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Design of a Mini Injection Molding Machine and Injection Analysis of Products Using CAE Software

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A B S T R A C T

The increasing amount of HDPE (High-Density Polyethylene) plastic waste requires more efficient and economical processing technologies, particularly for small- and medium-scale applications. This study aims to design a mini injection molding machine for processing HDPE plastic waste and to analyze the product injection process using Computer-Aided Engineering (CAE)-based software. The machine was designed using SolidWorks, focusing on the injection system, clamping system, and heating system. The injection process was analyzed using SolidWorks Plastics with variations in gate position and melt temperature to evaluate injection pressure, material flow distribution, and product defects. The results show that the designed machine is capable of producing a stable HDPE injection process using a screw with an L/D ratio of 20:1 and a ball screw-based clamping system. Simulation results indicate that a gate position located at the center of the product provides the best flow distribution with minimal weldline defects. The optimum melt temperature was found to be 240°C, with an injection pressure of approximately 10 MPa. These findings indicate that the integration of mini injection molding technology and CAE-based analysis has the potential to support more efficient plastic recycling processes while minimizing design revisions, material waste, and manufacturing costs in small-scale production systems.

K E Y W O R D S : *Injection molding, recycled HDPE, CAE, ball screw, weldline.*

1. INTRODUCTION

Plastic has become an essential material in modern life due to its lightweight, strength, ease of processing, and relatively low production cost. The development of industrial and technological sectors, along with population growth, has led to a continuous increase in the demand for plastic materials each year [1]. This condition has a direct impact on the rising volume of plastic waste, which has become one of the major environmental issues in many countries, including Indonesia. According to the Indonesian Olefin, Aromatic, and Plastic Industry Association (INAPLAS), although plastic consumption in Indonesia remains lower than in several developed countries such as South Korea, Japan, and Germany, Indonesia is among the largest contributors to global plastic waste. The high volume of plastic waste is influenced by suboptimal waste management systems, particularly in the processing and recycling stages [2]. The accumulation of poorly managed plastic waste can lead to environmental pollution, as most plastic materials require a very long time to degrade.

One of the approaches continuously developed in plastic waste management is the 3R concept (Reduce, Reuse, and Recycle). Among these, the recycling process has significant potential to reduce the volume of plastic waste while increasing the economic value of used materials [3]. However, the implementation of plastic recycling technology at small and medium scales still faces various challenges, particularly the limited availability of processing equipment that is relatively expensive, large in size, and requires complex operating systems [4]. These conditions have limited the adoption of manufacturing-based plastic processing technologies in small and medium enterprises (SMEs) as well as in educational laboratories. One of the manufacturing technologies that can be applied in plastic waste processing is the injection molding machine. The injection molding process works by melting thermoplastic material and then injecting it into a mold to produce products with the desired shape. This technology is widely used due to its several advantages, such as efficient material utilization, the ability to produce complex geometries, and high production capacity [5]. However, commercial injection molding machines generally have large dimensions, high investment costs, and complex construction systems, making them less suitable for small-scale plastic waste processing applications.

Based on these challenges, it is necessary to develop a mini injection molding machine with a simpler construction, lower manufacturing cost, and ease of operation. A small-scale machine is expected to serve as an alternative technology for more affordable plastic waste processing, particularly for small and medium enterprises (SMEs) and educational laboratories. In this study, a mini injection molding machine is designed to process HDPE (High-Density Polyethylene) plastic waste. HDPE is selected due to its good mechanical properties, recyclability, chemical resistance, and its widespread use in packaging and household products [6].

In addition to machine design, this study also performs an analysis of the product injection process using Computer-Aided Engineering (CAE) software based on SolidWorks Plastics. CAE analysis is employed to evaluate the characteristics of plastic material flow during the mold-filling process, temperature distribution, and potential product defects such as weldlines and air traps. The use of simulation methods is intended to reduce trial-and-error processes during manufacturing, thereby minimizing product development time, production costs, and the risk of process failure. By integrating the design of a mini injection molding machine with CAE-based injection process analysis, this study is expected to produce a more effective machine design for HDPE plastic waste processing while also determining more optimal injection process parameters.

2. METHODOLOGY

This study is an engineering research employing a design and numerical simulation approach aimed at developing a mini injection molding machine for processing HDPE (High-Density Polyethylene) plastic waste and analyzing the product injection process using Computer-Aided Engineering (CAE)-based software. The research was conducted through several stages, including literature review, machine design, product and mold base design, injection process analysis using CAE, and evaluation of the design and simulation results.

