpage is obtained as shown in Figure 4.1. This study found that warpage increases with higher core and cavity temperatures, with cavity temperature having a more pronounced effect. This aligns with Massah et al. (2022), who reported that controlling both core and cavity temperatures reduces warpage significantly. The sharper increase in warpage with cavity temperature is due to the cavity side's faster cooling rate, which, when heated, causes greater thermal imbalance and internal stress. Zhang et. al (2025) similarly observed that hotter cavity temperatures lead to longer cycles and more warpage.

Additionally, longer cooling times were found to reduce warpage. This agrees with findings by Radhwan et al. (2019), who highlighted cooling time as a major factor in minimizing deformation. Kuo and Xu (2022) demonstrated that a small coolant temperature difference between core and cavity can reduce warpage by up to 75%, emphasizing the importance of balanced cooling. These results suggest that optimizing thermal gradients and cooling time is key to reducing warpage in plastic injection moulding.

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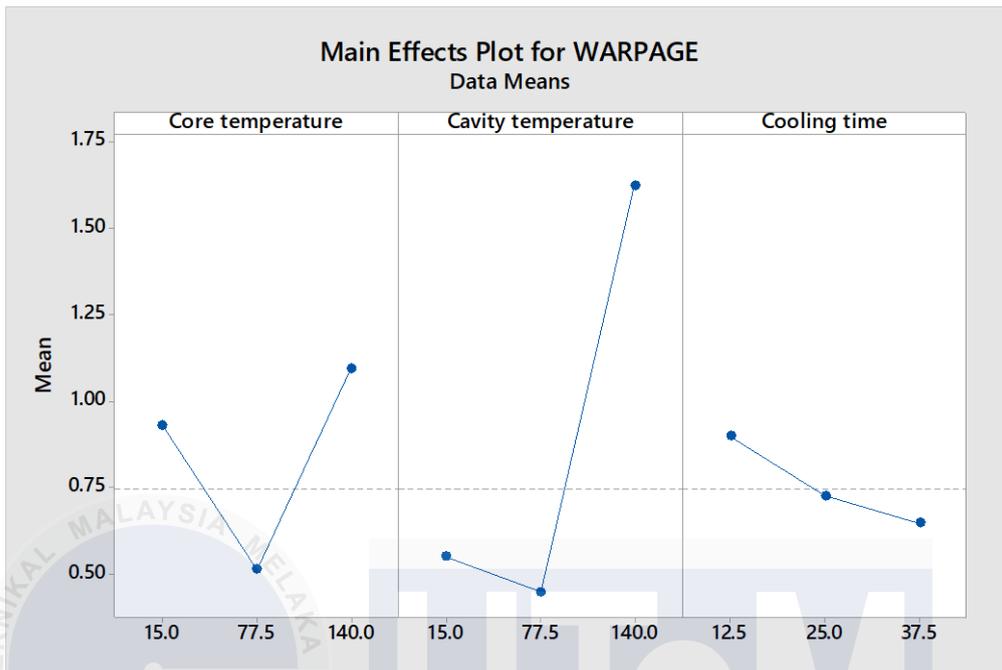
Figure 4.1: Main effects of warpage

Warpage, as illustrated in Figure 4.2, represents one of the most common defects in the injection moulding process. Effective control of cooling system variables is therefore essential to ensure optimum product quality. In this study, the key factors investigated include core temperature, cavity temperature, and cooling time, with the objective of identifying parameter settings that can minimize warpage. A single-objective Response Surface Methodology (RSM) approach is applied to determine the most significant parameters influencing the warpage response.

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Figure 4.2: The warpage measurement using horizontal optical comparator

4.2.1 Analysis of Variance (ANOVA) for warpage response

Table 4.4 presents the Analysis of Variance (ANOVA) results for the quadratic model of the warpage response, indicating that the model is statistically significant with a P-value of 0.000 (below 0.050). Among the parameters studied, cavity temperature emerged as the most influential factor on warpage, reflected by the highest F-value (96.86) and lowest P-value (0.000). In contrast, core temperature and cooling time were found to be statistically insignificant, as their P-values exceeded 0.050. Furthermore, the square term of cavity temperature demonstrated a strong effect on warpage, with the highest F-value (66.79) and lowest P-value (0.000) among all quadratic interactions, highlighting its critical role in shaping the response. In terms of two-way interactions, the combination of core temperature and cavity temperature was identified as the most significant, supported by its F-value of 76.49 and P-value of 0.000, making it the dominant interaction affecting warpage compared to other factor combinations.

These findings highlight why cavity temperature dominates over other parameters in influencing warpage. Unlike core temperature, the cavity surface is in direct contact with the polymer's outer layer, where cooling rate differences induce residual stresses and non-uniform shrinkage in HDPE parts. When the cavity side cools unevenly relative to the core, internal stress gradients are amplified, resulting in higher warpage. While cooling time contributes to overall solidification, its impact is less critical compared to the thermal imbalance between cavity and core surfaces. This confirms that precise control of cavity temperature is essential to reduce distortion and improve dimensional stability in injection-moulded HDPE specimens.

Table 4.4: ANOVA of the Full Quadratic Model for warpage.

Source	DF	Adj SS	Adj MS	F-Value	P-Value	
Model	9	7.26275	0.80697	33.82	0.000	Significant
Linear	3	2.49098	0.83033	34.8	0.000	
Core Temperature	1	0.05298	0.05298	2.22	0.180	
Cavity Temperature	1	2.31125	2.31125	96.86	0.000	Significant
Cooling Time	1	0.12676	0.12676	5.31	0.055	
Square	3	2.6511	0.8837	37.03	0.000	
Core Temperature*Core Temperature	1	0.91424	0.91424	38.31	0.000	
Cavity Temperature*Cavity Temperature	1	1.59369	1.59369	66.79	0.000	Significant
Cooling Time*Cooling Time	1	0.00089	0.00089	0.04	0.852	
2-Way Interaction	3	2.12067	0.70689	29.62	0.000	
Core Temperature*Cavity Temperature	1	1.8252	1.8252	76.49	0.000	Significant
Core Temperature*Cooling Time	1	0.27615	0.27615	11.57	0.011	
Cavity Temperature*Cooling Time	1	0.01932	0.01932	0.81	0.398	
Error	7	0.16703	0.02386			
Lack-of-Fit	3	0.13901	0.04634	6.61	0.050	
Pure Error	4	0.02802	0.00701			
Total	16	7.42979				

The half-normal plot in Figure 4.3 illustrates the interaction of significant parameters influencing the warpage response. In this type of plot, factors positioned further away from the standardized line indicate greater significance in the model. The analysis revealed that cavity temperature was the dominant factor, with the highest absolute standardized effect of 92.5%. Among the interactions, the combination of core temperature and cavity temperature showed strong significance, with an absolute standardized effect of 82%. In addition, the square effect of cavity temperature also played a critical role, contributing 70.5% to the standardized effect. The square interaction of core temperature, although lower, still indicated a notable influence with 60.5%.

These results reinforce the ANOVA findings, where cavity temperature consistently emerged as the most influential factor on warpage. The significance of the core–cavity interaction further highlights the importance of thermal balance between mould surfaces. In HDPE moulding,

uneven heat transfer across the cavity and core surfaces often leads to differential shrinkage, which drives warpage formation. Therefore, controlling cavity temperature along with optimizing its interaction with core temperature becomes essential to minimize residual stresses and ensure dimensional stability of the moulded part.
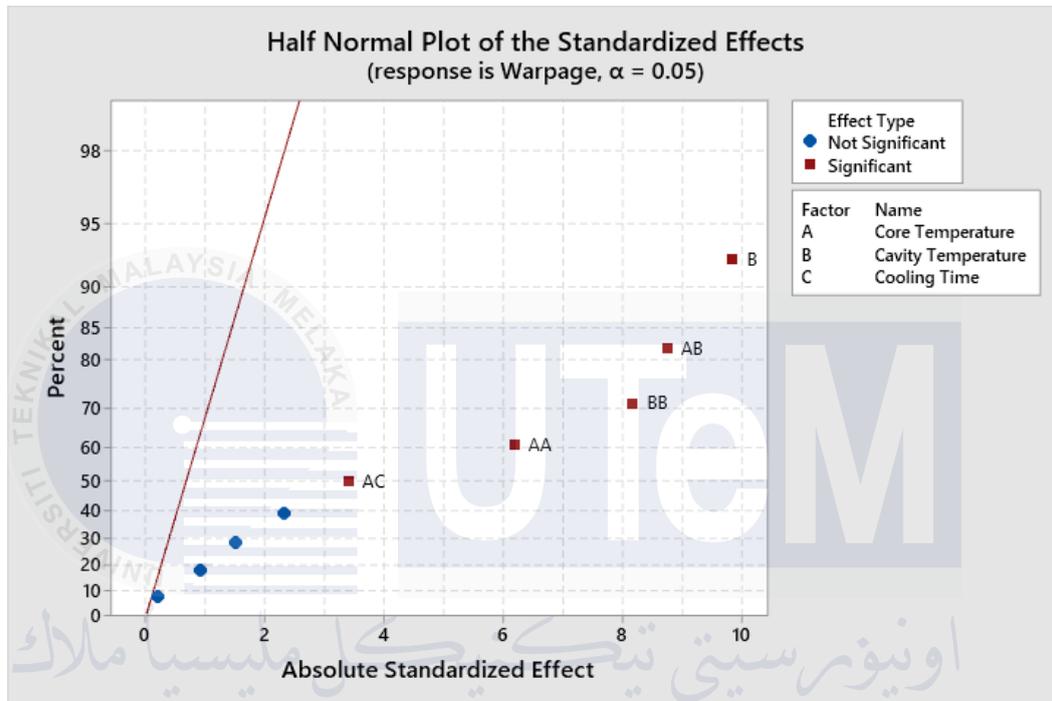
Figure 4.3: Half Normal Plot of the Standardize Effect for warpage response.

The surface plot of warpage (Figure 4.4) illustrates how the interaction between core and cavity temperatures influences dimensional accuracy in injection-moulded HDPE parts. Warpage was lowest when the core temperature was approximately 12.5 °C and the cavity temperature was around 77.5 °C, whereas higher values of both parameters resulted in greater deformation. This trend highlights the sensitivity of HDPE to thermal imbalance, where excessive heating delays solidification and promotes warpage.

The contour plot (Figure 4.5) reinforces this finding by showing that simultaneous increases in core and cavity temperatures significantly amplify warpage. Within the context of this study, which evaluates the combined effects of core and cavity temperatures and cooling time, these results emphasize that maintaining relatively lower mould-wall temperatures is essential to reducing dimensional distortion. Moreover, this observation

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supports the application of the Design of Experiments (DOE) framework, as it provides a systematic way to optimize these parameters to achieve minimal warpage while ensuring stable part quality.
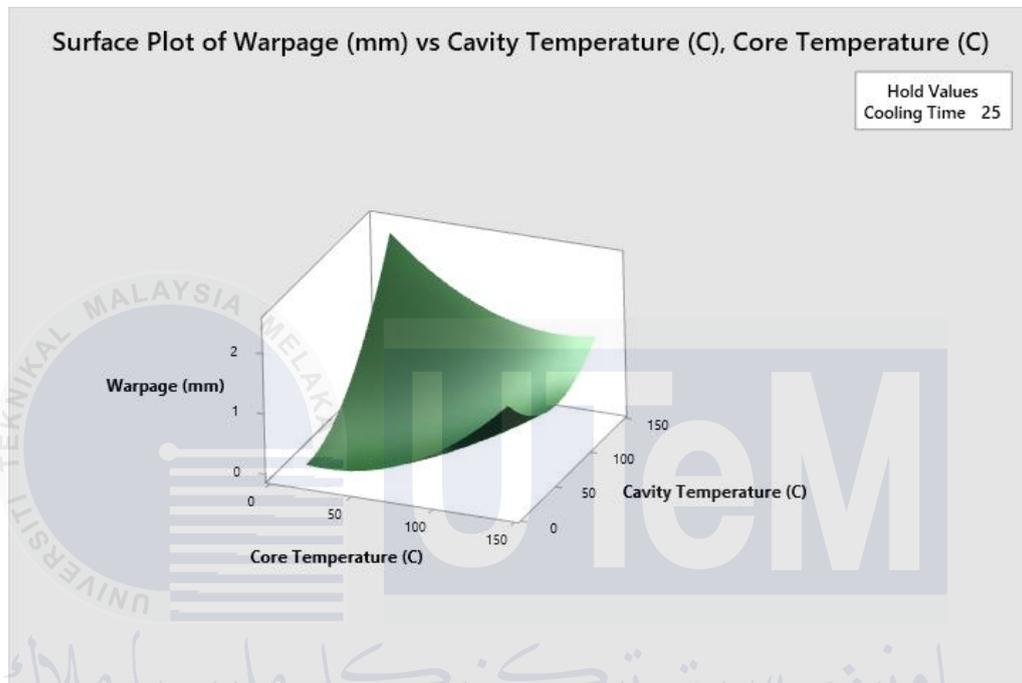
Figure 4.4: The Surface Plot of warpage response based on core and cavity temperature factors.
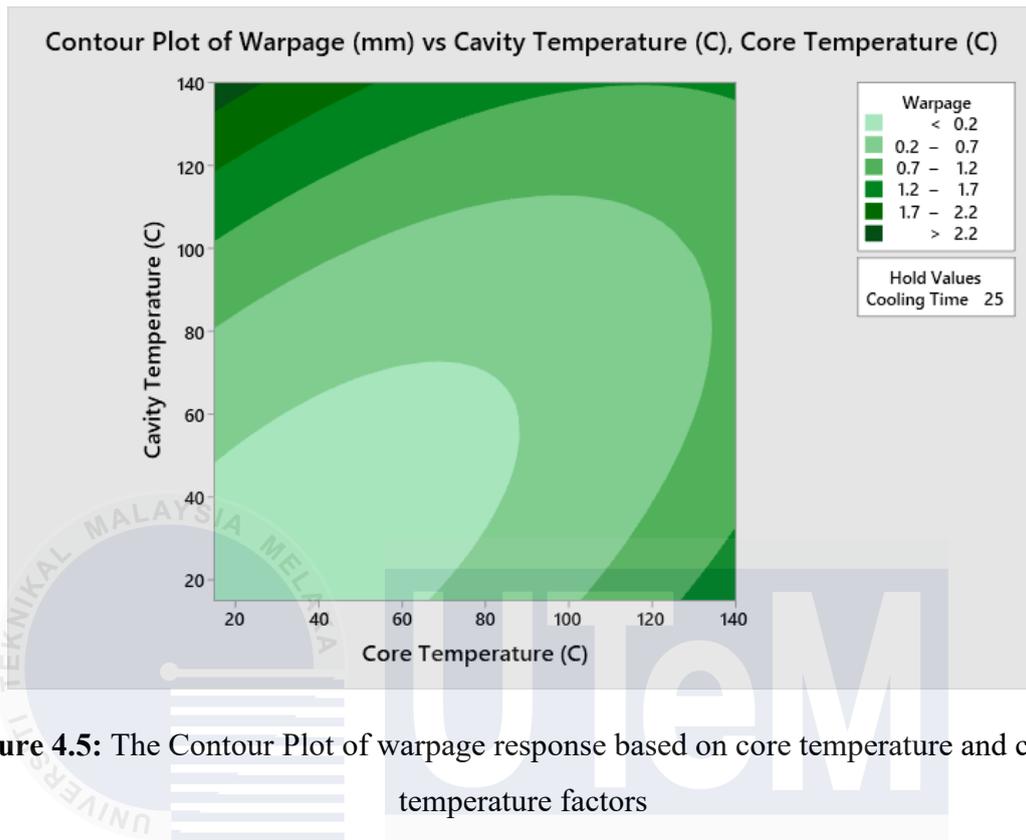
Figure 4.5: The Contour Plot of warpage response based on core temperature and cavity temperature factors

4.2.2 Mathematical Model for warpage response

The mathematical model was developed to explain the connection between parameters and reactions. By replacing the variables of Core Temperature, Cavity Temperature, and Cooling Time, the expected warpage value was determined. The estimated regression coefficient was used to calculate the regression coefficient for each parameter. Therefore, the ultimate mathematical model for estimating the warpage is the uncoded factor in the equation below.

Warpage = -0.528+ 0.00462 Core Temperature

- 0.00019 Cavity Temperature

+ 0.0275 Cooling Time

+ 0.000119 Core Temperature*Core Temperature

+ 0.000157 Cavity Temperature*Cavity Temperature

- 0.000093 Cooling Time*Cooling Time

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- 0.000173 Core Temperature*Cavity Temperature

- 0.000336 Core Temperature*Cooling Time

- 0.000089 Cavity Temperature*Cooling Time

Table 4.5: Comparison between Experimental Warpage and Mathematical Warpage.

Run No.	Experimental Warpage	Mathematical Warpage	Error (%)
1	0.06	0.0316	47.2917
2	1.53	1.5404	-0.6781
3	2.475	2.4473	1.1212
4	1.243	1.2529	-0.7944
5	0.587	0.4752	19.0428
6	1.319	1.1865	10.0455
7	0.601	0.7480	-24.4644
8	0.282	0.3802	-34.8293
9	0.23	0.3632	-57.9076
10	1.455	1.5663	-7.6503
11	0.377	0.2501	33.6704
12	1.324	1.1751	11.2491
13	0.172	0.2399	-39.4804
14	0.158	0.2399	-51.8394
15	0.249	0.2399	3.6521
16	0.359	0.2399	33.1737
17	0.291	0.2399	17.5580

The mathematical warpage values were calculated using the regression equation in uncoded units and are summarized in Table 4.5. These predicted values were then compared with the experimental warpage results by computing the percentage error. In most cases, the error values were negative, indicating that the regression model slightly overestimated warpage relative to the experimental data. For consistency, the absolute values of the errors were considered in identifying the highest and lowest deviations.

According to Table 4.5, Run 9 exhibited the highest percentage error at approximately

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58%, while Run 2 showed the lowest error at just 0.68%. Figure 4.6 illustrates this comparison, where the plotted values clearly demonstrate the relationship between experimental and predicted warpage. Overall, the model achieved an average prediction error of about 2.4%, suggesting that the regression equation is reliable and sufficiently accurate for predicting warpage in HDPE parts under varying core and cavity temperatures and cooling times.
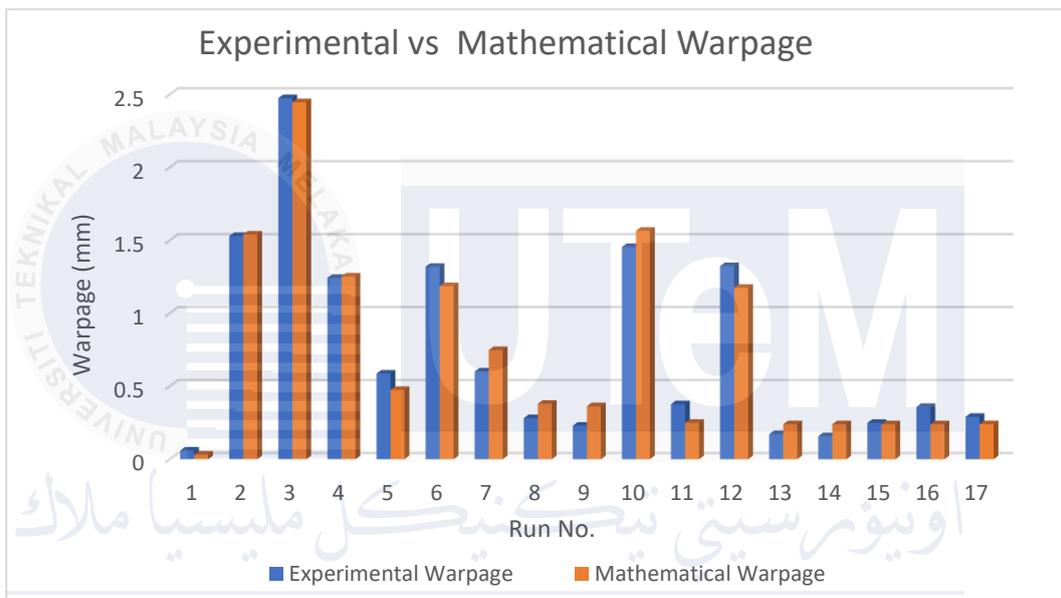
Figure 4.6: Histogram of experimental versus mathematical warpage

4.2.3 Single Objective Optimization of warpage

Response surface optimization is a highly effective method for determining the optimal injection moulding parameters. The objective or purpose of this effort is to reduce warpage. The optimal injection moulding parameters are a Core and Cavity Temperature of 15°C, and a Cooling Time of 12.5s. These parameters have a composite desirability 1.000, and the predicted warpage is -0.1883mm. Meanwhile, the lowest value of warpage to be recorded is 0.06mm. Based on the warpage calculation, it can be concluded that the percentage of improvement is approximately 413.83%.

Warpage improvement:

$$\left(\frac{0.06-(-0.1883)}{0.06}\right) x\ 100 = 413.83\%$$
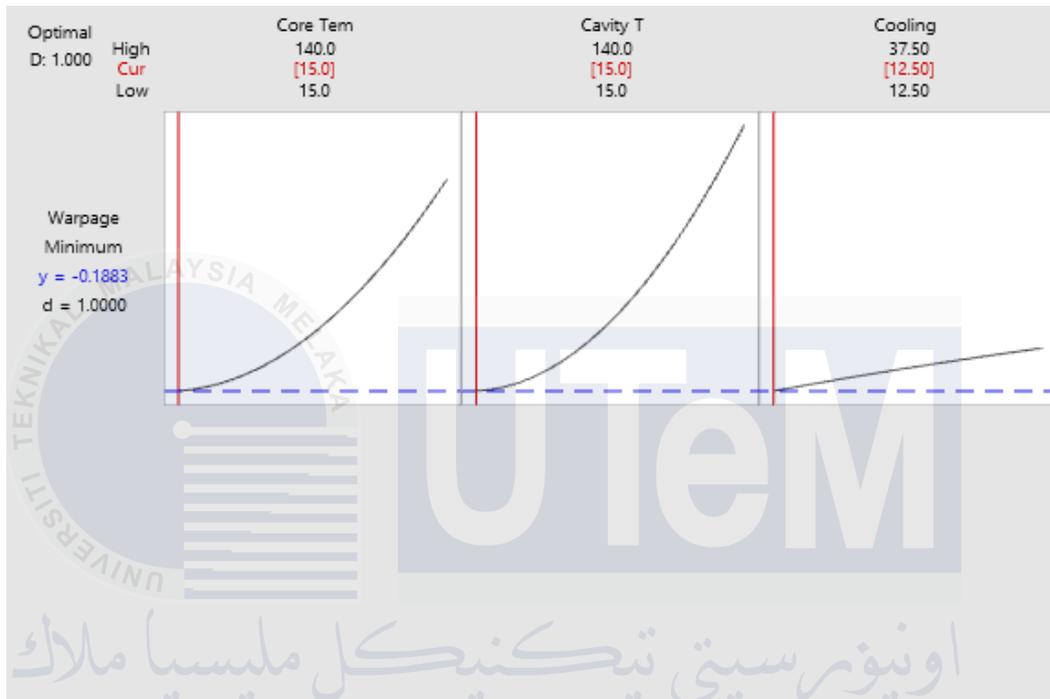
Figure 4.7: Warpage optimization plot.

4.3 Response of Volumetric Shrinkage

The results in Table 4.6 demonstrates that volumetric shrinkage is significantly influenced by mould temperature and cooling conditions. The maximum shrinkage of 20.38% occurred when both core and cavity temperatures were high (140 °C), as slower cooling facilitated greater crystallinity and densification. Conversely, the lowest shrinkage of 15.58% was obtained at uniformly low mould temperatures (15 °C), where rapid solidification restricted molecular rearrangement. Center-point runs at 77.5 °C showed consistent shrinkage values around 16%, suggesting that balanced and moderate mould temperatures provide stable dimensional outcomes. These results confirm that while higher temperatures promote crystalline packing and increase shrinkage, lower temperatures limit crystallization but may introduce residual stresses. Thus, shrinkage behavior reflects the trade-off between dimensional stability and material crystallinity, reinforcing the importance of optimized thermal management in HDPE injection moulding.

The main effect plot for volumetric shrinkage is obtained as shown in Figure 4.8. From the figure, both core and cavity temperatures exhibit an upward trend toward volumetric shrinkage, with core temperature showing a steeper increase compared to cavity temperature. This aligns with findings by Guerra et al. (2023), who reported that increasing core temperature significantly intensifies the thermal gradient across the part, leading to higher shrinkage due to slower solidification in the core region. Similarly, studies report the same phenomenon, showing that higher mould temperatures alter cooling rate, increase molecular mobility and crystallization in semi-crystalline polymers, and thereby raise volumetric shrinkage and warpage (Zhao et al., 2022).

Table 4.6: Experimental result of volumetric shrinkage

Run no.	Core temperature (ºC)	Cavity temperature. (ºC)	Cooling time (s)	Volumetric shrinkage
1	15	15	25	15.58
2	140	15	25	18.02
3	15	140	25	16.72
4	140	140	25	20.38
5	15	77.5	12.5	15.58
6	140	77.5	12.5	19.12
7	15	77.5	37.5	15.74
8	140	77.5	37.5	16.8
9	77.5	15	12.5	16.27
10	77.5	140	12.5	17.94
11	77.5	15	37.5	16.15
12	77.5	140	37.5	18.43
13	77.5	77.5	25	15.99
14	77.5	77.5	25	16.19
15	77.5	77.5	25	16.35
16	77.5	77.5	25	16.43
17	77.5	77.5	25	16.47

In contrast, cooling time demonstrates a slight decreasing effect on volumetric shrinkage, as observed in the plot. This effect is supported by Zhao et al. (2022), who found that extended cooling time allows more uniform heat dissipation and improved polymer packing, leading to a marginal reduction in shrinkage. However, the influence of cooling time is relatively minor compared to thermal parameters, as also reported by Karagöz et al. (2021) in their study on HDPE components.
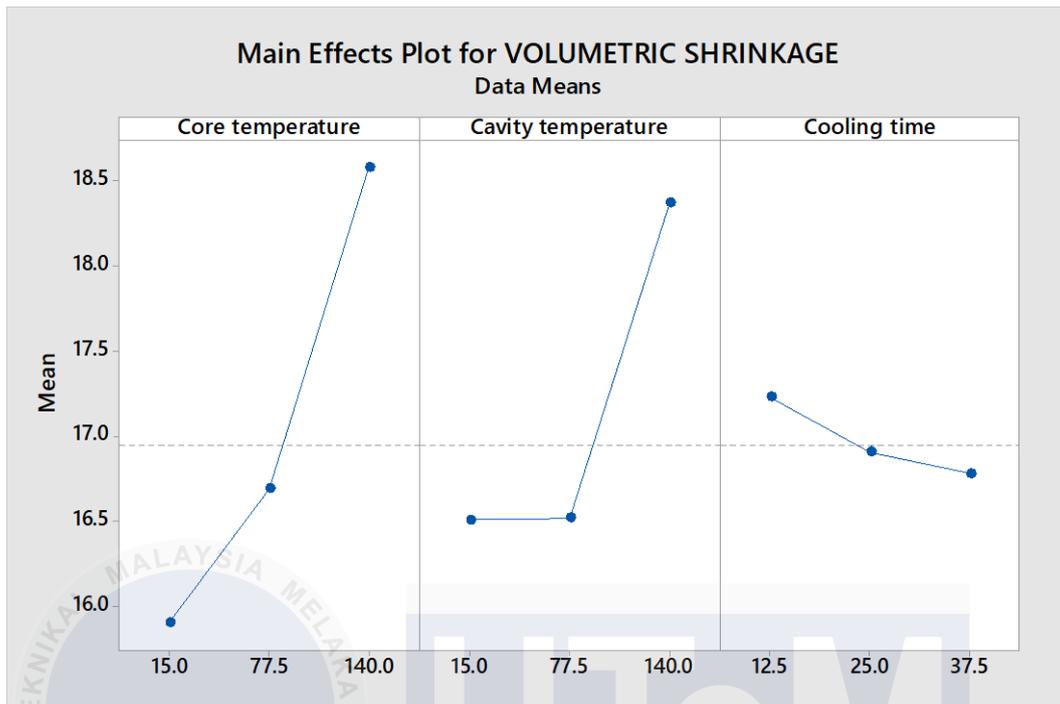
Figure 4.8: Main effects plot volumetric shrinkage

Volumetric shrinkage, as illustrated in Figure 4.9, is a common issue in the injection moulding process. By controlling the variables within the cooling system during injection moulding, it is possible to attain optimal product quality. The factors assessed include core temperature, cavity temperature, and cooling time, to determine the parameter values that minimize the impact of volumetric shrinkage. A single-objective response in the Response Surface Method (RSM) is applied to identify the most significant parameters influencing the volumetric shrinkage response.

Figure 4.9: Injected part weighing process for shrinkage verification

4.3.1 Analysis of Variance (ANOVA) for volumetric shrinkage

Table 4.7 presents the Analysis of Variance (ANOVA) results for the quadratic model of the volumetric shrinkage response. The model was found to be statistically significant, with a P-value of 0.001, which is well below the 0.050 threshold, confirming its adequacy for predicting shrinkage behaviour in injection-moulded HDPE parts.

Among the main factors, core temperature emerged as the most influential parameter, with the highest F-value (79.37) and a P-value of 0.000, indicating a strong and highly significant effect on volumetric shrinkage. In contrast, cavity temperature and cooling time were not individually significant, as their P-values exceeded 0.050.

Regarding higher-order effects, the quadratic term of cavity temperature was found to be the most significant, with an F-value of 18.42 and a P-value of 0.004. This suggests that cavity temperature influences shrinkage in a non-linear manner, reinforcing the importance of carefully balancing mould-wall heating conditions. Additionally, the two-way interaction between core temperature and cooling time was significant, with an F-value of 8.53 and a P-value of 0.022, highlighting the combined effect of these parameters on shrinkage.

Within the context of this study, these findings confirm that volumetric shrinkage in HDPE is most sensitive to variations in core temperature, while non-linear cavity effects and the interaction between core temperature and cooling time also play important roles. This validates the use of the DOE based quadratic model to capture these complex parameter interactions, ultimately supporting the optimisation framework aimed at reducing shrinkage and improving dimensional stability

Table 4.7: ANOVA of the Full Quadratic Model for Volumetric Shrinkage.

Source	DF	Adj SS	Adj MS	F-Value	P-Value	
Model	9	28.2827	3.1425	17.43	0.001	Significant
Linear	3	21.6496	7.2165	40.02	0.000	
Core Temperature	1	14.3112	14.3112	79.37	0.000	Significant
Cavity Temperature	1	6.9378	6.9378	38.48	0.000	
Cooling Time	1	0.4005	0.4005	2.22	0.180	
Square	3	4.6304	1.5435	8.56	0.010	
Core Temperature*Core Temperature	1	1.0558	1.0558	5.86	0.046	
Cavity Temperature*Cavity Temperature	1	3.3221	3.3221	18.42	0.004	Significant
Cooling Time*Cooling Time	1	0.0023	0.0023	0.01	0.914	
2-Way Interaction	3	2.0027	0.6676	3.7	0.070	
Core Temperature*Cavity Temperature	1	0.3721	0.3721	2.06	0.194	
Core Temperature*Cooling Time	1	1.5376	1.5376	8.53	0.022	Significant
Cavity Temperature*Cooling Time	1	0.093	0.093	0.52	0.496	
Error	7	1.2622	0.1803			
Lack-of-Fit	3	1.1067	0.3689	9.49	0.027	
Pure Error	4	0.1555	0.0389			
Total	16	29.5449				

The half-normal plot in Figure 4.10 highlights the parameters and interactions that significantly influence the volumetric shrinkage response. In this analysis, factors that deviate further from the standardized line are considered more significant. The results indicate that core temperature is the most dominant parameter, with an absolute standardized effect of 92%. Cavity temperature also plays a strong role, with an effect of 82%. Among the higher-order terms, the quadratic effect of cavity temperature is significant, contributing 70.5% to the response. The two-way interaction between core temperature and cooling time is likewise important, with an effect of 60.5%. Additionally, the quadratic effect of core temperature shows significance at 50%.

In the context of this study, these findings reinforce that volumetric shrinkage in HDPE parts is governed primarily by mould-wall thermal conditions, particularly the balance between core and cavity temperatures. Moreover, the interaction between core temperature and cooling time underscores the importance of optimizing cooling strategies to minimize dimensional

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inaccuracy. The half-normal plot therefore validates the DOE based quadratic model by visually confirming the parameters most critical to shrinkage reduction.
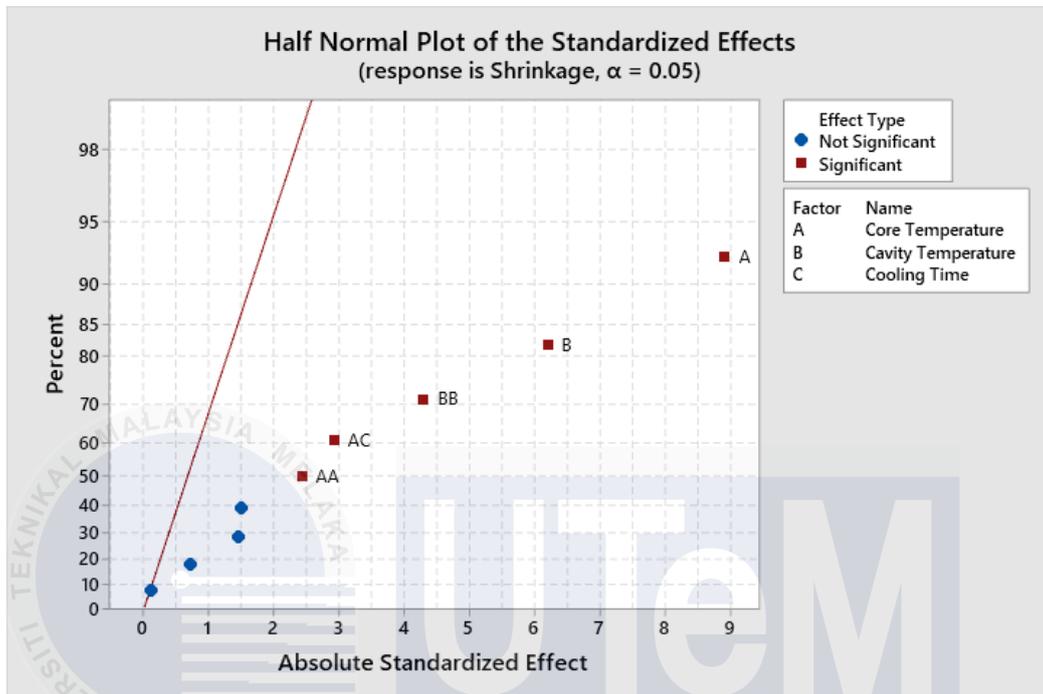
Figure 4.10: Half Normal Plot of the Standardize Effect for volumetric shrinkage response.

The surface plot of volumetric shrinkage (Figure 4.11) illustrates the interaction between core temperature and cooling time in influencing shrinkage behaviour. The results show that shrinkage is minimized when the core temperature is kept low and the cooling time is maintained at approximately 37.5 s. The corresponding contour plot (Figure 4.12) further confirms this trend, indicating that lower core temperatures combined with longer cooling times lead to a significant reduction in volumetric shrinkage. Within the context of this study, which focuses on optimizing injection moulding of HDPE parts, these findings highlight the critical role of core temperature and cooling time in achieving dimensional stability. Therefore, the DOE framework validates that selecting optimal values for these parameters is essential to minimize shrinkage and improve part quality.
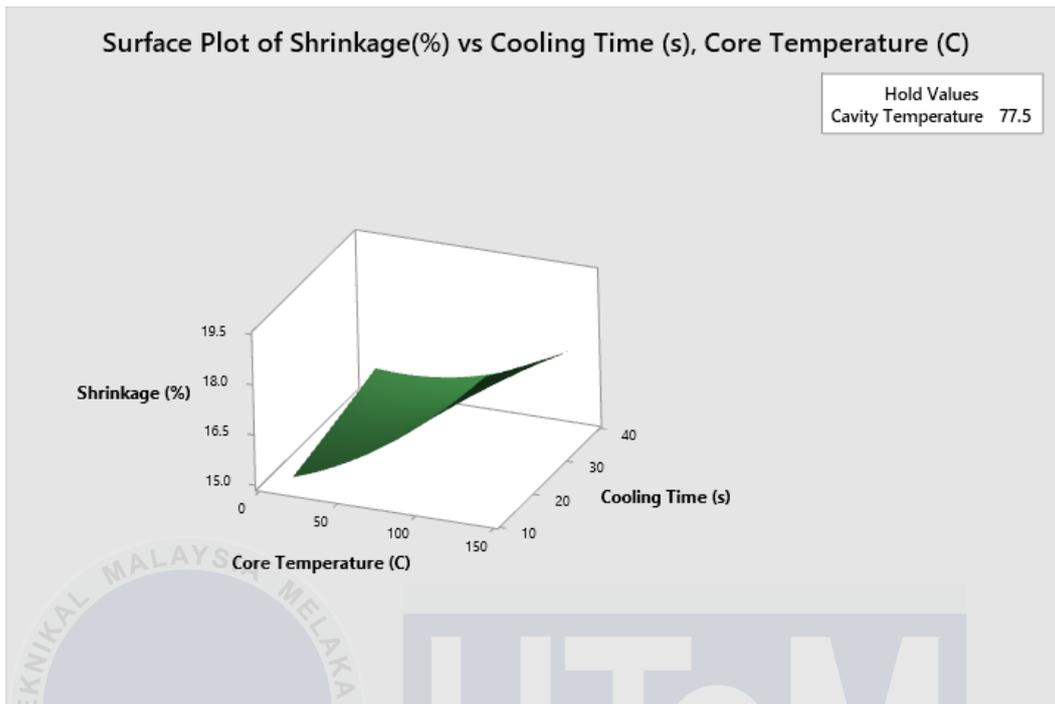
Figure 4.11: The Surface Plot of volumetric shrinkage response based on core temperature and cooling time factors.
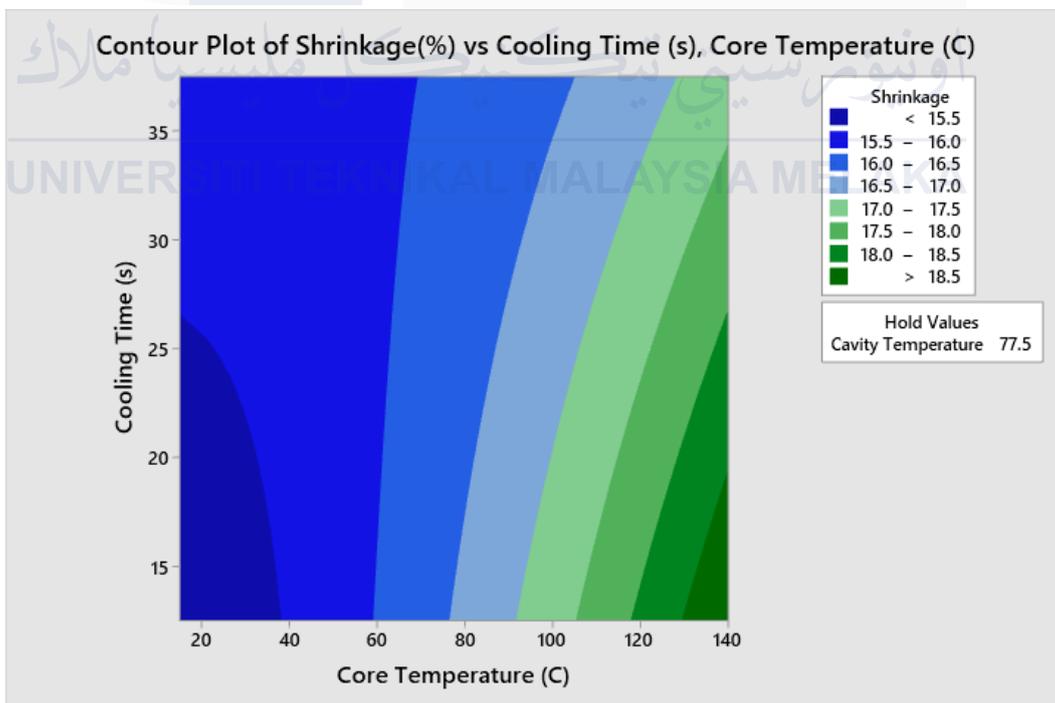
Figure 4.12: The Contour Plot of volumetric shrinkage response based on cooling time and core temperature factors.