The scope of this study focuses on the design of the main systems of the injection molding machine, which include the injection unit, drive system, clamping unit, and heating unit. The plastic material used in this study is recycled HDPE, as it possesses thermoplastic properties that allow it to be melted and reshaped through the injection process. Furthermore, the injection process analysis is limited to the effects of variations in gate position, filling time, and melt temperature on the quality of the molded products. The research stages were carried out systematically, as illustrated in Figure 1.

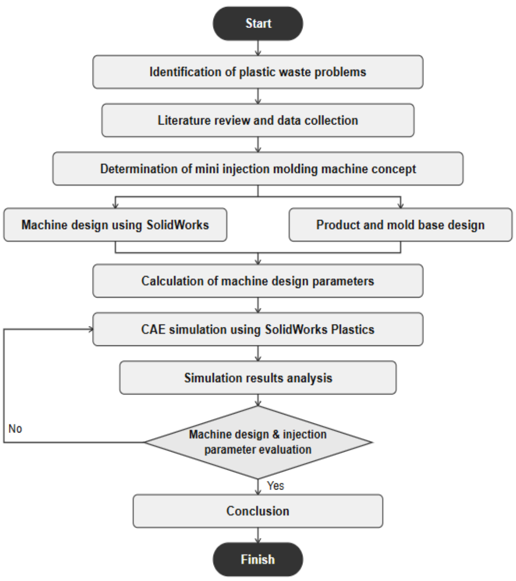

Figure 1. Research Flowchart

1. Literature Review and Data Collection

The initial stage of the research was conducted through a literature review to obtain data and references related to injection molding technology, plastic waste processing, HDPE material characteristics, plastic injection systems, and the application of CAE software in manufacturing processes. The literature review involved studying various sources such as scientific journals, manufacturing engineering textbooks, machine design handbooks, previous research articles, and other relevant technical references related to mini injection molding machines. The data obtained from the literature review were used as the basis for determining the machine design concept, material selection, design parameters, and the simulation methods employed in this study.

2. Design of the Mini Injection Molding Machine

The machine was designed using SolidWorks based on Computer-Aided Design (CAD) to produce three-dimensional (3D) models and technical drawings for each machine component. The use of CAD software aims to facilitate design visualization, component assembly, and design evaluation prior to the manufacturing process [7]. The designed mini injection molding machine consists of several main systems, namely the injection unit, transmission system, clamping unit, heating system, and the main frame. At this stage, the machine dimensions, injection system configuration, heating unit placement, and mold opening–closing mechanism were determined in accordance with the requirements of the HDPE injection process.

3. Screw and Barrel Design

The screw was designed as the main component of the injection system, functioning to convey, compress, mix, and melt the plastic material toward the nozzle. The screw design consists of three main zones, namely the feed zone, compression zone, and metering zone. Each zone has a different flight depth according to its respective function in the transportation and melting of the plastic material. The screw dimensions were determined based on the length-to-diameter (L/D) ratio commonly used in injection molding machines. In addition, parameters such as screw diameter, screw pitch, helix angle, and compression ratio were defined to achieve stable material flow during the injection process.

The barrel was designed as the heating chamber in which the screw operates during the plastic melting process. The barrel dimensions were adjusted to match the screw dimensions, taking into account the clearance between the screw and the barrel to ensure stable screw rotation and to minimize material leakage during the injection process.

4. Drive System and Clamping Unit Design

The drive system of the injection unit utilizes an AC motor connected to a gearbox, pulley, and belt to rotate the screw within the barrel. The motor selection was carried out based on calculations of the power and torque required by the screw during the injection process. Furthermore, the transmission system was designed to reduce the motor speed to match the required screw rotation for the HDPE melting process.

The motor serves as the main power source to drive the screw in the barrel during the melting and injection of HDPE material. The motor specifications were determined based on the power and torque requirements of the injection system to ensure stable material flow within the barrel. Therefore, motor power calculations are necessary to determine the appropriate motor capacity in accordance with the working load of the screw during the injection process. The motor power (P) is calculated using Equation (1).

$$P = \frac{F_{tot} \times r \times 2\pi \times N}{60 \times 10^6} \quad (1)$$

Where Pis the motor power (kW), F_{tot}is the total force acting on the screw (N), ris the radius of the screw shaft (mm), and Nis the screw rotational speed (RPM).

The required motor power (P_d) can be calculated using Equation (2).

$$P_d = F_c \times P \quad (2)$$

Where $P_d$is the required motor power (kW), $F_c$is the correction factor (1.2–2), and $P$is the motor power (kW).