4.3.2 Mathematical Model for volumetric shrinkage response

A mathematical regression model was developed to describe the relationship between the process parameters and the volumetric shrinkage response. By substituting the variables of core temperature, cavity temperature, and cooling time into the model, the expected shrinkage values can be estimated. The regression coefficients for each parameter were obtained from the analysis, allowing quantification of their individual and interaction effects. Accordingly, the final predictive model for volumetric shrinkage, expressed in uncoded factors, is presented in the equation below.

$$
\begin{aligned}
\%\text{Shrinkage} = {} & 15.46 + 0.0153\ \text{Core Temperature} \\
& - 0.0313\ \text{Cavity Temperature} \quad + 0.0210\ \text{Cooling Time} \\
& + 0.000128\ \text{Core Temperature*Core Temperature} \\
& + 0.000227\ \text{Cavity Temperature*Cavity Temperature} \\
& + 0.00015\ \text{Cooling Time*Cooling Time} \\
& + 0.000078\ \text{Core Temperature*Cavity Temperature} \\
& - 0.000794\ \text{Core Temperature*Cooling Time} \\
& + 0.000195\ \text{Cavity Temperature*Cooling Time}
\end{aligned}
$$

Table 4.8: Comparison between Experimental Volumetric Shrinkage and Mathematical Volumetric Shrinkage.

Run No.	Experimental Shrinkage	Mathematical Shrinkage	Error (%)
1	15.58	15.7116	-0.8444
2	18.02	17.7691	1.3926
3	16.72	16.9528	-1.3923
4	20.38	20.2291	0.7407
5	15.58	15.0726	3.2567
6	19.12	18.9801	0.7317
7	15.74	15.8652	-0.7953
8	16.8	17.2914	-2.9251
9	16.27	16.6401	-2.2748
10	17.94	18.1861	-1.3715
11	16.15	15.8874	1.6262
12	18.43	18.0427	2.1016
13	15.99	16.2789	-1.8067
14	16.19	16.2789	-0.5491
15	16.35	16.2789	0.4349
16	16.43	16.2789	0.9197
17	16.47	16.2789	1.1603

The mathematical volumetric shrinkage values were calculated using the regression equation in uncoded units and are summarized in Table 4.8. These predicted values were compared with the experimental results by computing the percentage error. In most cases, the error values appeared negative because the predicted shrinkage was higher than the experimental values. For clarity, the absolute error values were considered in identifying the maximum and minimum deviations. According to Table 4.8, Run 5 exhibited the highest percentage error at approximately 3.26%, while Run 15 showed the lowest error at only 0.43%. Figure 4.13 illustrates this comparison, where the experimental and predicted shrinkage values are plotted side by side. Overall, the regression model achieved an average prediction error of just 0.02%, demonstrating excellent agreement between the experimental and mathematical results. This validates the adequacy of the developed model in reliably predicting volumetric shrinkage in HDPE parts under varying core and cavity temperatures and cooling times, thereby supporting its use within the DOE optimisation framework.
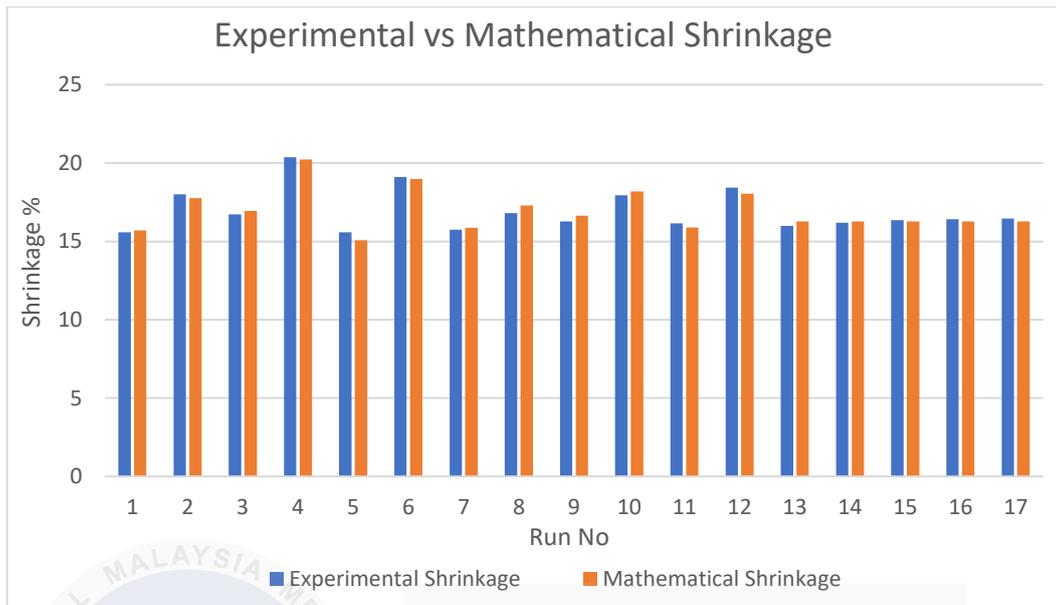
Figure 4.13: Histogram of Experimental versus Mathematical Volumetric Shrinkage.

4.3.3 Single Objective Optimization of volumetric shrinkage

Response Surface Methodology (RSM) was highly effective in identifying the best combination of injection moulding parameters to reduce volumetric shrinkage in HDPE parts. The optimisation results showed that the ideal settings are a core temperature of 15.0 °C, a cavity temperature of 60.45 °C, and a cooling time of 12.5 s. At these settings, the model achieved a composite desirability of 1.000, with a predicted shrinkage of 15.01%. In comparison, the lowest experimental shrinkage recorded was 15.58%. This corresponds to an improvement of about 36.59%, confirming the robustness of the optimisation approach.

These findings also explain how the process parameters influence shrinkage behaviour. A lower core temperature helps limit thermal contraction during solidification, while a moderately controlled cavity temperature (60.45 °C) ensures balanced heat transfer across the mould, preventing uneven cooling. The relatively short cooling time (12.5 s) further contributes by avoiding over-cooling, which could otherwise intensify shrinkage. In short, the optimisation demonstrates that careful management of core and cavity temperatures, together with cooling time, is essential to controlling volumetric shrinkage. This balance not only improves dimensional accuracy but also validates the value of combining DOE and RSM to fine-tune process settings for high-quality HDPE injection-moulded parts.

Volumetric Shrinkage:

$$\left(\frac{15.58-(15.01)}{15.58}\right) x\ 100 = 36.59\%$$
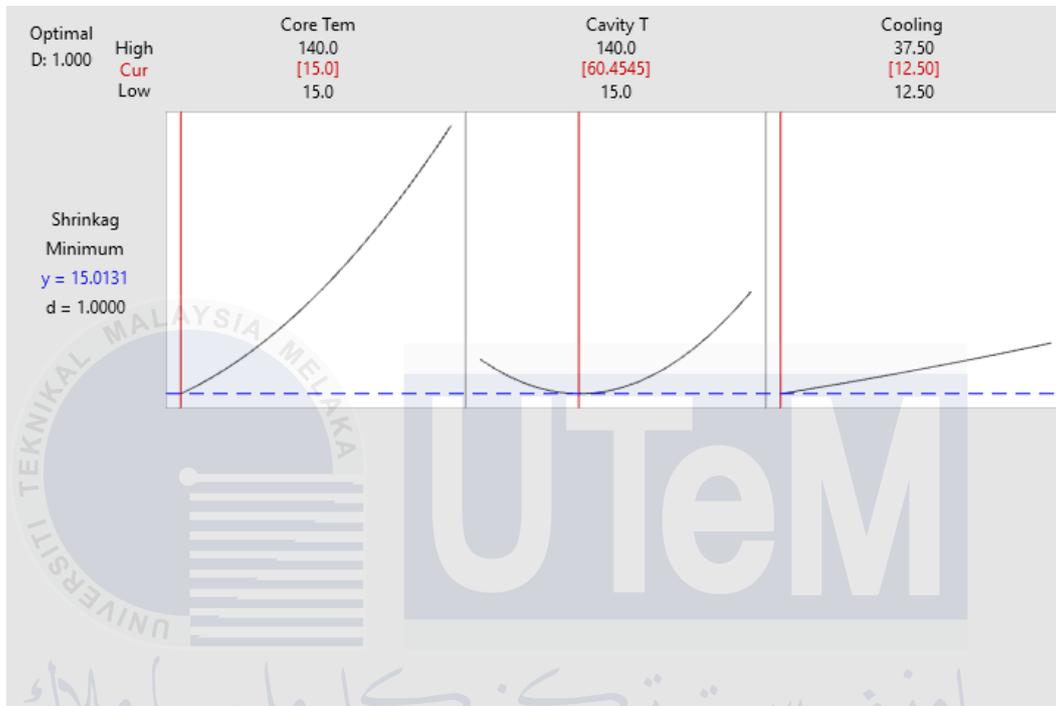
Figure 4.14: Optimization Plot for volumetric shrinkage.

4.4   Mechanical Properties Responses

The mechanical property results presented in Table 4.9 highlight the critical role of thermal conditions in balancing strength, stiffness, and ductility in HDPE injection moulding. The maximum UTS of 21.52 MPa was obtained at high core and cavity temperatures (140 °C), reflecting enhanced crystallinity and molecular packing. Similarly, Young's modulus reached its highest value of 7.44 GPa under high core temperature with short cooling, confirming that elevated mould temperatures improve stiffness. However, these conditions significantly reduced ductility, with elongation dropping to 91.79%, as more crystalline structures restrict chain mobility. Conversely, low-temperature moulding (15 °C) produced the highest elongation of 299.31%, but at the expense of lower UTS and modulus due to limited crystallization. The center-point runs demonstrated more balanced mechanical properties, with moderate strength, stiffness, and elongation values, indicating that mid-range thermal conditions provide stable and reliable outcomes. These findings demonstrate the inherent trade-

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off between stiffness and ductility in semi-crystalline polymers and emphasize the importance of optimizing mould temperatures and cooling conditions to achieve the desired balance of mechanical performance in injection-moulded HDPE.

Table 4.9: Experimental result of mechanical properties

Run no.	Core temperature (ºC)	Cavity temperature. (ºC)	Cooling time (s)	Ultimate tensile strength (UTS)	Young's modulus,	Percentage elongation
1	15	15	25	19.52	4.95	299.31
2	140	15	25	20.97	6.06	115.96
3	15	140	25	20.33	5.38	124.04
4	140	140	25	21.52	5.61	91.79
5	15	77.5	12.5	19.74	4.91	113.19
6	140	77.5	12.5	21.3	7.44	102.37
7	15	77.5	37.5	19.82	4.93	121.16
8	140	77.5	37.5	20.88	5.6	108.59
9	77.5	15	12.5	21.03	5.41	101.83
10	77.5	140	12.5	21.33	5.76	94.88
11	77.5	15	37.5	20.94	5.56	96.77
12	77.5	140	37.5	21.4	5.37	92.13
13	77.5	77.5	25	20.55	5.09	93.76
14	77.5	77.5	25	20.58	5.09	107.27
15	77.5	77.5	25	20.75	5.12	105.88
16	77.5	77.5	25	20.81	5.31	92.16
17	77.5	77.5	25	20.81	5.27	93.33

Figure 4.15 until 4.17 show the influence of core temperature, cavity temperature and cooling time towards ultimate tensile strength (UTS)**,** Young's modulus, and percentage elongation.
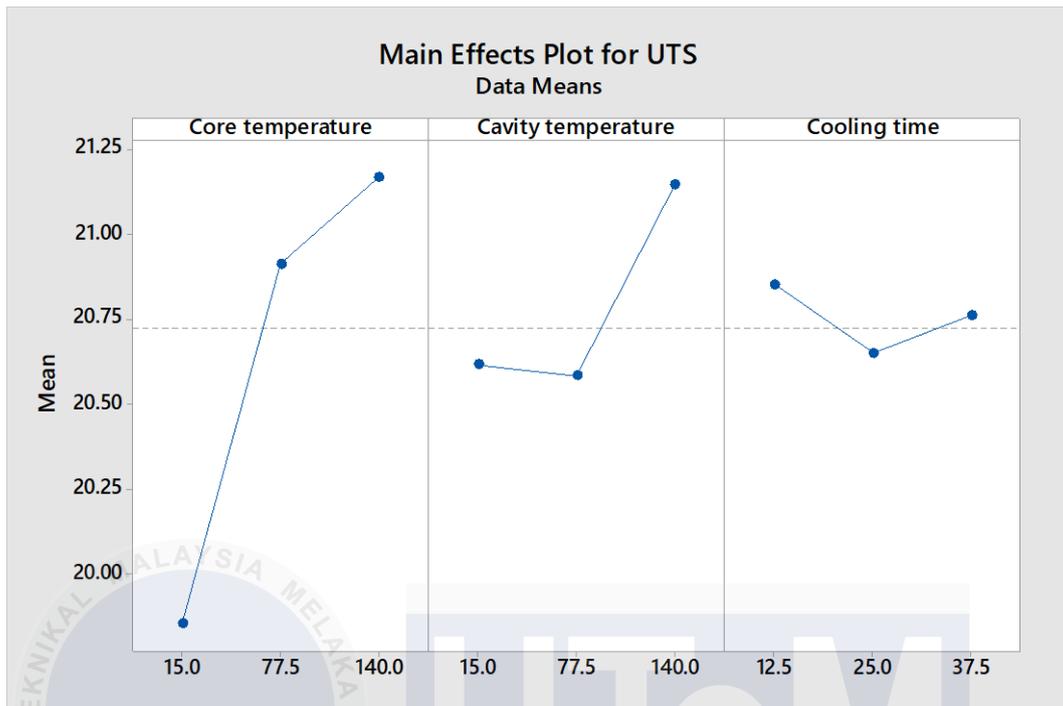
Figure 4.15: Main effect plot for UTS
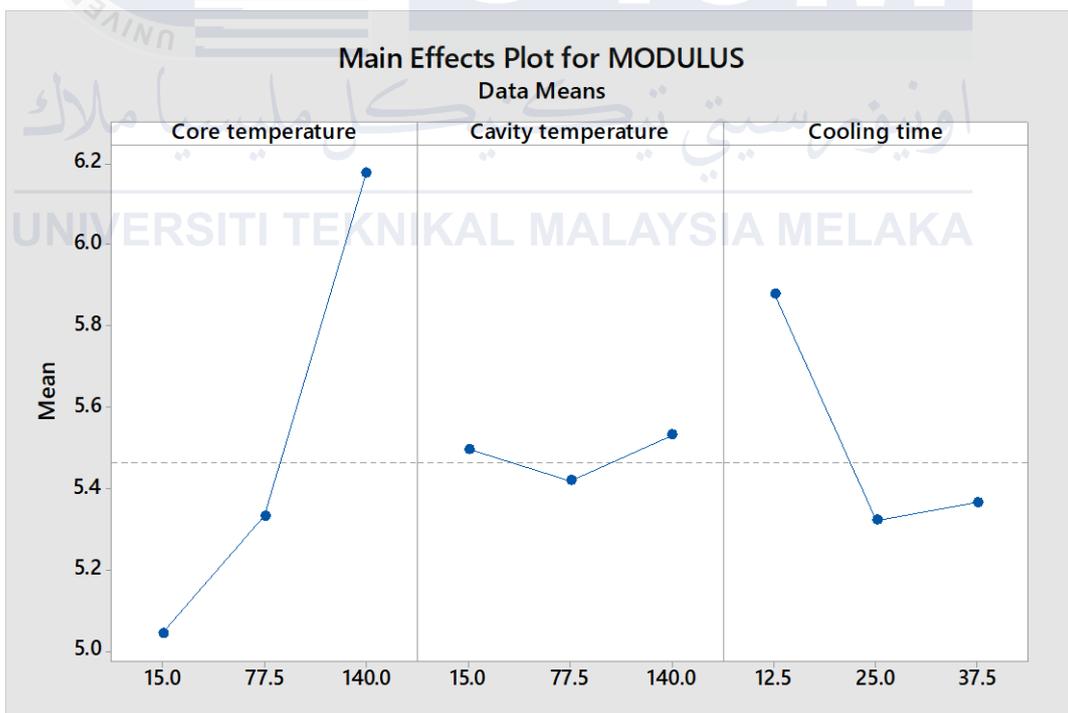
Figure 4.16: Main effect plot for Young's modulus
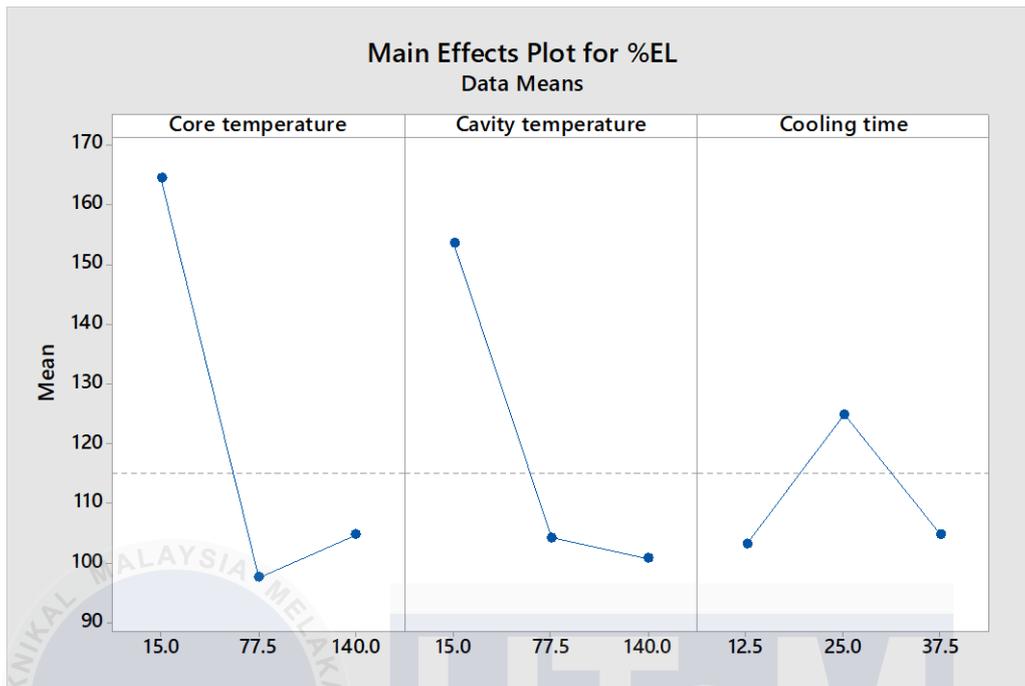
Figure 4.17: Main effect plot for % EL

4.4.1 Influence of Core Temperature

The results of this study demonstrate that core temperature has the most significant influence on the mechanical properties of injection-moulded plastic parts, namely UTS, Young's modulus, and percentage elongation. This is consistent with previous research that highlights the core region as critical to controlling internal solidification and crystallization behaviour Eixeres, et al. (2025), Core temperature directly affects the cooling and solidification of the internal structure of the polymer melt. Variations in core temperature lead to differences in molecular orientation, crystallinity, and residual stress, which together determine the part's mechanical strength, stiffness, and ductility. In this study, changes in core temperature resulted in substantial variations across all three mechanical responses, confirming its dominant role. These findings align with the conclusions of Chai et al. (2024), who noted that core-side thermal conditions strongly influence internal structure development and mechanical integrity.

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4.4.2 Influence of Cavity Temperature

Cavity temperature was also found to influence the mechanical properties, although its impact was less pronounced compared to core temperature. It showed a moderate effect on UTS and percentage elongation, largely because of its role in shaping the outer skin layer of the part during solidification. However, its influence on Young's modulus was minimal, as this property is primarily governed by the internal crystalline structure controlled by the core temperature. These findings align with Qi (2025), who reported that cavity-side thermal control can improve surface quality and slightly enhance ductility, but has limited effect on internal stiffness.

4.4.3 Influence of Cooling Time

Cooling time demonstrated a more significant influence on Young's modulus, but comparatively less impact on UTS and elongation. This indicates that longer cooling durations promote more uniform heat dissipation and stress relaxation, which enhances stiffness. However, since UTS and elongation are more sensitive to the initial cooling rate and thermal gradients established at the early stage of solidification, the overall duration of cooling alone does not dominate their optimization. Similar trends were observed in earlier studies, where Zengeya et al. (2023) and Hu et al. (2022) reported that extended cooling improves dimensional stability but contributes less to tensile strength and ductility.

Taken together, these results reinforce that core temperature remains the most critical factor for improving overall mechanical performance in injection-moulded HDPE parts. Cavity temperature and cooling time also influence specific properties, but their effects are secondary.

4.5 Response of Ultimate Tensile Strength (UTS)

Ultimate Tensile Strength (UTS), shown in Figure 4.18, represents a critical mechanical response in injection moulding, as it directly reflects the load-bearing capacity and overall reliability of the finished part. Achieving a satisfactory UTS is therefore essential to ensuring product quality. In this study, the cooling system variables core temperature, cavity temperature, and cooling time were carefully evaluated to determine their influence on UTS. These parameters govern the thermal history of HDPE during solidification, which in turn affects molecular orientation, crystallinity, and stress distribution within the moulded part. By applying a single-objective Response Surface Methodology (RSM) approach, the analysis

identified the most significant factors contributing to UTS, providing a systematic framework for parameter optimization.

Figure 4.18: The broken specimens were tested for mechanical property responses using a Universal Testing Machine

4.5.1 Analysis of Variance (ANOVA) for Ultimate Tensile Strength (UTS) Response

Table 4.10 presents the Analysis of Variance (ANOVA) results for the quadratic model of the Ultimate Tensile Strength (UTS) response. The model was found to be highly significant, with a P-value of 0.000, well below the 0.050 threshold. Among the parameters evaluated, core temperature emerged as the most influential factor, as indicated by its highest F-value (199.33) and lowest P-value (0.000). This confirms that variations in core temperature play a dominant role in determining UTS in HDPE injection-moulded parts.

In contrast, cavity temperature and cooling time were not statistically significant contributors, since their P-values exceeded 0.050. This suggests that while these factors may affect other properties such as warpage or shrinkage, their direct influence on tensile strength is limited. The analysis also highlighted the importance of non-linear effects. The square term of core temperature was found to be highly significant, with an F-value of 44.35 and a P-value of 0.000, making it the most influential among the quadratic terms. This result indicates that the relationship between core temperature and UTS is not simply linear, but involves curvature—meaning that both excessively low and excessively high values of core temperature can reduce UTS. Overall, these findings reinforce the conclusion that core temperature control is critical for enhancing the mechanical strength of HDPE parts, validating the DOE and RSM approach as a powerful tool for identifying optimal process settings.

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Table 4.10: ANOVA of the Full Quadratic Model for Ultimate Tensile Strength (UTS).

Source	DF	Adj SS	Adj MS	F-Value	P-Value	
Model	9	5.35006	0.59445	34.26	0.000	Significant
Linear	3	4.03645	1.34548	77.55	0.000	
Core Temperature	1	3.45845	3.45845	199.33	0.000	Significant
Cavity Temperature	1	0.5618	0.5618	32.38	0.001	
Cooling Time	1	0.0162	0.0162	0.93	0.366	
Square	3	1.22781	0.40927	23.59	0.000	
Core Temperature*Core Temperature	1	0.7695	0.7695	44.35	0.000	Significant
Cavity Temperature*Cavity Temperature	1	0.41118	0.41118	23.7	0.002	
Cooling Time*Cooling Time	1	0.11118	0.11118	6.41	0.039	
2-Way Interaction	3	0.0858	0.0286	1.65	0.263	
Core Temperature*Cavity Temperature	1	0.0169	0.0169	0.97	0.357	
Core Temperature*Cooling Time	1	0.0625	0.0625	3.6	0.100	
Cavity Temperature*Cooling Time	1	0.0064	0.0064	0.37	0.563	
Error	7	0.12145	0.01735			
Lack-of-Fit	3	0.05785	0.01928	1.21	0.413	
Pure Error	4	0.0636	0.0159			
Total	16	5.47151				

The half-normal plot shown in Figure 4.19 indicates the interaction of significant parameters to the Ultimate Tensile Strength (UTS) response. When the factor plot is distant from the standardized line, it indicates that the factor is significant in this analysis model. Based on the results, the Core Temperature is the most important factor over the absolute standardized effect with 92.5%. Meanwhile, the Cavity Temperature factor is also over the absolute standardized effect with 71.5%. For the square interactions, the interactions of Core temperature, Cavity Temperature, and Cooling Time are significant as they are plotted over the absolute standardized effect with 81.5%, 61%, and 50%.

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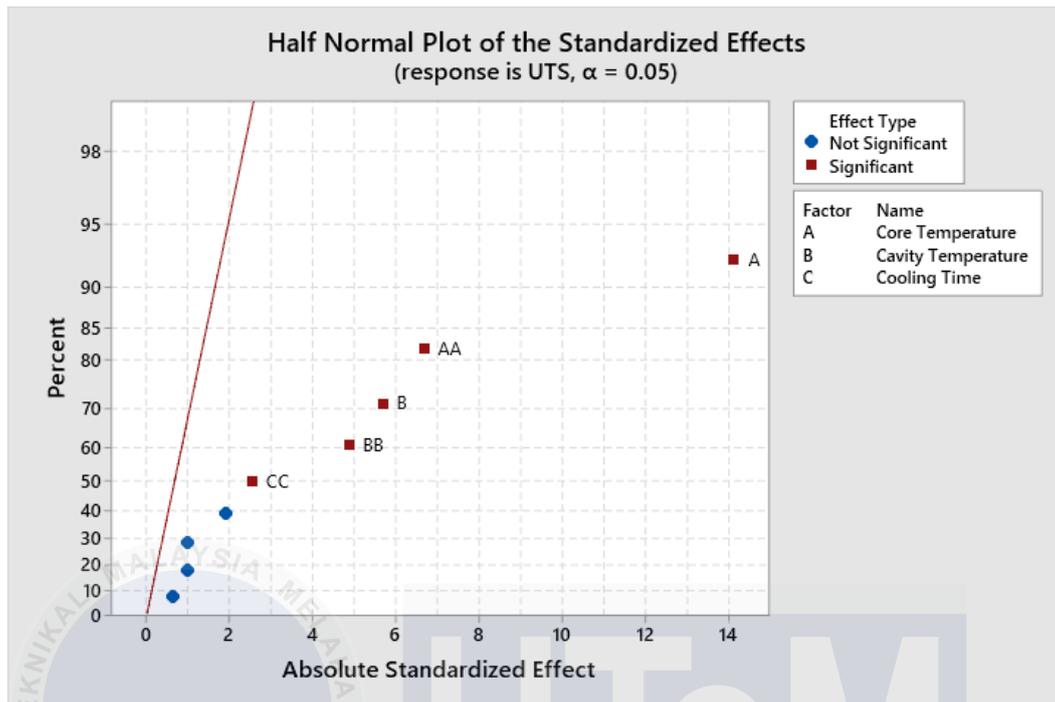
Figure 4.19: Half Normal Plot of the Standardize Effect for Ultimate Tensile Strength (UTS) response

The surface plot of Ultimate Tensile Strength (UTS) shown in Figure 4.20 illustrates the interaction between core temperature and cooling time in influencing the UTS response. The results indicate that UTS decreases when both core temperature and cooling time are set at higher values. In contrast, lower core temperature combined with shorter cooling times contributes to improved tensile strength. Similarly, the contour plot in Figure 4.21 further highlights this interaction. It clearly shows that increasing both core temperature and cooling time leads to a reduction in UTS, reinforcing the conclusion that excessive thermal exposure negatively impacts the load-bearing capacity of HDPE parts.

These findings suggest that careful control of core temperature and cooling duration is essential to maximize tensile strength. In particular, maintaining lower core temperatures while avoiding unnecessarily long cooling cycles supports the development of a stronger internal structure, with reduced risk of over-crystallization or residual stress. This observation validates the DOE and RSM approach, which effectively captures the parameter interactions and helps identify the optimal balance for enhancing UTS in injection-moulded HDPE components.
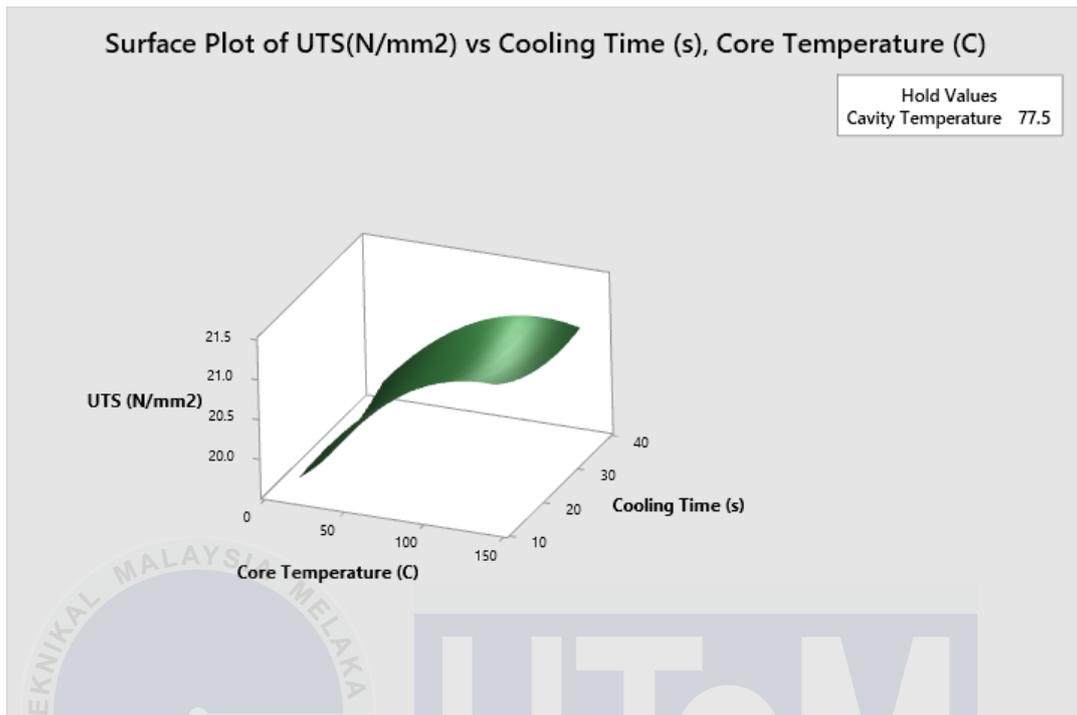
Figure 4.20: The Surface Plot of Ultimate Tensile Strength (UTS) Response based on core temperature and cooling time factors.
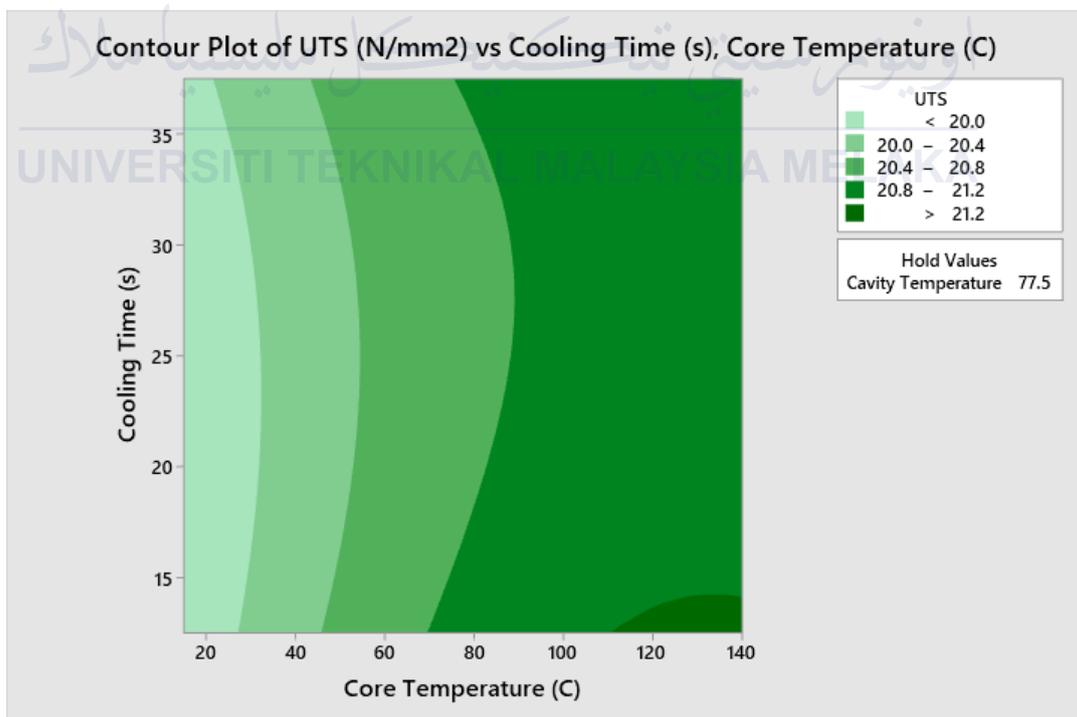
Figure 4.21: The Contour Plot of Ultimate Tensile Strength (UTS) response based on core temperature and cooling time factors.

4.5.2 Mathematical Model for Ultimate Tensile Strength (UTS) Response

The mathematical model was developed to describe the relationship between process parameters and the UTS response. By substituting the values of core temperature, cavity temperature, and cooling time into the model, the expected Ultimate Tensile Strength (UTS) can be predicted. The regression coefficients were estimated for each parameter, allowing the formulation of a predictive equation. Accordingly, the final regression model for estimating UTS is expressed in uncoded factors, as shown in the equation below.

$$
\begin{aligned}
\text{UTS} = {} & 19.809 + 0.03277 \text{ Core Temperature} \\
& - 0.00815 \text{ Cavity Temperature} - 0.0472 \text{ Cooling Time} \\
& - 0.000109 \text{ Core Temperature*Core Temperature} \\
& + 0.000080 \text{ Cavity Temperature*Cavity Temperature} \\
& + 0.001040 \text{ Cooling Time*Cooling Time} \\
& - 0.000017 \text{ Core Temperature*Cavity Temperature} \\
& - 0.000160 \text{ Core Temperature*Cooling Time} \\
& + 0.000051 \text{ Cavity Temperature*Cooling Time}
\end{aligned}
$$

Table 4.11: Comparison between Experimental Ultimate Tensile Strength (UTS) and Mathematical Ultimate Tensile Strength (UTS).

Run No.	Experimental UTS	Mathematical UTS	Error (%)
1	19.52	19.5971	-0.3949
2	20.97	22.9571	-9.4758
3	20.33	20.0515	1.3701
4	21.52	21.4427	0.3592
5	19.74	19.5949	0.7353
6	21.3	21.8267	2.4728
7	19.82	19.7537	0.3347
8	20.88	21.8793	-4.7859
9	21.03	21.5250	-2.3538
10	21.33	20.9153	1.9441
11	20.94	21.3541	-1.9777
12	21.4	20.9038	2.3186
13	20.55	20.6996	-0.7279
14	20.58	20.6996	-0.5810
15	20.75	20.6996	0.2430
16	20.81	20.6996	0.5306
17	20.81	20.6996	0.5306

The mathematical values of Ultimate Tensile Strength (UTS), calculated using the regression equation in uncoded units, are presented in Table 4.11. These values were compared with the experimental UTS results by computing the percentage error. In most runs, the calculated error was negative, reflecting that the predicted UTS values were higher than those obtained experimentally. To identify the extreme cases, the absolute error values were considered.

According to Table 4.11, run 2 recorded the highest error percentage at approximately 9.48%, while run 15 showed the lowest error at 0.24%. Figure 4.22 provides a graphical comparison of experimental and predicted UTS values, based on the data from Table 4.11. Overall, the average error between experimental and mathematical UTS was approximately 0.85%, indicating that the regression model provides a reliable prediction of UTS in HDPE parts under varying cooling conditions.
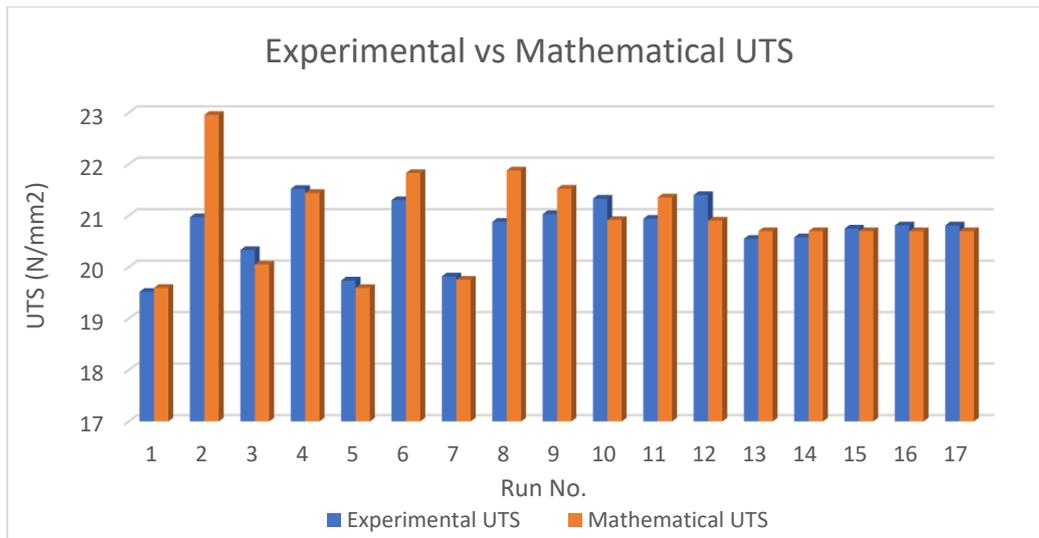
Figure 4.22: Histogram of Experimental versus Mathematical Ultimate Tensile Strength (UTS).

4.5.3 Single Objective Optimization of Ultimate Tensile Strength (UTS)

Response surface optimization proved to be a highly effective tool for determining the optimal injection moulding parameters to maximize Ultimate Tensile Strength (UTS). The objective of this analysis was to identify the parameter settings that yield the best tensile performance in HDPE parts. The optimal combination was found at a core temperature of 129.9 °C, a cavity temperature of 140 °C, and a cooling time of 12.5 s. At these settings, the model achieved a composite desirability of 1.000, with a predicted UTS of 21.75 N/mm².

In comparison, the lowest UTS value recorded during experimentation was 19.52 N/mm². This corresponds to an improvement of approximately 11.4%, confirming that optimization of the cooling system variables can significantly enhance mechanical strength. The single-response optimization plot for UTS is shown in Figure 4.23, illustrating the desirability profile and the predicted improvement.

These findings highlight the strong influence of thermal control—particularly core and cavity temperature—on tensile performance, and they validate the use of the DOE–RSM framework as a reliable approach for process optimization in HDPE injection moulding.