The transmission unit functions to transfer power from the motor rotation to the screw. In this design, a pulley and belt system is used as the transmission unit. The pulley diameter can be determined using Equation (3).

$$\frac{n_1}{n_2} = \frac{D_p}{d_p} = i \quad (3)$$

Where $n_1$is the rotational speed of the driving pulley (RPM), $n_2$is the rotational speed of the driven pulley (RPM), $d_p$is the diameter of the driving pulley (mm), $D_p$is the diameter of the driven pulley (mm), and $i$is the transmission ratio between the driving and driven pulleys. The belt length (L) can be calculated using Equation (4).

$$L = 2C + \frac{\pi}{2}\left(D_p + d_p\right) + \frac{\left(D_p - d_p\right)^2}{4C} \quad (4)$$

Where Lis the belt length (mm), Cis the center distance between the pulley shafts (mm), d_pis the diameter of the driving pulley (mm), and D_pis the diameter of the driven pulley (mm). Where Lis the belt length (mm), Cis the center distance between the pulley shafts (mm), d_pis the diameter of the driving pulley (mm), and D_pis the diameter of the driven pulley (mm).

5. Heating Unit Design

The heating unit was designed using band heaters installed along the barrel to melt the HDPE material during the injection process. The heater power was determined by calculating the heat flux based on the material's operating temperature, barrel dimensions, and the thermal conductivity of the barrel material. In this study, three band heaters were used, positioned in the feed zone, compression zone, and metering zone. Temperature control was carried out using a temperature controller, relay, and thermocouple to maintain temperature stability during the plastic melting process.

6. Product and Mold Base Design

The product designed in this study is an HDPE-based keychain. During the product design process, a draft angle analysis was conducted using SolidWorks to facilitate product release from the mold and to minimize defects caused by surface friction between the product and the cavity during the ejection process. After completing the product design, the mold base was designed, including the cavity, core, and runner system. The cavity design considered the shrinkage factor of HDPE material to ensure that the dimensions of the molded product remain consistent with the initial design specifications. In addition, the runner and gate systems were designed to support a more uniform material flow distribution during the cavity filling process.The results of the product design and draft angle analysis are presented in Figure 2.

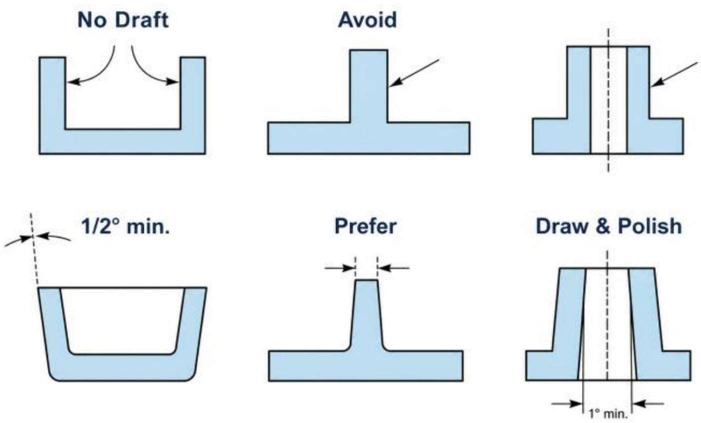

Figure 2. Product Design and Draft Angle [8]

7. Injection Process Analysis Using CAE

The injection process analysis was carried out using SolidWorks Plastics based on Computer-Aided Engineering (CAE). The simulation was performed to evaluate the flow characteristics of HDPE material during the mold-filling process and to predict potential product defects prior to manufacturing [9]. The simulation procedure began with the creation of the product model, followed by the meshing process to divide the model into smaller elements, allowing for more accurate numerical computation. After meshing, the HDPE material properties were defined, along with the injection process parameters, including variations in gate position and melt temperature. The parameters analyzed in the simulation included material flow distribution, injection pressure, filling time, weldline formation, and the potential occurrence of air traps in the molded product. The simulation results were used to determine the most optimal injection process parameters for the designed product.

3. RESULTS AND DISCUSSION

1. Screw and Barrel Design

The screw was designed as the main component of the injection system, functioning to convey, compress, mix, and melt HDPE plastic material toward the nozzle. In this study, a screw length-to-diameter ratio (L/D ratio) of 20:1 was applied. This ratio was selected because it provides a more stable melting and mixing process in small-scale injection molding machines. A higher L/D ratio improves material homogenization and flow stability during the injection process [10].

Based on this ratio, the screw diameter was designed to be 20 mm, with a total screw length of 400 mm. The screw was divided into three main zones: the feed zone, compression zone, and metering zone. The feed zone length was designed to be 240 mm, or approximately 60% of the total screw length, while the transition zone and metering zone were each 80 mm. This configuration was intended to ensure a gradual transportation and melting process of HDPE material, resulting in a more stable material flow toward the nozzle. Furthermore, the screw was designed with a feed zone depth of 3.5 mm and a metering zone depth of 1.4 mm, resulting in a compression ratio of 2.5:1. This compression ratio falls within the commonly used range for modern injection molding machines, which is 2.5:1 to 3:1 [11]. The use of this compression ratio aims to generate sufficient melt pressure without causing thermal degradation of HDPE during the injection process.