UTS improvement:

$$\left(\frac{19.52-(21.7461)}{19.52}\right) x\ 100 = 11.4\%$$

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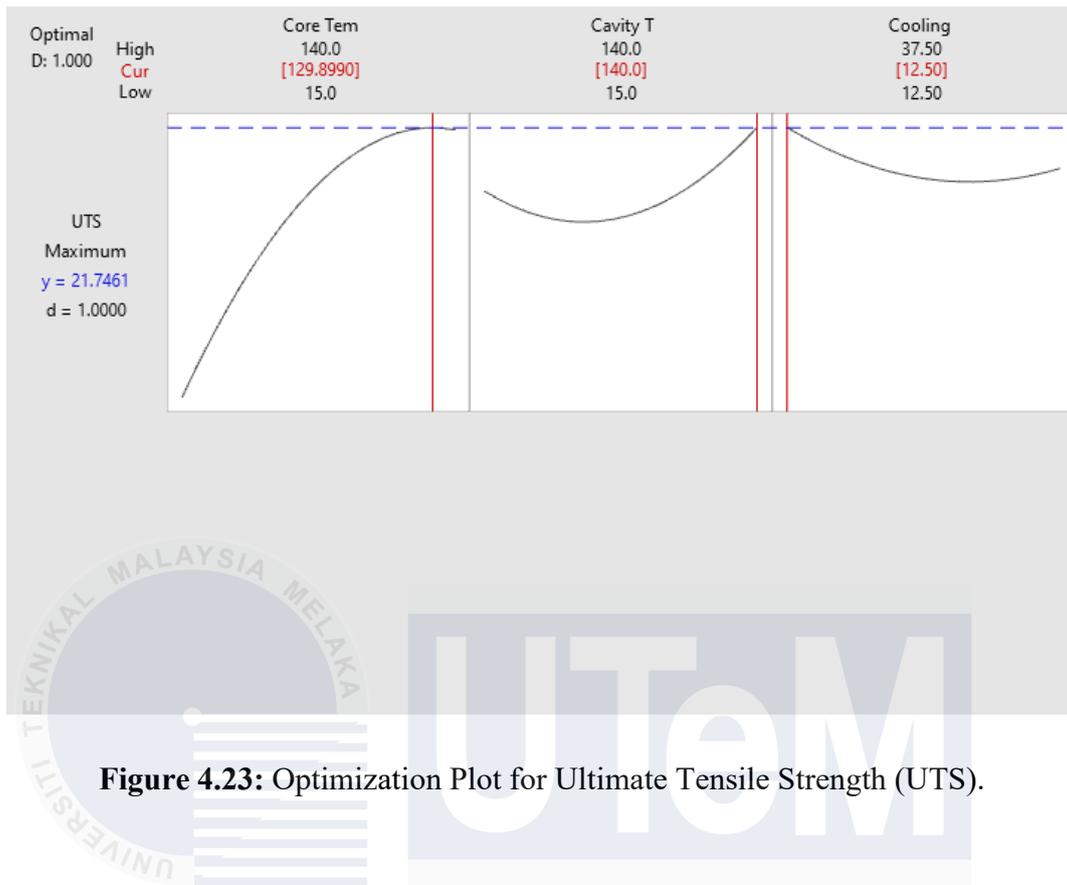
Figure 4.23: Optimization Plot for Ultimate Tensile Strength (UTS).

4.6 Response of Young's Modulus

Young's Modulus is another critical mechanical property in injection moulding, as it reflects the stiffness of the finished product and its ability to resist deformation under applied load. Achieving an optimal modulus is essential for ensuring structural reliability and functional performance in HDPE parts.

In this study, the cooling system variables core temperature, cavity temperature, and cooling time were systematically evaluated to determine their influence on Young's Modulus. These parameters directly affect the thermal history and solidification rate of the polymer, which in turn governs crystallinity and internal stress distribution. A single-objective Response Surface Methodology (RSM) approach was applied to identify the most significant factors influencing this response, providing a structured pathway to optimize stiffness while maintaining overall product quality.

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4.6.1 Analysis of Variance (ANOVA) for Young's Modulus Response

Table 4.12 presents the Analysis of Variance (ANOVA) results for the quadratic model of Young's Modulus. The model was found to be statistically significant, with a P-value of 0.000, which is well below the threshold of 0.050. Among the parameters studied, core temperature was identified as the most influential factor, reflected in its highest F-value (22.74) and lowest P-value (0.025). This confirms that variations in core temperature play a dominant role in determining stiffness in HDPE injection-moulded parts.

In contrast, cavity temperature and cooling time were not statistically significant, as their P-values exceeded 0.050. However, the analysis revealed a significant two-way interaction between core temperature and cooling time, with an F-value of 7.63 and a P-value of 0.028, making it the strongest interaction effect in the model. This finding suggests that while cooling time alone does not significantly affect modulus, its combination with core temperature has a notable influence on stiffness development.

Overall, these results highlight that core temperature control, along with its interaction with cooling time, is critical to optimizing Young's Modulus in HDPE parts. This supports the broader conclusion of the study that internal thermal control (core side) plays a more decisive role than cavity-side adjustments in enhancing mechanical performance.

Table 4.12: ANOVA of the Full Quadratic Model for Young's Modulus.

Source	DF	Adj SS	Adj MS	F-Value	P-Value	
Model	9	4.93764	0.54863	4.84	0.025	Significant
Linear	3	3.10935	1.03645	9.15	0.008	
Core Temperature	1	2.57645	2.57645	22.74	0.002	Significant
Cavity Temperature	1	0.00245	0.00245	0.02	0.887	
Cooling Time	1	0.53045	0.53045	4.68	0.067	
Square	3	0.69689	0.2323	2.05	0.196	
Core Temperature*Core Temperature	1	0.28354	0.28354	2.5	0.158	
Cavity Temperature*Cavity Temperature	1	0.01752	0.01752	0.15	0.706	
Cooling Time*Cooling Time	1	0.3408	0.3408	3.01	0.126	
2-Way Interaction	3	1.1314	0.37713	3.33	0.086	
Core Temperature*Cavity Temperature	1	0.1936	0.1936	1.71	0.232	
Core Temperature*Cooling Time	1	0.8649	0.8649	7.63	0.028	Significant
Cavity Temperature*Cooling Time	1	0.0729	0.0729	0.64	0.449	
Error	7	0.79327	0.11332			
Lack-of-Fit	3	0.74855	0.24952	22.32	0.006	
Pure Error	4	0.04472	0.01118			
Total	16	5.73091				

The half-normal plot in Figure 4.24 illustrates the significance of parameters influencing the Young's Modulus response. In this type of plot, factors that deviate furthest from the standardized line are considered the most significant contributors. The results confirm that core temperature is the dominant factor, exceeding the absolute standardized effect at 92%. This reinforces earlier ANOVA findings that core-side thermal control plays the most critical role in determining stiffness.

In addition, the analysis identified a significant interaction effect between core temperature and cooling time, which exceeded the standardized effect at 82%. This interaction highlights that while cooling time alone is not a strong predictor of modulus, its combination with core temperature substantially influences stiffness development. In practical terms, this means that the cooling duration can either enhance or weaken the effect of core temperature, depending on the balance of settings.

Together, these results emphasize that Young's Modulus in HDPE parts is primarily governed by core-side temperature control, with secondary but meaningful influence from its interaction with cooling time. This insight further supports the DOE–RSM framework as an effective approach for uncovering both main and interaction effects in mechanical property optimization.
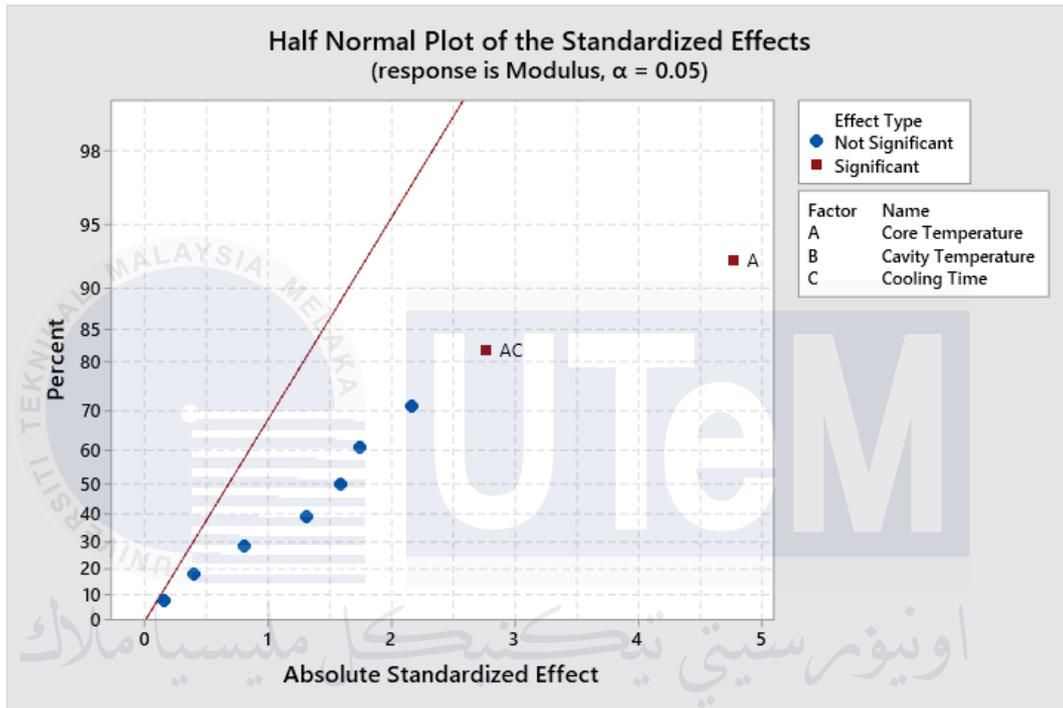
Figure 4.24: Half Normal Plot of the Standardize Effect for Young's Modulus response.

The surface plot of Young's Modulus shown in Figure 4.25 illustrates the interaction between core temperature and cooling time. The results indicate that Young's Modulus increases significantly when the core temperature is high (around 140 °C) and the cooling time is kept relatively short. This suggests that a higher core-side temperature promotes better molecular packing and stiffness development, while prolonged cooling can diminish this effect due to relaxation of internal stresses.

Similarly, the contour plot in Figure 4.26 reinforces this trend, showing a clear rise in Young's Modulus with increasing core temperature, particularly when cooling time remains at lower levels. Together, these plots highlight that the combination of high core temperature and short cooling duration is most favorable for enhancing stiffness in HDPE parts.

Therefore, optimization of Young's Modulus requires careful adjustment of both parameters, with core temperature acting as the dominant factor and cooling time playing a modifying role. This observation is consistent with the DOE–RSM framework applied in this study, which effectively reveals how parameter interactions influence mechanical performance in injection-moulded components.
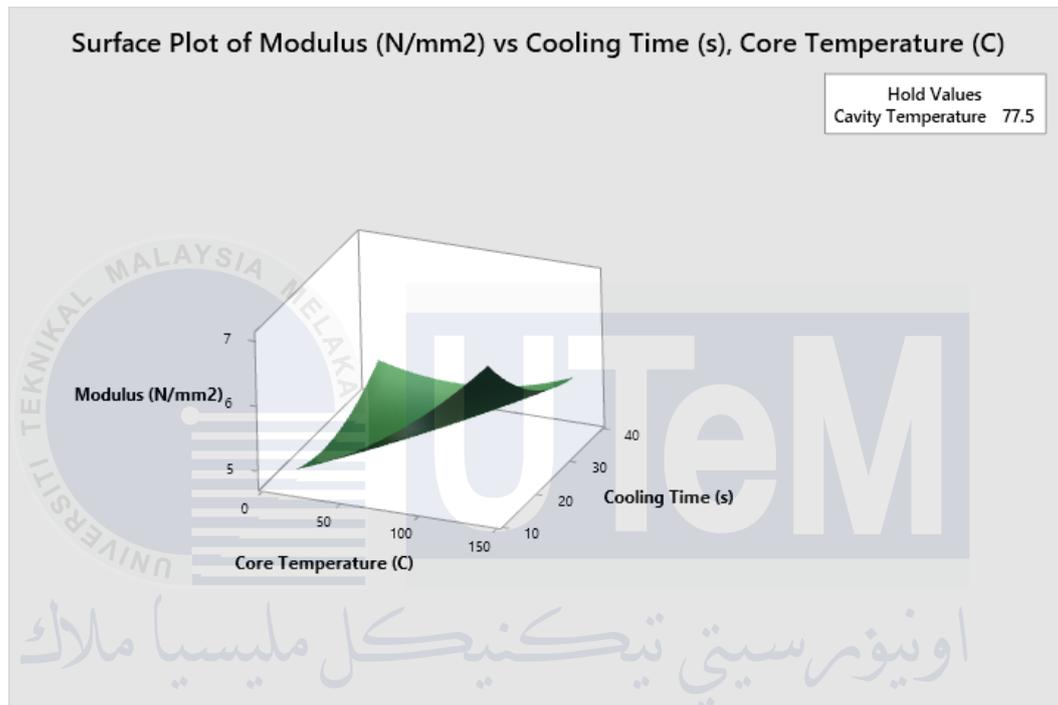
Figure 4.25: The Surface Plot of Young's Modulus response based on core temperature and cooling time factors.
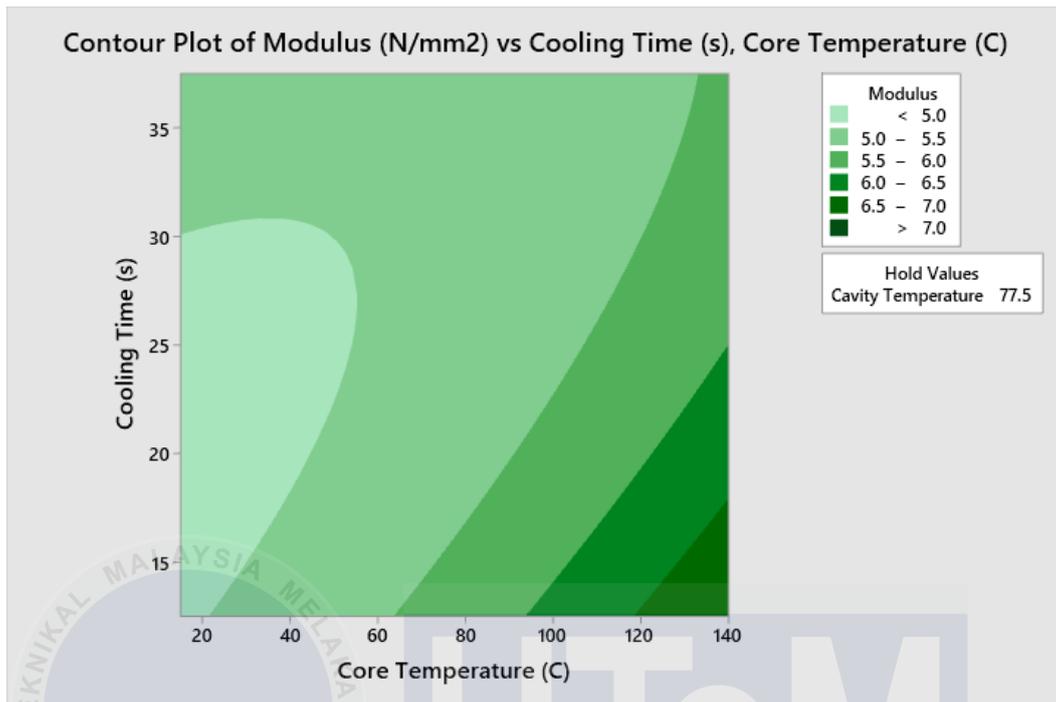
Figure 4.26: The Contour Plot of Young's Modulus response based on core temperature and cooling time factors.

4.6.2   Mathematical Model for Young's Modulus Response

The mathematical model was developed to describe the relationship between the process parameters and the Young's Modulus response. By substituting the values of core temperature, cavity temperature, and cooling time into the model, the expected Young's Modulus can be predicted. The regression coefficients were estimated for each parameter, allowing the model to quantify their individual and interactive effects. Consequently, the final mathematical model for predicting Young's Modulus is expressed in uncoded factors, as presented in the equation below..

Modulus   = 4.776 + 0.01803 Core Temperature

           + 0.00641 Cavity Temperature - 0.0521 Cooling Time

           + 0.000066 Core Temperature*Core Temperature

           + 0.000017 Cavity Temperature*Cavity Temperature

           + 0.00182 Cooling Time*Cooling Time

           - 0.000056 Core Temperature*Cavity Temperature

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- 0.000595 Core Temperature*Cooling Time

- 0.000173 Cavity Temperature*Cooling Time

Table 4.13: Comparison between Experimental Young's Modulus and Mathematical Young's Modulus

Run No.	Experimental Modulus	Mathematical Modulus	Error (%)
1	4.95	4.6957	5.1379
2	6.06	6.2638	-3.3630
3	5.38	5.1807	3.7049
4	5.61	5.8738	-4.7023
5	4.91	4.9491	-0.7953
6	7.44	7.3824	0.7742
7	4.93	5.3632	-8.7878
8	5.6	5.5642	0.6397
9	5.41	5.6289	-4.0461
10	5.76	5.9467	-3.2414
11	5.56	5.3837	3.1708
12	5.37	5.1609	3.8940
13	5.09	5.1793	-1.7538
14	5.09	5.1793	-1.7538
15	5.12	5.1793	-1.1576
16	5.31	5.1793	2.4620
17	5.27	5.1793	1.7217

The Young's Modulus values were calculated using the regression equation in uncoded units and are presented in Table 4.13. These predicted values were then compared with the experimental results by computing the error between them. In most cases, the error values were negative, as the predicted Young's Modulus was slightly higher than the experimental values. To determine the highest and lowest error magnitudes, the negative signs were disregarded. As shown in Table 4.13, run 7 exhibited the highest error percentage, approximately 8.79%, while run 8 showed the lowest error percentage, approximately 0.64%. Figure 4.27 illustrates the comparison between experimental and predicted Young's Modulus values, based on the data in Table 4.13. Overall, the average error between the experimental and predicted Young's

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Modulus was found to be approximately 0.48%, demonstrating that the developed regression model provides a reliable prediction of Young's Modulus response.
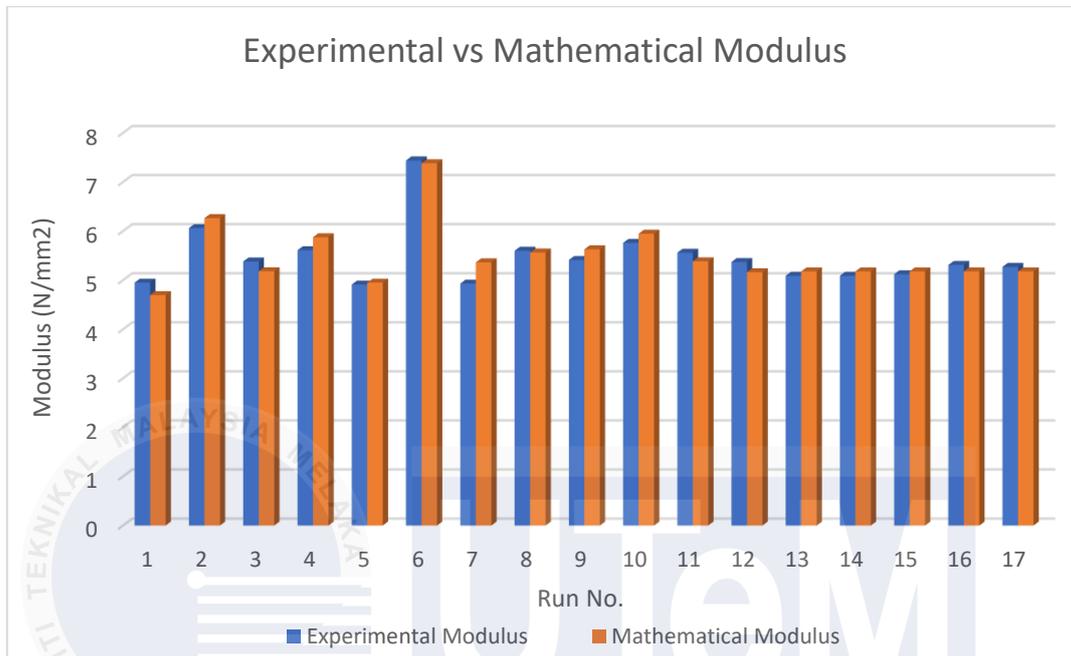
Figure 4.27: Histogram of Experimental versus Mathematical Young's Modulus.

4.6.3 Single Objective Optimization of Young's Modulus

Response surface optimization proved to be a highly effective method for determining the optimal injection moulding parameters influencing Young's Modulus. The goal of this optimization was to identify parameter settings that yield the most favorable stiffness characteristics in HDPE parts. The analysis determined that the optimal conditions are a core temperature of 15 °C, a cavity temperature of 15 °C, and a cooling time of 17.55 s. Under these conditions, the model predicted a Young's Modulus of 4.5919 N/mm². By comparison, the lowest recorded Young's Modulus was 4.91 N/mm². Based on these results, the percentage of improvement in stiffness is approximately 6.48%.

This outcome highlights the critical role of low thermal settings combined with extended cooling in enhancing the stiffness of HDPE moulded parts. Such control not only improves Young's Modulus but also aligns with the overall goal of reducing dimensional variability and warpage, reinforcing the importance of thermal and cooling balance in injection moulding optimization.

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Young's Modulus improvement:

$$\left(\frac{4.91 - (4.5919)}{4.91}\right) x\ 100 = 6.48\%$$
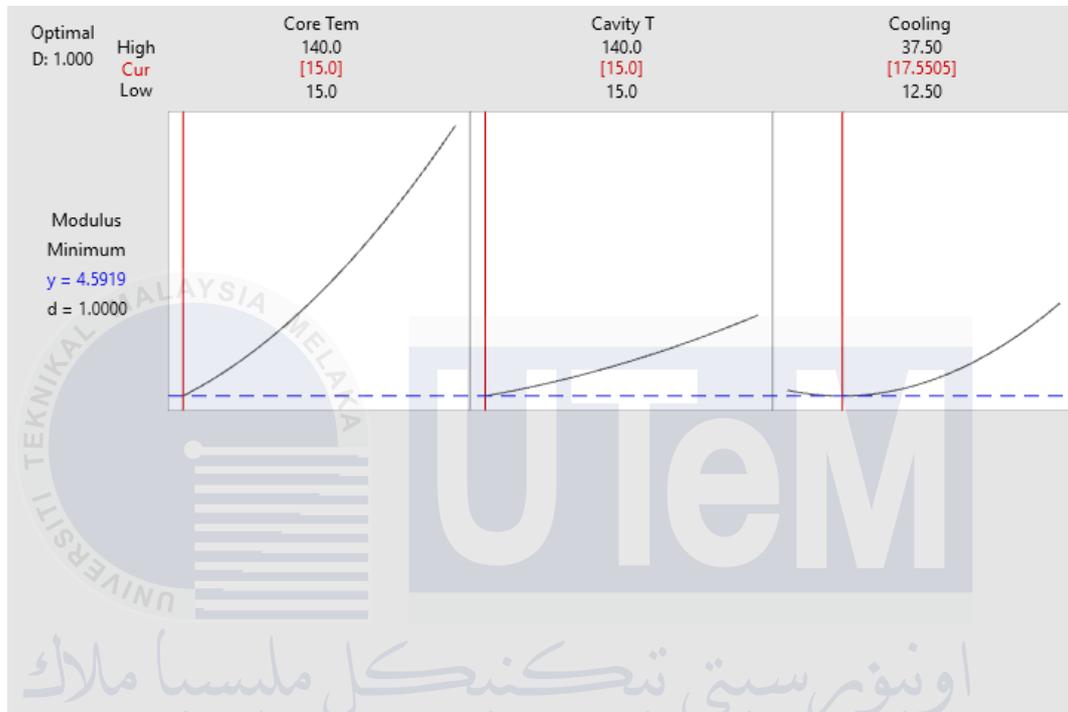
Figure 4.28: Optimization Plot for Young's Modulus

4.7   Response of % Elongation

Percentage elongation (% Elongation) is another key mechanical property to consider in the injection moulding process, as it reflects the ductility and flexibility of the finished part. Achieving an optimal % Elongation is critical for ensuring that HDPE products can withstand deformation without premature failure. In this study, the influence of cooling system variables—core temperature, cavity temperature, and cooling time—was evaluated to identify their contribution to % Elongation. Using the Response Surface Methodology (RSM) under a single-objective framework, the analysis focused on determining the most significant parameters affecting % Elongation, thereby providing a basis for fine-tuning moulding conditions to achieve balanced strength and ductility.

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4.7.1 Analysis of Variance (ANOVA) for % Elongation

Table 4.14 presents the Analysis of Variance (ANOVA) results for the quadratic model assessing the % Elongation response. The results indicate that the model is not statistically significant, as the overall P-value is 0.132, which exceeds the threshold of 0.050. This finding suggests that within the range of process parameters investigated core temperature, cavity temperature, and cooling time, none of the factors or their interactions exerted a sufficiently strong influence to significantly affect % Elongation. Consequently, % Elongation appears to be less sensitive to variations in the thermal and cooling conditions compared to other mechanical properties such as UTS or Young's Modulus.

Table 4.14: ANOVA of the Full Quadratic Model for % Elongation.

Source	DF	Adj SS	Adj MS	F-Value	P-Value	
Model	9	28542	3171.33	2.38	0.132	**Not Significant**
Linear	3	12711.3	4237.11	3.19	0.094	
Core Temperature	1	7139.5	7139.53	5.37	0.054	
Cavity Temperature	1	5566.7	5566.71	4.19	0.080	
Cooling Time	1	5.1	5.09	0	0.952	
Square	3	10120.8	3373.58	2.54	0.140	
Core Temperature*Core Temperature	1	5798.5	5798.54	4.36	0.075	
Cavity Temperature*Cavity Temperature	1	2072.3	2072.31	1.56	0.252	
Cooling Time*Cooling Time	1	2478.6	2478.61	1.86	0.214	
2-Way Interaction	3	5709.9	1903.3	1.43	0.313	
Core Temperature*Cavity Temperature	1	5707.8	5707.8	4.29	0.077	
Core Temperature*Cooling Time	1	0.8	0.77	0	0.982	
Cavity Temperature*Cooling Time	1	1.3	1.33	0	0.976	
Error	7	9310.3	1330.04			
Lack-of-Fit	3	9089.5	3029.85	54.9	0.001	
Pure Error	4	220.8	55.19			
Total	16	37852.3				

The Pareto chart illustrating the standardized effects of the quadratic model for the % Elongation response is presented in Figure 4.29. This response accounts for the factors Core Temperature (A), Cavity Temperature (B), and Cooling Time (C). According to the Pareto chart, all model terms—including B, C, BB, CC, AC, BC, and AB—fall well below the standardized effect threshold of 2.365. This confirms that the quadratic model for % Elongation is not statistically significant, as none of the parameters or their interactions demonstrate a meaningful contribution to the response. Therefore, it is necessary to remove these insignificant terms in order to simplify and improve the predictive reliability of the % Elongation model.
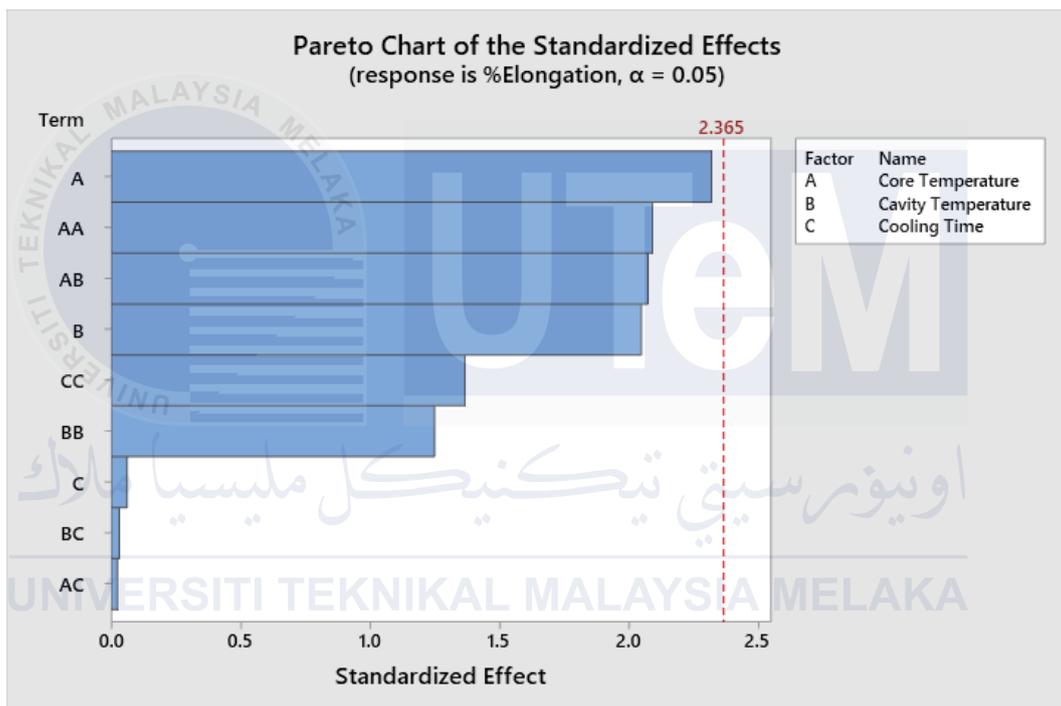
Figure 4.29: Pareto Chart of the Standardized Effects of the residual quadratic model for % Elongation

The half-normal plot shown in Figure 4.30 illustrates the distribution of factors in relation to their significance for the % Elongation response. In this type of plot, factors positioned further away from the standardized line are considered significant contributors, whereas factors clustered near the line are deemed insignificant. In this case, all terms are plotted close to the standardized line, indicating that none of the parameters or their interactions are significant for the quadratic model. This outcome further supports the ANOVA and Pareto chart findings, confirming that % Elongation is minimally influenced by variations in core temperature, cavity temperature, and cooling time within the experimental range.

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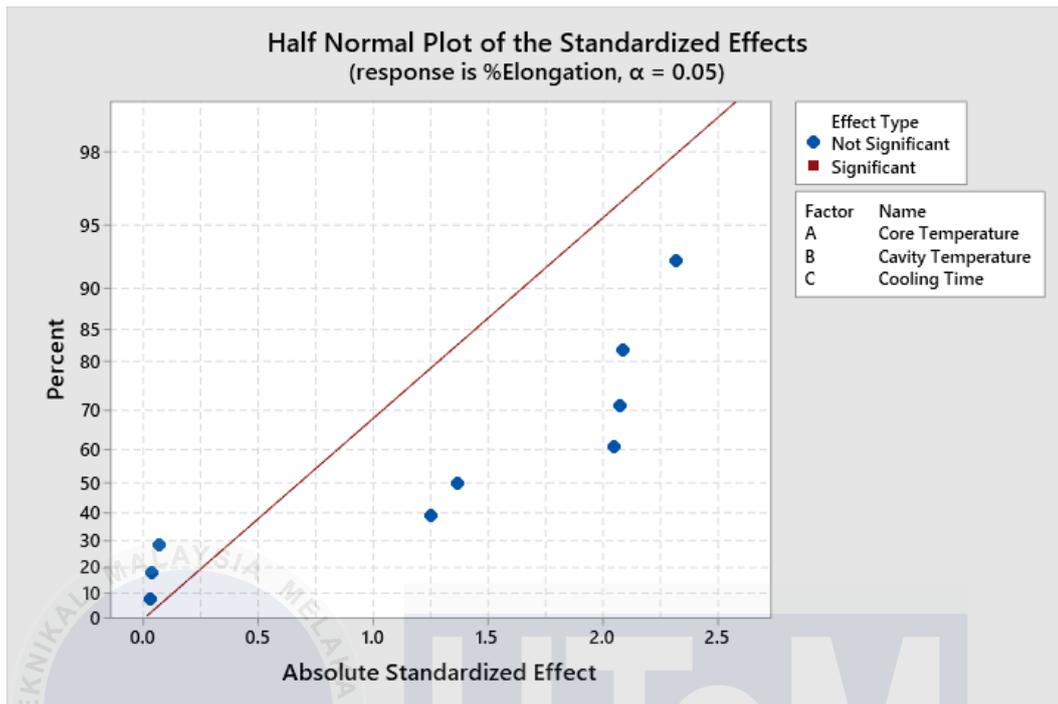
Figure 4.30: Half normal plot of the Standardized Effects of the residual quadratic model for % Elongation

To improve the % Elongation model, the insignificant interaction terms AC and BC were eliminated from the analysis. Following this refinement, the remaining terms—A (Core Temperature), B (Cavity Temperature), C (Cooling Time), AA, BB, CC, and AB—were retained for the subsequent Analysis of Variance (ANOVA). The results of this reduced quadratic model are presented in Table 4.15. Notably, the model performance improved substantially after the elimination process, with the P-value decreasing from 0.132 to 0.030, thereby confirming the overall significance of the reduced model. This refinement highlights the value of model reduction in enhancing statistical robustness and ensuring that only meaningful terms are retained for analyzing the % Elongation response in HDPE specimens.

Table 4.15: ANOVA after the elimination process for % Elongation.

Source	DF	Adj SS	Adj MS	F-Value	P-Value	
Model	7	28539.9	4077.13	3.94	0.030	Significant
Linear	3	12711.3	4237.11	4.09	0.043	
Core Temperature	1	7139.5	7139.53	6.9	0.028	Significant
Cavity Temperature	1	5566.7	5566.71	5.38	0.046	
Cooling Time	1	5.1	5.09	0	0.946	
Square	3	10120.8	3373.58	3.26	0.074	
Core Temperature*Core Temperature	1	5798.5	5798.54	5.6	0.042	Significant
Cavity Temperature*Cavity Temperature	1	2072.3	2072.31	2	0.191	
Cooling Time*Cooling Time	1	2478.6	2478.61	2.4	0.156	
2-Way Interaction	1	5707.8	5707.8	5.52	0.043	
Core Temperature*Cavity Temperature	1	5707.8	5707.8	5.52	0.043	
Core Temperature*Cooling Time	9	9312.4	1034.71			
Cavity Temperature*Cooling Time	5	9091.6	1818.33	32.95	0.002	Significant
Error	4	220.8	55.19			
Lack-of-Fit	16	37852.3				
Pure Error	4	220.8	55.19			
Total	16	37852.3				

The surface plot of % Elongation shown in Figure 4.31 illustrates the interaction between core temperature and cavity temperature in influencing the % Elongation response. The results indicate that % Elongation is higher when both the core and cavity temperatures are maintained at relatively low values. Similarly, the contour plot in Figure 4.32 further reinforces this trend, clearly showing that reducing both parameters leads to an increase in % Elongation. This suggests that lower thermal conditions promote greater ductility in the HDPE specimens, likely due to reduced thermal stresses and a more uniform cooling profile during solidification. Therefore, to maximize the % Elongation response, the process requires optimal control of both core and cavity temperatures, emphasizing the importance of coordinated thermal management within the injection moulding cycle.
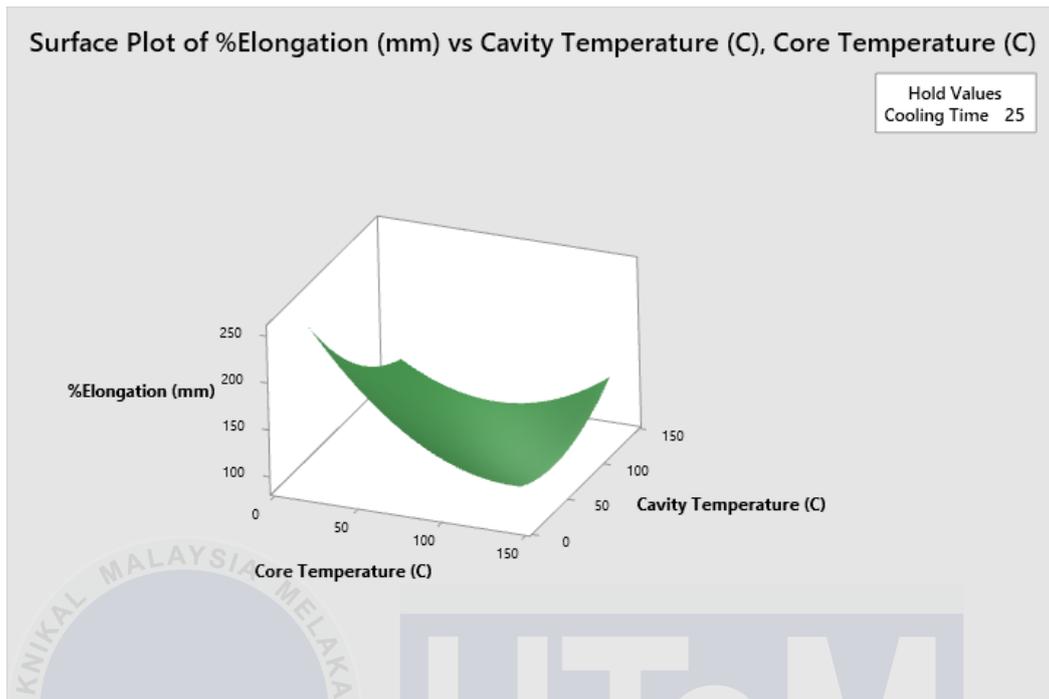
Figure 4.31: The Surface Plot of % Elongation response based on core temperature and cavity temperature factors.
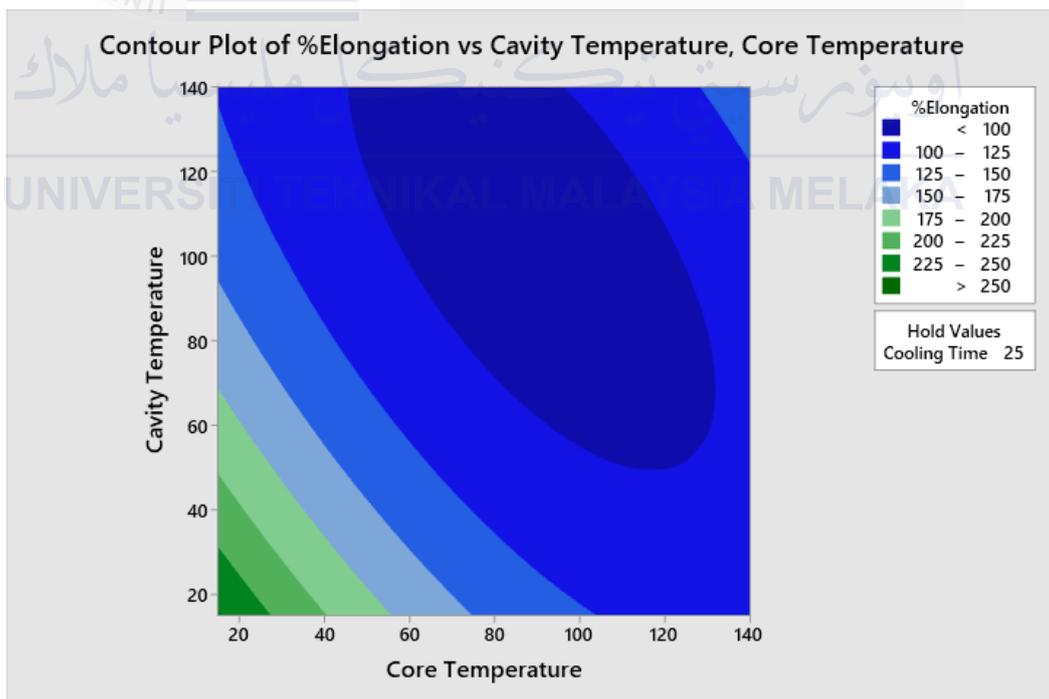
Figure 4.32: The Contour Plot of % Elongation response based on core temperature and cavity temperature factors.