The screw pitch was designed to be 12 mm, with a helix angle of 17.7°. This selection is based on optimal plastic material flow conditions within the barrel, thereby improving material pumping efficiency [12]. The results of the screw and barrel design are presented in Figure 3.

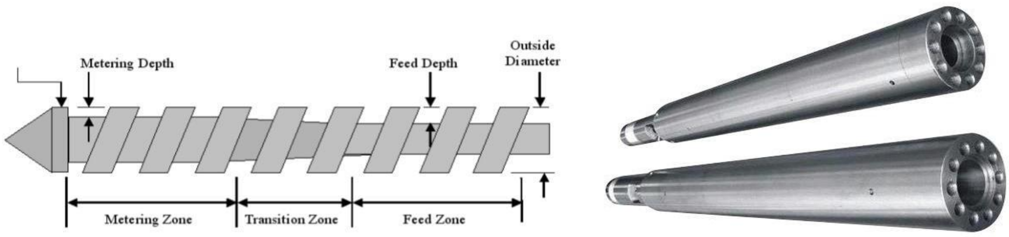

Figure 3. Screw and Barrel Design

The barrel was designed as a heating chamber for the material, with an inner diameter of 20.1 mm and an outer diameter of 50 mm. A clearance value of 0.05 mm between the screw and the barrel was applied to maintain stable screw rotation while minimizing material leakage during the injection process. The barrel material was selected as medium carbon steel due to its good mechanical strength and thermal resistance under injection molding operating temperatures

2. Motor and Transmission System Design of the Injection Unit

The drive system was designed to determine the required motor power and transmission system capable of producing the screw rotation needed for the HDPE injection process. Based on the force analysis, the total force acting on the screw was calculated to be 990.92 N, resulting from the combined effects of torsional forces on the barrel, screw flights, and screw support. Subsequently, the motor power was calculated using Eq. (1), yielding a required power of 31.1 Watts. After applying a correction factor of 1.2 using Eq. (2), the required motor power increased to 37.3 Watts, equivalent to 0.05 HP. Although the calculated power requirement is relatively low, an AC motor with a capacity of 0.25 HP and a speed of 1400 RPM was selected in this study. The selection of a higher-capacity motor was intended to provide a safety factor against load fluctuations during the melting and injection processes. The motor used is a YC712-4 type with a shaft diameter of 14 mm. To achieve the appropriate screw rotation for HDPE melting, the transmission system was designed using a gearbox reducer and a pulley-belt system. A gearbox with a reduction ratio of 1:40 was used to reduce the motor speed from 1400 RPM to 35 RPM. Furthermore, a pulley and belt transmission was applied to obtain a final screw rotation speed of 30 RPM. Based on Eq. (3), the driving pulley diameter was determined to be 76.2 mm, while the driven pulley diameter was 3.5 inches. The belt length was calculated using Eq. (4), resulting in a theoretical value of 615.44 mm. Since this size is not commercially available, a standard belt length of 635 mm was selected. The use of standard components aims to simplify the manufacturing and maintenance processes. The design of the injection unit transmission system is presented in Figure 4.

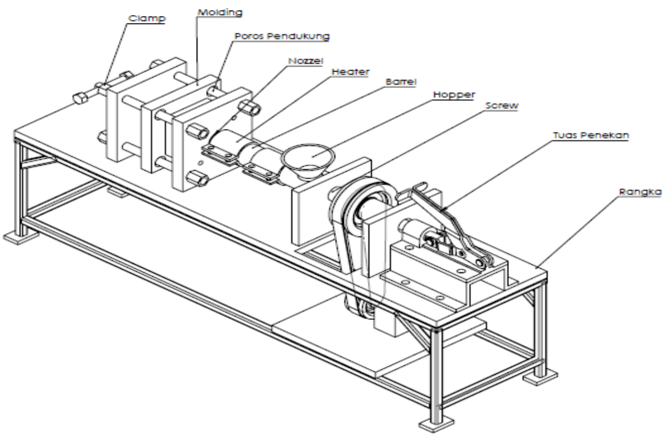

Figure 4. Injection Unit Transmission System

The use of a combination of a low-power AC motor, gearbox reducer, and pulley-belt transmission system offers several advantages, including lower energy consumption, simpler construction, and more economical manufacturing costs compared to conventional hydraulic systems. The use of mechanical transmission systems in mini injection molding machines can reduce energy consumption and operational costs in small-scale manufacturing processes.

3. Clamping Unit Design and Ball Screw Selection

The clamping system was designed to keep the mold securely closed during the injection process, preventing material leakage due to injection pressure. In this study, the clamping mechanism utilizes a ball screw system driven by an electric motor. The use of a ball screw was selected due to its high mechanical efficiency, precise motion control, and simpler construction compared to hydraulic systems. The injection pressure required to fill the cavity was determined to be 9.7 N/mm². Subsequently, based on a projected product area of 2219.91 mm², the injection force was determined to be 21,533.1 N. The projected shape of the product used in the calculation is shown in Figure 5.

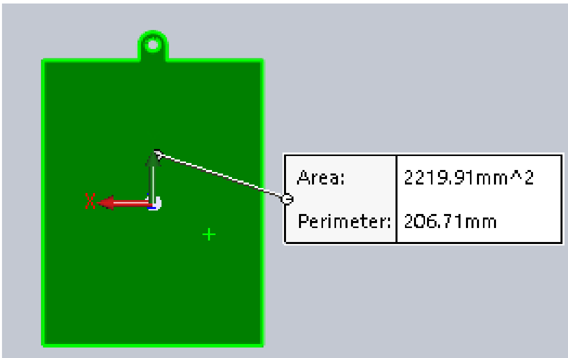

Figure 5. Projected Area of the Product

Based on the calculated injection force, the clamping force was determined to be 23,686.4 N, equivalent to 2,414.5 kgf. This value was used as the basis for selecting the ball screw specification. Based on the maximum static load capacity, a ball screw of type SFU02504-4 was selected, which can withstand loads up to 3,795 kgf, thereby ensuring safe operating conditions. The use of a ball screw mechanism in the clamping system represents one of the design contributions of this study, as it enables high-precision linear motion with a more compact construction compared to conventional hydraulic systems. Ball screw actuator systems can improve mold position stability during the injection process and reduce energy losses associated with hydraulic fluid systems. In addition, the use of a mechanical system provides advantages in maintenance and operation, particularly for small-scale machines. From a design engineering perspective, the application of a ball screw mechanism in a mini injection molding machine offers a more compact clamping system that is easier to integrate with electric motors. This approach differs from conventional injection molding machines, which typically rely on hydraulic systems with more complex structures and higher operational costs.

4. Motor and Transmission Design of the Clamping Unit

The motor selection for the clamping unit was based on the torque requirement resulting from the axial force acting on the ball screw. The required torque was calculated to be 13.6 Nm, considering a screw pitch of 4 mm and a ball screw efficiency of 90%. Subsequently, the motor power was calculated using Eq. (1), resulting in a required power of 71.17 Watts. After applying a correction factor of 1.5 using Eq. (2), the required motor power increased to 106.76 Watts. Based on these results, a DC motor type Tokushu Denso TD3284G with a power rating of 120 Watts and an output speed of 165 RPM was selected. The transmission system in the clamping unit utilizes a combination of pulley and belt to reduce the motor speed to approximately 47 RPM at the ball screw. Based on calculations using Eq. (3), the diameter of the driven pulley was determined to be 7 inches. Furthermore, the belt length was calculated using Eq. (4), resulting in a standard length of 1,092 mm. The use of a DC motor in the clamping unit provides the advantage of easier control of rotational direction, allowing the mold opening and closing process to be carried out more flexibly in the mini injection molding machine.

5. Heating Unit Design

The heating unit was designed using three band heaters installed at the feed zone, compression zone, and metering zone along the barrel. The placement of heaters in these three zones aims to achieve a more uniform temperature distribution along the barrel, allowing the HDPE melting process to occur optimally. The heat flux was calculated by taking into account the thermal conductivity of the barrel material, operating temperature, and barrel wall thickness. Based on the calculation results, the heat flux value was found to be 36,666.67 W/m². Subsequently, the heater power requirement was determined to be 575.7 Watts. Based on this result, a standard band heater with a power rating of 600 Watts, a diameter of 50 mm, and a height of 100 mm was selected for each heating zone.

The temperature control system utilizes a combination of a temperature controller, relay, and thermocouple. This system functions to maintain a stable operating temperature according to the set value. When the temperature exceeds the specified limit, the temperature controller sends a signal to the relay to cut off the electrical current to the heater, thereby bringing the temperature back within the desired range [13]. The use of a three-zone heating configuration in this study aims to produce a more uniform melt temperature distribution along the barrel. The stability of temperature distribution within the barrel significantly affects the quality of plastic material flow and contributes to reducing product defects such as short shots and sink marks in the injection molding process. Therefore, the multi-zone heating configuration applied in this study is expected to improve the stability of the recycled HDPE melting process. The overall design of the mini injection molding machine is presented in Figure 6.