4.7.2 Mathematical Model for % Elongation Response

The mathematical model was developed to explain the connection between parameters and reaction. By replacing the variables of Core Temperature, Cavity Temperature, and Cooling Time, the expected % Elongation value was determined. The estimated regression coefficient was used to calculate the regression coefficient for each parameter. Therefore, the ultimate mathematical model for estimating the % Elongation is the uncoded factor in the equation below.

$$
\begin{aligned}
\%\text{Elongation} = {}& 218.8 - 2.700 \text{ Core Temperature} \\
& - 2.052 \text{ Cavity Temperature} + 7.83 \text{ Cooling Time} \\
& + 0.00950 \text{ Core Temperature*Core Temperature} \\
& + 0.00568 \text{ Cavity Temperature*Cavity Temperature} \\
& - 0.155 \text{ Cooling Time*Cooling Time} \\
& + 0.00967 \text{ Core Temperature*Cavity Temperature}
\end{aligned}
$$

Table 4.16: Comparison between Experimental % Elongation and Mathematical % Elongation

Run No.	Experimental %Elongation	Mathematical %Elongation	Error (%)
1	299.31	251.6038	15.9387
2	115.96	115.6725	0.2479
3	124.04	123.2225	0.6591
4	91.79	138.3850	-50.7626
5	113.19	139.6913	-23.4131
6	102.37	80.6607	21.2067
7	121.16	142.3225	-17.4666
8	108.59	81.0006	25.4069
9	101.83	122.0100	-19.8173
10	94.88	68.0819	28.2442
11	96.77	122.6100	-26.7025
12	92.13	70.8694	23.0768
13	93.76	97.9241	-4.4412
14	107.27	97.9241	8.7125
15	105.88	97.9241	7.5141
16	92.16	97.9241	-6.2544
17	93.33	97.9241	-4.9224

The mathematical % Elongation was calculated using the regression equation in uncoded units, as presented in Table 4.16. The experimental results were then compared to the predicted values by computing the percentage error. In several runs, the error values appeared negative because the mathematical predictions were higher than the experimental % Elongation values. For the purpose of identifying the extremes, the negative sign was disregarded. According to the results, Run 4 exhibited the highest error percentage, at approximately 50.76%, while Run 2 recorded the lowest error percentage, at around 0.25%. The comparison between the experimental and predicted % Elongation values is illustrated in Figure 4.33, which was plotted using the data from Table 4.16. Overall, the average error across all runs was calculated at approximately 1.34%, indicating a reasonably good level of agreement between the experimental measurements and the regression model.
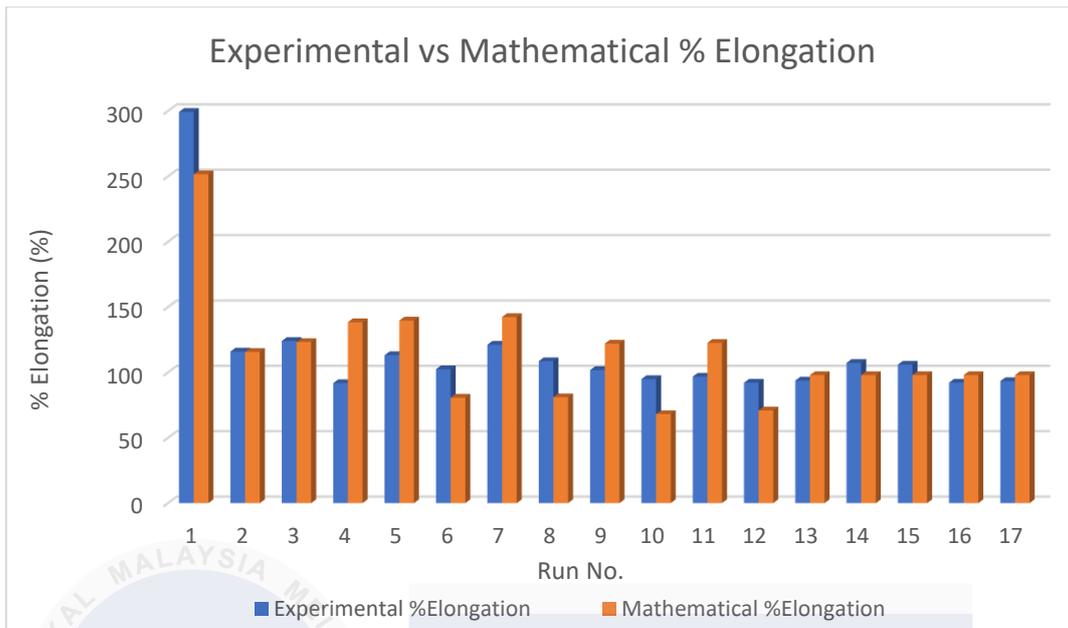
Figure 4.33: Histogram of Experimental versus Mathematical % Elongation.

4.7.3 Single Objective Optimization of % Elongation

Response surface optimization proved to be an effective approach for determining the optimal injection moulding parameters that maximize % Elongation. The optimization results indicate that the best parameter settings are a Core Temperature of 15°C, a Cavity Temperature of 15°C, and a Cooling Time of 25.13 s. Under these conditions, the model achieved a composite desirability of 0.7711, with a predicted % Elongation of 251.81 mm. In comparison, the lowest recorded % Elongation was 91.79 mm. Based on these results, the percentage of improvement was calculated at approximately 174.33%, demonstrating the strong potential of process parameter tuning to enhance ductility in HDPE parts. This outcome highlights the importance of maintaining lower mould wall temperatures combined with extended cooling durations, as these conditions appear to facilitate stress relaxation and improve flexibility during solidification.

% Elongation improvement:

$$\left(\frac{91.79-(251.8081)}{91.79}\right)x\ 100 = 174.33\%$$

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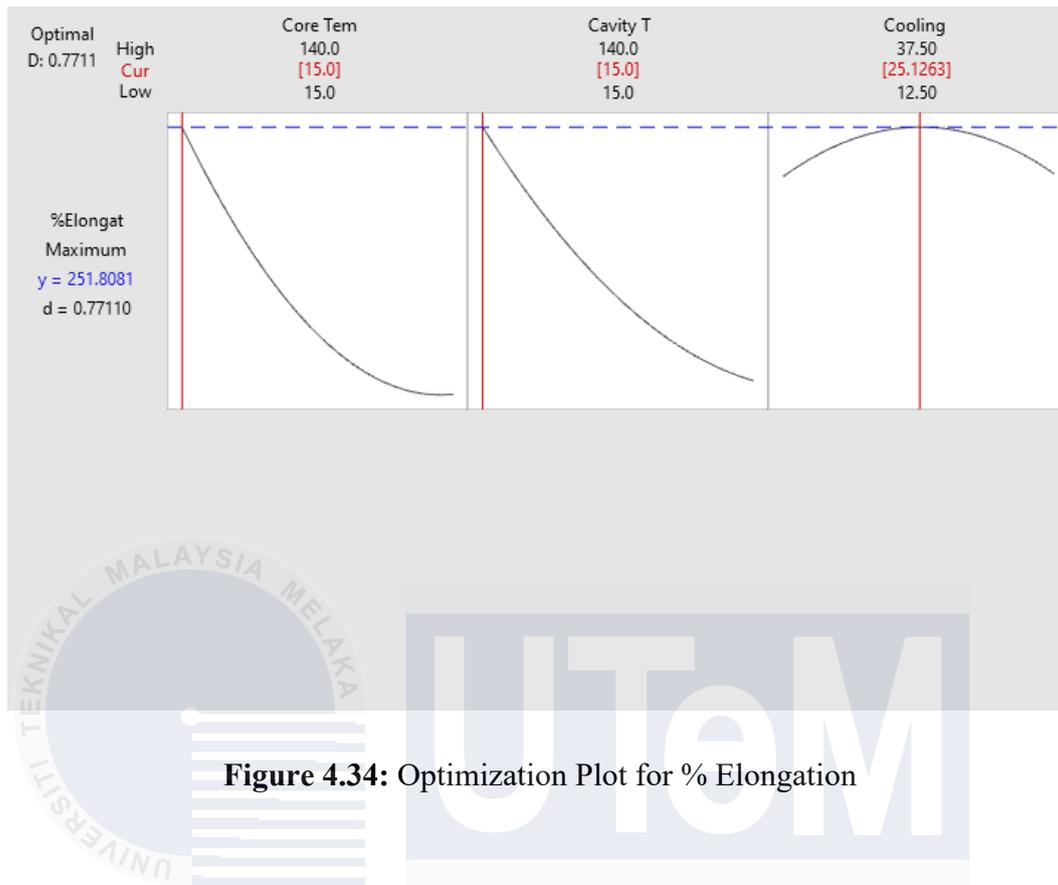
Figure 4.34: Optimization Plot for % Elongation

4.8   Multi Objective Optimization of Response

The fundamental objective of multiple response optimization is to determine the most effective combination of process parameters that achieve the best overall performance across multiple quality responses. In this study, the optimization framework was designed to address both dimensional stability and mechanical performance of HDPE injection-moulded parts. Specifically, the goal was to minimize warpage and volumetric shrinkage which directly affect dimensional accuracy, while simultaneously maximizing Ultimate Tensile Strength (UTS), Young's Modulus, and % Elongation to ensure superior mechanical integrity and ductility. The targets for injection moulding parameters and responses are summarized in Table 4.17, which serves as the foundation for the multiple response optimization strategy under the Design of Experiments (DOE) and Response Surface Methodology (RSM) framework applied in this study.

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Table 4.17: Target for Injection Moulding Parameter and Response

Injection Moulding Parameter and Response	Target
Core Temperature (°C)	In Range
Cavity Temperature (°C)	In Range
Cooling Time (s)	In Range
Warpage (mm)	Minimize
Volumetric shrinkage (%)	Minimize
Ultimate Tensile Strength(N/mm^2)	Maximize
Young's Modulus (N/mm2)	Maximize
% Elongation (mm)	Maximize

The multi-objective optimization of core temperature, cavity temperature, and cooling time is illustrated in Table 4.18 and Figure 4.35 below. This analysis indicates that the optimal parameters for achieving the desired response are a core temperature of 44.04°C, a cavity temperature of 15°C, and a cooling time of 37.5s. The anticipated injection moulding characteristics resulting from these parameters are warpage of 0.1216 mm, volumetric shrinkage of 15.8127%, ultimate tensile strength (UTS) of 20.3826 N/mm², Young's Modulus of 5.2867 N/mm², and % elongation of 170.4306 mm.

Table 4.18: Multi-Objective Optimization of Response

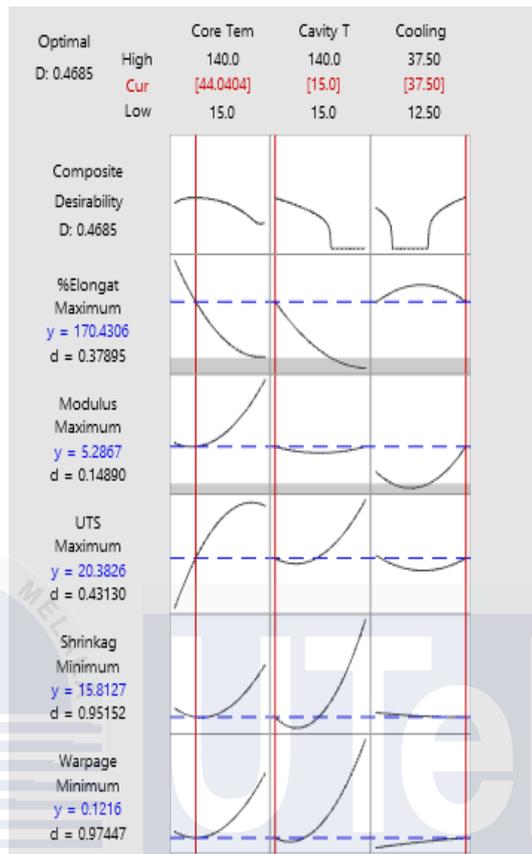| Response	Goal	Lower	Target	Upper	Weight	Importance
Warpage (mm)	Minimum		0.06	2.475	1	1
Shrinkage (%)	Minimum		15.58	20.380	1	1
UTS (N/mm^2)	Maximum	19.52	21.52		1	1
Modulus (N/mm^2)	Maximum	4.91	7.440		1	1
% Elongation (mm)	Maximum	91.79	299.31		1	1

Figure 4.35: Multi-Objective Optimization for warpage, volumetric shrinkage, UTS, Young's Modulus and % Elongation.

Figure 4.35 illustrates the results of the multi-objective optimization for the responses of warpage, volumetric shrinkage, ultimate tensile strength (UTS), Young's modulus, and percentage elongation. The optimization was performed to identify the best combination of core temperature, cavity temperature, and cooling time that balances dimensional accuracy and mechanical performance of the HDPE injection-moulded parts.

The optimized processing parameters were identified as core temperature of 44.0 °C, cavity temperature of 15.0 °C, and cooling time of 37.5 s. At these conditions, the predicted responses achieved significant improvements. Warpage was minimized to 0.1216 mm, demonstrating that cavity temperature and cooling balance were effective in reducing deformation. Volumetric shrinkage reached 15.8127%, showing that shrinkage could be controlled by optimizing core–cavity temperature differences. UTS was improved to 20.3826 N/mm², indicating that optimized cooling supported better polymer chain orientation and reduced internal stresses. Young's Modulus achieved 5.2867 N/mm², confirming enhanced stiffness and

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structural integrity. % Elongation was maximized to 170.4306 mm, reflecting improved ductility, which is critical for impact resistance in HDPE applications.

These results highlight the importance of simultaneously considering both dimensional stability (warpage and shrinkage) and mechanical properties (UTS, modulus, elongation). By applying Response Surface Methodology (RSM), the study effectively balanced multiple responses rather than optimizing a single objective. This holistic optimization approach reflects the practical requirements of industrial injection moulding, where parts must not only meet geometric tolerances but also maintain mechanical reliability.

4.9 Result Validation

Based on the multi-objective optimization results shown in Table 4.19, which include warpage, volumetric shrinkage, UTS, Young's modulus, and % elongation, a validation process was carried out. The optimal parameter settings of core temperature of 44.0 °C, cavity temperature of 15.0 °C, and cooling time of 37.5 s, were applied both in the experimental trials and in the mathematical models generated through RSM analysis. This step was crucial to confirm that the optimized conditions not only produced reliable results in the predictive model but also translated effectively into real-world injection moulding conditions. The comparison between the experimental outcomes and the predicted values demonstrated strong agreement, reinforcing the accuracy and robustness of the optimization model. This validation strengthens the reliability of the study by proving that the chosen process parameters can consistently minimize warpage and shrinkage while enhancing the mechanical properties of HDPE parts under practical manufacturing conditions.

Table 4.19: Multi-Objective optimization for warpage, volumetric shrinkage, UTS, Young's Modulus and % Elongation

Parameters/ Responses	Core Temperature	Cavity Temperature	Cooling Time
Optimal value	44.0°C	15.0°C	37.5s
Warpage	0.1216 mm		
Volumetric Shrinkage	15.8127%		
(UTS)	20.3826 N/mm²		
Young's Modulus	5.2867 N/mm²		
% Elongation	170.4306 mm		

4.9.1 Experimental real-world condition validation

The mathematical equations developed using the Response Surface Methodology (RSM) were employed to predict the responses at the optimal process parameters: core temperature of 44.0 °C, cavity temperature of 15.0 °C, and cooling time of 37.5 s. These equations represent the quadratic regression models generated during the optimization process, linking the selected parameters to the responses of warpage, volumetric shrinkage, ultimate tensile strength (UTS), Young's modulus, and percentage elongation. By substituting the optimal parameter values into the respective regression equations, the predicted outcomes for each response were obtained. These predicted values were then compared with the experimental validation data to evaluate the accuracy and reliability of the developed models. Below are the mathematical model calculations, where the optimal parameter values were substituted into the developed regression equations to predict the responses.

a. $\text{Warpage} = -0.528 + 0.00642(44) - 0.00019(15) + 0.0275(37.5) + 0.000119(44 \times 44) + 0.000157(15 \times 15) - 0.000093(37.5 \times 37.5) - 0.000173(44 \times 15) - 0.000336(44 \times 37.5) - 0.000089(15 \times 37.5) = 0.1200$

b. Volumetric shrinkage $= 15.46 + 0.0153(44) - 0.0313(15) + 0.0210(37.5) +$
$$0.000128(44 \times 44) + 0.000227(15 \times 15) +$$
$$0.00015(37.5 \times 37.5) + 0.000078(44 \times 15) -$$
$$0.000794(44 \times 37.5) + 0.000195(15 \times 37.5) = 15.8121$$

c. UTS $= 19.809 + 0.03277(44) - 0.00815(15) - 0.0472(37.5) -$
$$0.000109(44 \times 44) + 0.000080(15 \times 15) + 0.001040(37.5 \times 37.5) -$$
$$0.000017(44 \times 15) - 0.000160(44 \times 37.5) + 0.000051(15 \times 37.5) =$$
$$20.3816$$

d. Young's Modulus $= 4.776 + 0.0183(44) + 0.00641(15) - 0.0521(37.5) +$
$$0.000066(44 \times 44) + 0.000017(15 \times 15) +$$
$$0.00182(37.5 \times 37.5) - 0.000056(44 \times 15) -$$
$$0.000595(44 \times 37.5) - 0.000173(15 \times 37.5) = 5.2867$$

e. % Elongation $= 218.8 - 2.70(44) - 2.052(15) + 7.83(37.5) +$
$$0.00950(44 \times 44) + 0.00568(15 \times 15) - 0.155(37.5 \times 37.5) +$$
$$0.00967(44 \times 15) = 170.928$$

Table 4.20: Mathematical model and experimental validation data

	Predicted optimized value	Mathematical model validation	Experimental value	% Error
Warpage	0.1216 mm	0.1200 mm	0.1324mm	8.88
Volumetric Shrinkage	15.8127%	15.8121%	15.6331%	1.14
(UTS)	20.3826 N/mm²	20.3826 N/mm²	21.750 N/mm²	6.69
Young's Modulus	5.2867 N/mm²	5.2867 N/mm²	5.8348 N/mm²	8.50
% Elongation	170.4306 mm	170.9280 mm	159.1214 mm	6.63

Table 4.20 displays a close agreement between the predicted and experimental results confirmed that the developed quadratic regression models were statistically significant and capable of accurately representing the relationships between process parameters and responses.

Minor deviations observed between predicted and experimental values can be attributed to unavoidable variations in machine performance, material behaviour, or environmental conditions during moulding. The close alignment between predicted and experimental results validation confirmed that the mathematical models successfully captured the nonlinear relationships among the parameters. This highlights the robustness of the RSM approach in optimizing multiple responses simultaneously and supports the practical applicability of the developed models in real injection moulding conditions.

Overall, the validation process demonstrates that the RSM-based mathematical models are robust and suitable for predicting warpage, shrinkage, and mechanical properties of HDPE injection-moulded parts. This confirms the effectiveness of the optimization approach and strengthens the credibility of the study findings.
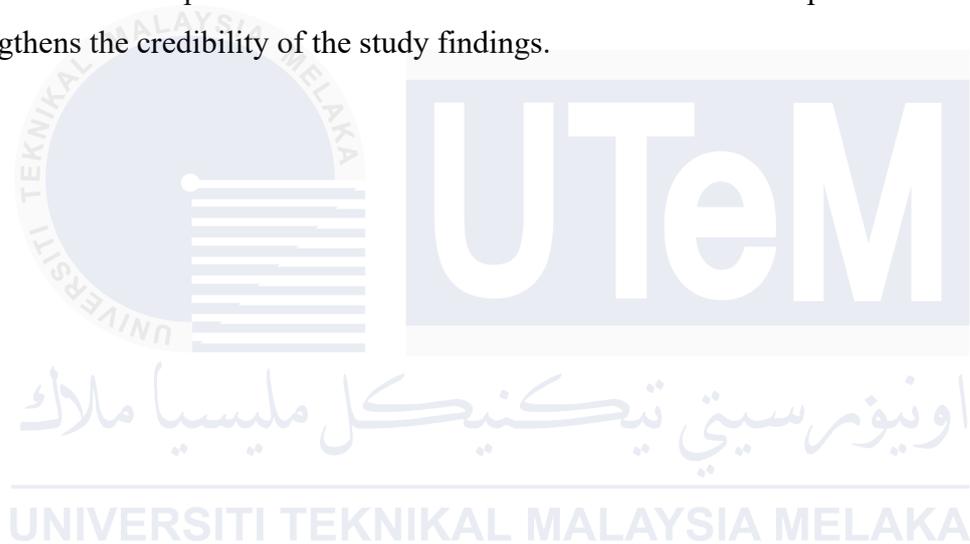
CHAPTER 5

COCLUSIONS

5.0   Conclusion

This research set out to identify the optimal injection moulding parameters, core temperature, cavity temperature, and cooling time, that most significantly influence the quality of moulded parts, particularly in terms of shrinkage, warpage, ultimate tensile strength (UTS), Young's modulus, and percentage elongation. The study objectives were addressed systematically through experimental design, statistical modelling, optimization, and validation.