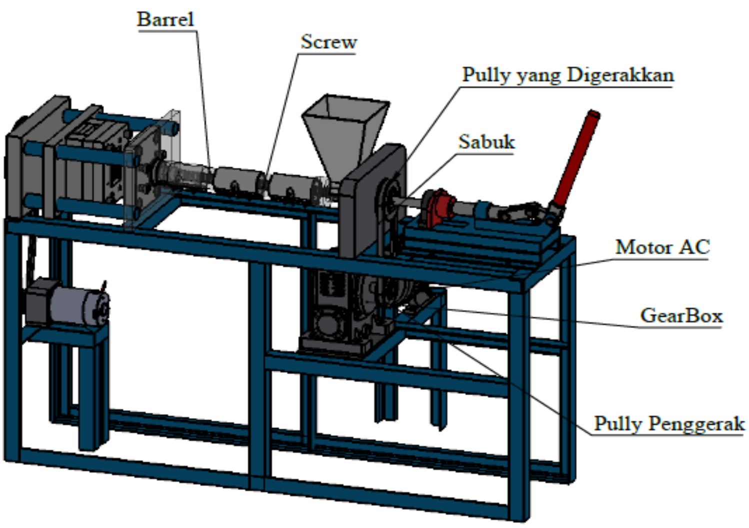

Figure 6. Design of the Mini Injection Molding Machine

The integration of a multi-zone heating system with automatic temperature control is a key factor in maintaining the stability of the HDPE melting process, particularly in mini injection molding machines with relatively small barrel capacity.

6. Product Design

The product designed in this study is an HDPE-based keychain, with dimensions adjusted to match the capacity of the previously designed mini injection molding machine. The product shape was selected by considering the level of geometric complexity, ease of manufacturing, and the flow capability of the plastic material within the mold cavity. The designed product geometry is presented in Figure 7.

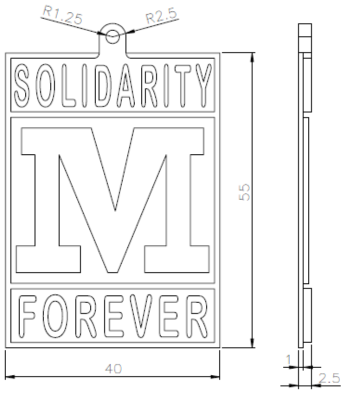

Figure 7. Product Design

In the injection molding process, product design has a significant influence on the quality of the molded output and the ease of product release from the mold. Therefore, in this study, a draft angle analysis was conducted using SolidWorks. The draft angle refers to the inclination angle on the product surface that facilitates the release of the product from the cavity and reduces defects caused by surface friction during the ejection process [14]. The draft angle used in this study is 2°. This value was selected based on design recommendations for thermoplastic products in injection molding processes, which typically range from 1° to 3° [10]. The results of the draft analysis before applying the inclination are shown in Figure 8.

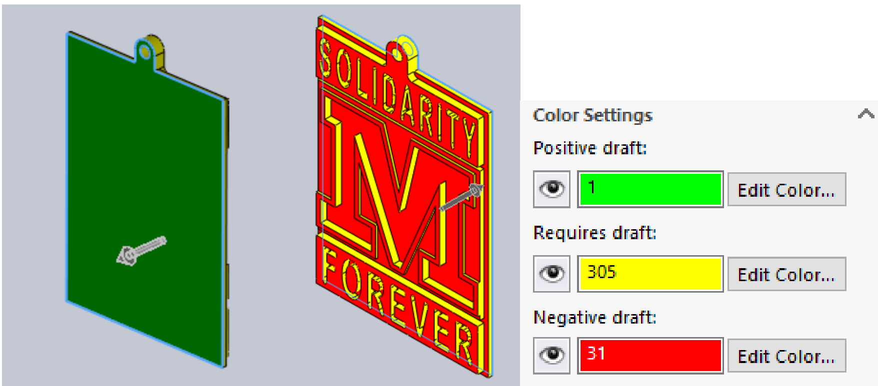

Figure 8. Draft Analysis Results Before Applying Inclination

The analysis results indicate the presence of yellow areas (requires draft), which signify that certain parts of the product do not yet have an appropriate draft angle. In addition, green areas represent positive draft formed by the cavity, while red areas indicate negative draft formed by the core. Based on the initial analysis, there are 305 regions that still require adjustment of the draft angle. Subsequently, design optimization was performed by applying a 2° draft angle to the critical areas of the product. The results of the analysis after the optimization process are shown in Figure 9.

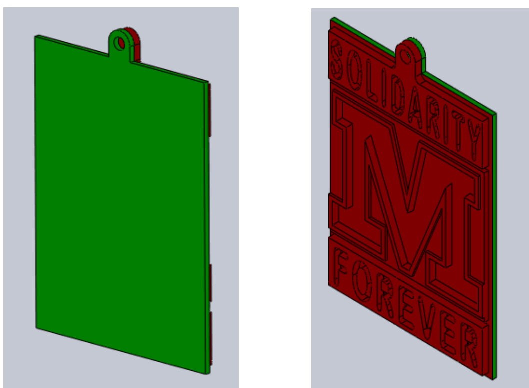

Figure 9. Draft Analysis Results After Applying Inclination

Based on the post-optimization analysis, no yellow areas were observed, indicating that all product surfaces meet the required draft angle criteria. This result shows that the product design complies with the fundamental principles of injection molding design and is expected to reduce the risk of defects during the product ejection process from the mold. The use of CAD-based draft angle analysis in this study represents an important approach to improving product design quality prior to manufacturing. Optimizing the draft angle can reduce friction between the product and the cavity, thereby minimizing deformation and surface defects in injection-molded products. In addition, the use of design simulation prior to production can reduce trial-and-error processes during manufacturing [15]. To determine the product volume more accurately, an analysis was conducted using the mass properties feature in SolidWorks. CAD software was selected due to the relatively complex geometry of the product, making manual volume calculations less effective. Based on the analysis, the product volume was found to be 3742.26 mm³, with a mass of 3.56 grams at an HDPE density of 952 kg/m³. These data were subsequently used as the basis for cavity mold design and determining the required injection material volume. In this study, the integration of CAD-based product design and draft angle analysis represents one of the research contributions in the development of a mini injection molding machine for HDPE plastic waste processing. This approach enables a more systematic and efficient product design process prior to actual manufacturing.

7. Mold Base Design

The mold base was designed to develop a mold system capable of supporting the optimal injection process of HDPE material. In this study, the mold consists of two main components: the cavity and the core. The cavity forms the outer surface of the product, while the core is used to shape the internal features according to the designed geometry. The dimensions of the cavity and core were determined based on the CAD-designed product dimensions, considering the shrinkage factor of HDPE material during the cooling process. Thermoplastic materials such as HDPE undergo volumetric shrinkage when transitioning from a molten to a solid state; therefore, the cavity dimensions must be slightly larger than the final product dimensions [10]. The shrinkage factor of HDPE used in this study was 2%. Based on the shrinkage factor of HDPE material, the cavity volume was obtained as 3971.28 mm³, with a material mass of 3.78 grams. The design results of the cavity and core using SolidWorks are presented in Figure 10.

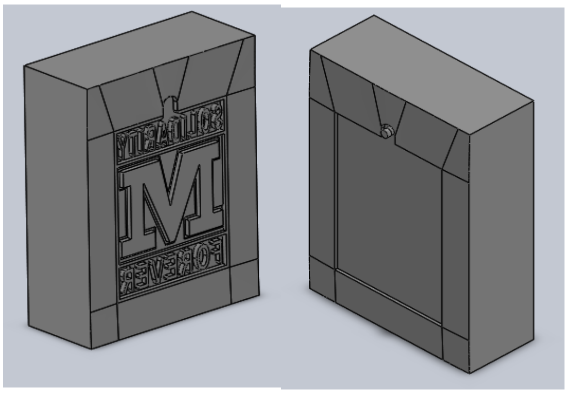

Figure 10. Core and Cavity Design

The use of CAD software in the design of the cavity and core provides advantages in improving mold dimensional accuracy and facilitating design modifications. Errors in cavity design can lead to dimensional defects in the product and uneven material flow distribution during the injection process. In addition to the cavity and core, this study also includes the design of a runner system, which functions as the channel for plastic material flow into the cavity. Since only a single cavity is used in this design, a sprue gate or direct gate type was selected. This type of gate was chosen due to its simple construction and suitability for small-scale products with relatively short material flow paths [14]. The base diameter of the sprue gate was determined to be 4 mm, while the tip diameter of the sprue gate was determined to be 3 mm. In addition, the sprue angle was designed to be 2° to support smooth material flow into the cavity. The runner system design is presented in Figure 11.