From the first objective, which focused on determining the effects of parameters on responses, the results of the ANOVA revealed that:

- Core temperature emerged as the most critical factor for volumetric shrinkage, UTS, Young's modulus, and percentage elongation. Unlike shrinkage or tensile properties, warpage is highly sensitive to thermal imbalance across the mould. The cavity surface, being the first contact area for the molten polymer, dictates the skin layer's cooling rate and crystallization pattern. When cavity temperature is not controlled optimally, uneven shrinkage occurs between the cavity and core surfaces, generating internal stresses that manifest as warpage. The findings of this thesis highlight that cavity temperature has a disproportionate effect on warpage compared to other factors, because even small deviations in surface temperature distribution amplify dimensional distortion in thin-walled HDPE parts. Therefore, cavity-side thermal control is critical for achieving flatness and dimensional accuracy.

- Cavity temperature had the strongest influence on warpage, making it the dominant parameter in this response. Unlike shrinkage or tensile properties, warpage is highly sensitive to thermal imbalance across the mould. The cavity surface, being the first contact area for the molten polymer, dictates the skin layer's cooling rate and crystallization pattern. When cavity temperature is not controlled optimally, uneven shrinkage occurs between the cavity and core surfaces, generating internal stresses that

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manifest as warpage. The findings of this thesis highlight that cavity temperature has a disproportionate effect on warpage compared to other factors, because even small deviations in surface temperature distribution amplify dimensional distortion in thin-walled HDPE parts. Therefore, cavity-side thermal control is critical for achieving flatness and dimensional accuracy.

- Interactions among parameters (core, cavity, and cooling time) were found to be less significant overall, though certain pairwise interactions showed noticeable effects. Although the main effects of core and cavity temperature dominate the responses, interactions among parameters (core–cavity, core–cooling time, and cavity–cooling time) still play secondary but meaningful roles. For instance, the core–cavity interaction influences warpage, as simultaneous increases in both temperatures intensify distortion from thermal stress. Likewise, the core–cooling time interaction affects volumetric shrinkage, where prolonged cooling at high core temperatures helps reduce voids but risks uneven shrinkage if not carefully balanced. While these interactions are not significant across all responses, they provide important insight into how parameter combinations can either amplify or counteract one another, highlighting the need to consider them in practical moulding conditions.

For the second objective, which aimed to optimize the parameters, the use of half-normal plots and surface response plots revealed the following insights:

- Warpage was minimized by reducing both core and cavity temperatures, resulting in values below 2.48 mm.
- Volumetric shrinkage was minimized by combining higher core temperature with shorter cooling time, reaching levels below 20.38%.
- UTS improved when the core temperature and cooling time were optimally balanced, achieving values above 19.52 N/mm².
- Young's modulus was optimized by applying higher core temperature with shorter cooling time, exceeding 4.91 N/mm².
- % Elongation increased when both core and cavity temperatures were set at lower values, surpassing 91.79 mm.

The validation process confirmed that the mathematical models developed through Response Surface Methodology (RSM) reliably predict the behavior of injection moulding responses under optimized parameter settings. The close agreement between the predicted and

experimental results for warpage, shrinkage, UTS, Young's modulus, and elongation demonstrates the robustness of the regression equations and their ability to capture the nonlinear relationships among process parameters. Although minor deviations were observed, these were within acceptable ranges and can be attributed to normal variations in machine performance and material behavior. This successful validation directly supports Objective 3 of the study, proving that the proposed models are accurate, practical, and applicable in real-world manufacturing conditions.

This study contributes to knowledge by establishing a clear understanding of how core temperature, cavity temperature, and cooling time collectively influence both dimensional accuracy and mechanical performance in injection moulded HDPE parts. The findings highlight that core temperature is the dominant factor for shrinkage, UTS, Young's modulus, and elongation, while cavity temperature plays the most significant role in warpage, with certain interactions such as core–cavity temperature and core–cooling time further shaping responses.

By applying a Box–Behnken Design with 17 experimental runs and validating regression-based models through RSM, the research confirms high predictive reliability with minimal error (0.02–2.40%), demonstrating the robustness of statistical optimization in polymer processing. Importantly, the study advances understanding of how process parameters can be tuned to balance stiffness and ductility, while also providing practical parameter settings for minimizing defects, reducing material waste, and improving production efficiency. These contributions not only extend the scientific basis of thermal management in injection moulding but also offer actionable guidelines for industry in optimizing part quality and performance.

In conclusion, this study demonstrated that RSM is an effective and reliable approach to optimize injection moulding parameters. By identifying the critical effects of core temperature, cavity temperature, and cooling time, the research provides practical insights that reduce warpage and shrinkage while simultaneously enhancing mechanical properties such as UTS, Young's modulus, and % elongation.

5.1   Recommendations

Building on the findings of this research, several recommendations are proposed to guide future studies and expand on the insights gained. These recommendations highlight areas that can further improve the understanding and optimization of injection moulding processes:

a) Focus on mould design integration with simulation tools.

In this study, the analysis was based on process parameters such as core temperature, cavity temperature, and cooling time, with the emphasis on their impact on shrinkage, warpage, and mechanical properties. For future research, it is recommended that a dedicated mould design, rather than solely part design, be developed and integrated into Moldflow Plastic Insight (MPI) software. This approach will provide more realistic simulations of heat transfer, cooling performance, and dimensional accuracy, ultimately offering more reliable predictions of the part's responses under real-world manufacturing conditions.

b) Exploration of different polymeric materials.

While this research focused on a specific material system, future studies should extend the investigation to other engineering polymers with distinct characteristics. For instance, polycarbonate (PC), known for its strength, impact resistance, and optical clarity, can be used to evaluate how varying core and cavity temperatures, as well as cooling time, affect the behaviour of more rigid thermoplastics. Comparing the performance of PC with polymers such as HDPE or ABS would provide broader insights into how process parameters influence both mechanical integrity and dimensional stability across different material classes.

These recommendations will not only deepen the scientific understanding of polymer processing but also provide practical guidelines for manufacturers seeking to tailor process settings for diverse materials and product requirements.

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Gantt chart of PhD activities with milestones
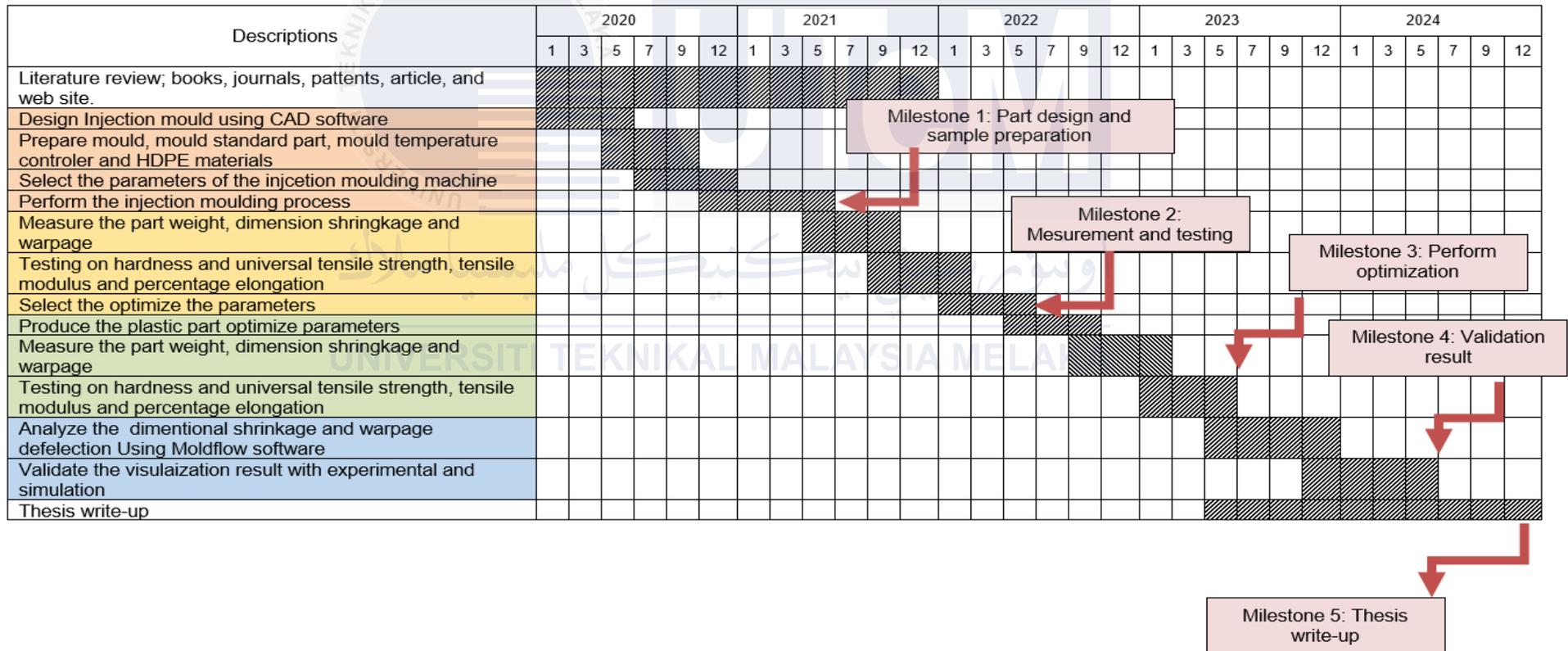
APPENDIX B

MATERIAL SAFETY DATA SHEET HDPE

SAFETY DATA SHEET

1. IDENTIFICATION OF THE SUBSTANCE/PREPARATION AND OF THE COMPANY/UNDERTAKING

PRODUCT NAME: InnoPlus HD1010J
CHEMICAL NAME: High Density Polyethylene
TYPICAL APPLICATION: InnoPlus HD1010J is recommended for producing toys, auto parts, household products and beverage spout caps.
MANUFACTURER: PTT Global Chemical Public Company Limited
8 Padang Rd., Map Ta Phut, Muang Rayong District,
Rayong 21150, Thailand
24-HOUR EMERGENCY: Thailand; +66(0)-3897-6323
CONTACT   +66(0)-3897-6793

2. HAZARDS IDENTIFICATION

CLASSIFICATION OF THE SUBSTANCE OR MIXTURE

- **Classification according to Globally Harmonized System (GHS):**
The substance is not classified as hazardous according to GHS.
- **Classification according to Regulation (EC) No 1272/2008 (CLP):**
The substance is not classified as hazardous according to the CLP regulation.
- **Classification according to Directive 67/548/EEC or Directive 1999/45/EC:**
The substance is not classified as hazardous according to Directive 67/548/EEC or Directive 1999/45/EC.

LABEL ELEMENTS

- **Labelling according to GHS:**   None
- **Labelling according to Regulation (EC) No 1272/2008:**   None
- **Hazard pictograms:**   None
- **Signal word:**   None
- **Hazard statements:**   None
- **Precautionary statements :**
    Prevention: Not Applicable
    Response: Not Applicable
    Storage: Not Applicable
    Disposal: Not Applicable
- **Additional information:**
    Pellets on the floor may cause a serious slipping hazard.
    Skin or eye contact with hot polymer can cause thermal burns.
    Processing the polymer at high temperatures may form vapors that irritate the eyes and respiratory tract.

OTHER HAZARDS

- **Results of PBT and vPvB assessment**
    - PBT: Not determined
    - vPvB: Not determined

1. COMPOSITION/INFORMATION ON INGREDIENTS

Component	CAS no.	Weight %
Polyethylene	9002-88-4	>99
Additives	-	<1.0

2. FIRST AID MEASURES
INHALATION
Remove to fresh air. If patient is not breathing or breathing irregular, provide artificial respiration or oxygen. Obtain medical attention by physician if symptoms persist.
EYE CONTACT
Immediately flush eyes with plenty of water for several minutes. Be sure to remove any contact lens. Get medical attention if irritations persist.
SKIN CONTACT
Wash skin with soap and water. Quickly remove contaminated cloth or shoes. Obtain medical if irritation occurs.
INGESTION
Do not induce vomiting, consult a physician immediately.
NOTES TO PHYSICIAN
No specific treatment. Treat symptomatically.

3. FIRE-FIGHTING MEASURES

SUITABLE EXTINGUISHING MEDIA :	Water haze, Foam, Chemical powder.
UNSUITABILITY EXTIGUISHING MEDIA :	None
HAZARDS DECOMPOSITION PRODUCT(S) :	Decomposition products may include carbon dioxide. Normally combustion forms water vapor and may produce carbon monoxide and other hydrocarbons. The products of the burning are dangerous.
SPECIAL PROTECTIVE EQUIPMENT :	Use personal protective equipment or self-contained breathing apparatus (SCBA) when fighting fires in enclosed areas or confined room.

4. ACCIDENTAL RELEASE MEASURES
PERSONAL PRECAUTIONS
Eliminate all sources of ignition in vicinity of spilled material. Wear appropriate personal protective equipment when cleaning up spills.
ENVIRONMENTAL PRECAUTIONS
Avoid dispersal of split materials to natural waters, soil or sewers.

METHODS FOR CLEANING UP

Sweep up or vacuum split materials and place in a designated, labeled waste container. Contact licensed waste disposal contractor to dispose.

1. HANDLING AND STORAGE

HANDLING

Use good housekeeping for safe handling of the product. No smoking, drinking or eating in handling and store area. Avoid spilling the product, as this might cause falls. Potential toxic/irritating fumes may be evolved from heated material. Provide appropriate ventilation for such processing conditions. Take precautionary measures against explosion risks, as all types of polymers may develop dust during transporting or grinding of granules.

STORAGE

Protect from heat and direct sunlight in a dry, cool and well-ventilated area. Take precautionary measures to prevent the formation of static electricity. Do not store together with oxidizing and self-igniting products.

2. EXPOSURE CONTROLS/PERSONAL PROTECTION

EXPOSURE LIMITS

No exposure limits value known.

EXPOSURE CONTROLS

Respiratory Protection:	Product processing, heat sealing of film or operations involving the use of wires or blades heated above 300°C may produce dust, vapor or fumes. To minimize risk of overexposure to dust, vapor or fumes it is recommended that a local exhaust system is placed above the equipment, and that the working area is properly ventilated. If ventilation is inadequate, use certified respirator that will protect against dust/mist.
Skin and Body Protection:	Hot material: Wear heat-resistant protective gloves, clothing and face shield able to withstand the temperature of the molten product. Cold material: None required; however, use of gloves is good industrial practice.
Hand Protection:	Hot material: Wear heat-resistant protective gloves able to withstand the temperature of the molten product. Cold material: None required; however, use of gloves is good industrial practice.
Eyes Protection:	Safety glasses with side shields. Use dust goggles if high dust concentration is generated.

3. PHYSICAL AND CHEMICAL PROPERTIES

• **Appearance:**	Pellets
• **Physical state:**	Solid
• **Color:**	Off-white
• **Odor:**	Paraffin-like

- **Odor threshold:** No data available
- **pH:** Not applicable
- **Melting point:** 125 to 135 °C
- **Boiling point** Not applicable
- **Flash point:** No data available
- **Evaporation rate:** Not applicable
- **Flammability (solid, gas):** No
- **Upper/lower explosion limits:** Not applicable
- **Vapor pressure:** Not applicable
- **Vapor density** Not applicable
- **Relative density:** No data available
- **Density at 23°C** 0.945-0.970 g/cm3
- **Solubility in water:** Insoluble.
- **Partition coefficient, n-octane/water:** No data available
- **Auto-ignition temperature:** 350°C approx.
- **Decomposed temperature:** No data available
- **Viscosity, kinematic:** Not applicable
- **Viscosity, dynamic:** No data available
- **Explosive properties:** High dust concentrations have a potential for sparking or explosion
- **Oxidizing properties:** No

2. STABILITY AND REACTIVITY

CHEMICAL STABILITY: Stability; under normal conditions of storage and use.
CONDITIONS TO AVOID: Not applicable
INCOMPATIBILITY MATERIALS: Incompatibility; to avoid strong oxidizing agents such as chlorates, nitrates, peroxides, etc.
HAZARDOUS DECOMPOSITION: Will not occur; under normal conditions of storage and use.
PRODUCTS

3. TOXICOLOGICAL INFORMATION

ACUTE TOXICITY
LD50 oral, rat No determined.
PRIMARY IRRITANT EFFECT
Skin: No irritant effect.
Eyes: No irritant effect.
Sensitization: No sensitizing effect known.
ADDITIONAL TOXICOLOGICAL INFORMATION
When used and handled according to specifications, the product does not have any harmful effects according to our experience and the information provided to us.

1. ECOLOGICAL INFORMATION
TOXICITY
The product is not toxic, small particles can have physical effects on water and soil organisms.
PERSISTENCE AND DEGRADABILITY
This product is not biodegradable.
RESULTS OF PBT AND vPvB ASSESSMENT
• **PBT**   : Not determined
• **vPvB**   : Not determined
OTHER ADVERSE EFFECTS
No know significant effects or critical hazards.

2. DISPOSAL CONSIDERATIONS
WASTE TREATMENT METHODS
Recycle to process, if possible. Avoid contact of spilled material and runoff with soil and surface waterways. Consult an environmental professional to determine if local, regional or national regulations would classify spilled or contaminated materials as hazardous waste. Use only approved transporters, recyclers, and treatment, storage or disposal facilities. Dispose of in accordance with all applicable local and national regulations.

3. TRANSPORT INFORMATION
UN-NUMBER:
• ADR, IMDG, IATA   Not regulated
UN PROPER SHIPPING NAME:
• ADR, IMDG, IATA   Not regulated
TRANSPORT HAZARD CLASS (ES):
• ADR, IMDG, IATA
• Class   Not regulated
PACKING GROUP:
• ADR, IMDG, IATA   Not regulated
ENVIRONMENTAL HAZARDS:
• Marine pollutant: No
SPRECIAL PRECAUTIONS FOR USER: Not applicable.
TRANSPORT IN BULK: Not applicable.
• Transport/Additional information: Not dangerous according to the above specifications.
• UN "Model Regulation":   -

1. REGULATION INFORMATION

PACKAGING AND LABELLING: No special requirement.
INVENTORIES: Australian Inventory (AICS).
     Canada Inventory (DSL).
     China Inventory (IECS).
     EC Inventory (EINECS).
     Japan Inventory (ENCS).
     Korea Inventory (ECL).

DISCLAIMER:

• This Applications specified herein is for reference only and not suitable for using in the manufacturing of any products in medical and pharmaceutical sectors.

• Determination of suitability of the product for the use and purpose shall be the customer's responsibility. Customer is obligated to inspect and test the product for such suitability. Customer is responsible for appropriate, safe, legal use processing and handling of the product.

• To our best knowledge, information contained herein is true and accurate as of the date of its publication. However, we make no representations or warranties with respect to accuracy, reliability and completeness of the information contained herein for any purpose.

• No warranties, express or implied, which extend beyond the description herein are given by us. Nothing herein shall constitute any implied warranty of merchantability or fitness for a particular purpose.

• We assume no liability for any use of the product in combination with other materials. The information contained herein entirely relates to the product when it is not used in combination with any third party's materials.

2. OTHER INFORMATION

HISTORY

Date of Issue: Aug 2019
Revision: 2
Indicates information that has changed from previously issued version.
NOTICE

This Safety Data Sheet has been based upon data considered to be accurate at the time of its preparation. Despite our efforts, it may not be up to date or applicable to the circumstances of any particular case. We take no responsibility for inappropriate use, processing and handling by purchasers and uses of the product.

MATERIAL SAFETY DATA SHEET OIL (TEXOIL HTF 32)

LUBTEX®
Specialty Lubricants

TECHNICAL DATA SHEET

TEXOIL HTF 32
Heat Transfer Fluid

DESCRIPTION

TEXOIL HTF 32 is a heat transfer fluid with good oxidation resistance. It is recommended for heat transfer installation using thermal fluid circulation, in open and closed circuits.

APPLICATION

TEXOIL HTF 32 are suitable for heating and temperature control in all industries, and particularly for following manufacturing processes:
- Steam production
- Paper Industry
- Timber Industry
- Textile Industry
- Oil & Gas

OUTSTANDING FEATURES

- Good oxidation stability and ageing resistance.
- Good heat transfer characteristics.
- Low foaming characteristics.
- Protects against corrosion.
- Low vapour pressure.
- Minimum carbon deposits.
- Good compatibility with sealing material

Technical Data (typical values)	TEXOIL HTF 32
Appearance	Yellow
Density at 15 °C, kg/m³	865
Kinematic Viscosity at 40 °C, mm²/s	30
Pour Point, °C	- 15
Maximum **bulk** temperature, °C	290
Maximum **film** temperature, °C	310

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