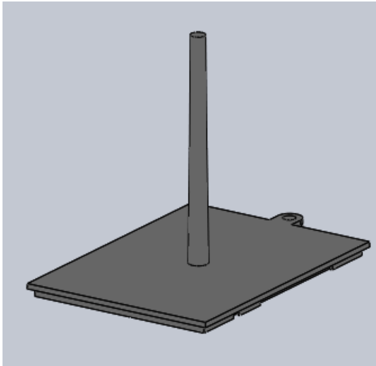

Figure 11. Runner System Design

Based on the analysis using SolidWorks, the total volume of plastic material required to fill the cavity and runner system is 4373.32 mm³, with a total mass of 4.16 grams. These data were used as the basis for determining the screw injection capacity and material requirements in the manufacturing process. In this study, the use of a simple sprue gate in the mini injection molding machine represents an approach that supports the development of low-cost mold design for small-scale HDPE plastic waste processing. This approach offers advantages in terms of ease of mold manufacturing and injection process efficiency.

8. Injection Process Analysis Using CAE

The injection process was analyzed using SolidWorks Plastics, a Computer-Aided Engineering (CAE) software, to evaluate the flow behavior of recycled HDPE material during the cavity filling process. Two key parameters were investigated: gate position and melt temperature. The analysis focused on their influence on injection pressure, material flow distribution, and the formation of product defects such as weldlines and air traps.

a. Effect of Gate Position

Three gate position variations were tested under constant process conditions: a melt temperature of 210°C and a filling time of 5 seconds. The gate position determines the material flow path into the cavity and directly affects the required injection pressure and the likelihood of defect formation.

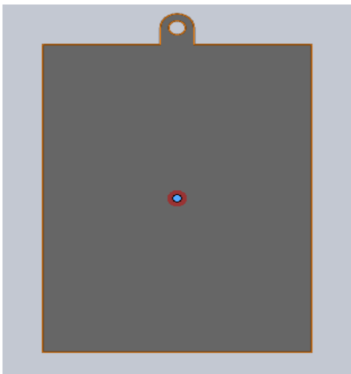

Figure 12. Three gate position variations used in the simulation

Table 1. Comparison of Injection Pressure and Weldline Condition for Each Gate Position Variation

Gate Position	Injection Pressure (MPa)	Weldline Condition
Gate 1 (Center)	6.36	Least — most uniform flow
Gate 2	8.40	Relatively high
Gate 3	7.88	Moderate

Gate 1, positioned at the center of the product, produced the lowest injection pressure (6.36 MPa) and the fewest weldlines among all three variations. This result can be attributed to the shorter and more balanced flow path from the gate to all sections of the cavity, which reduces pressure losses during filling. In contrast, Gate 2 required the highest injection pressure (8.40 MPa) due to a longer flow path, while Gate 3 yielded intermediate results with a moderate weldline distribution. These findings are consistent with the literature [14], which shows that a centrally located gate with a shorter flow path reduces the risk of weldline formation and improves cavity filling efficiency.

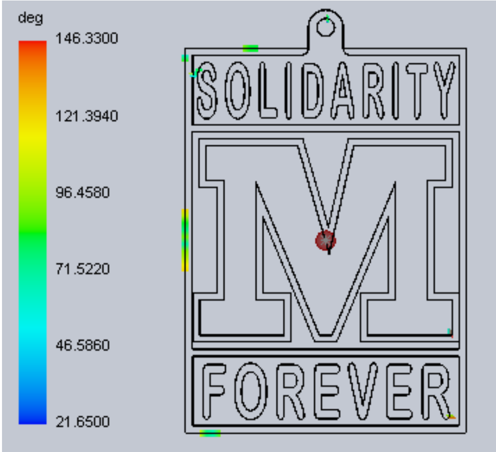

Figure 13. Simulation result for Gate 1 injection pressure of 6.36 MPa with the most uniform flow distribution

b. Effect of Melt Temperature

Following the selection of Gate 1 as the optimal gate position, the analysis proceeded to evaluate the effect of melt temperature on the injection process. Three temperature levels were tested 180°C, 210°C, and 240°C while maintaining a constant filling time of 5 seconds. Melt temperature directly influences the viscosity of HDPE: as temperature increases, viscosity decreases, allowing the material to flow more easily and fill the cavity more effectively.

Table 2. Melt Temperature Variations

Melt Temperature (°C)	Injection Pressure (MPa)	Remarks
180	11.88	Highest pressure; more weldlines and air traps
210	10.95	Improved flow distribution
240	10.40	Lowest pressure; fewest defects (optimal)

At 180°C, the relatively high viscosity of HDPE restricted material flow, resulting in an injection pressure of 11.88 MPa accompanied by a greater number of weldlines and air traps. As the temperature was raised to 210°C, the viscosity decreased and the injection pressure dropped to 10.95 MPa, with a noticeably improved flow distribution. The most favorable condition was achieved at 240°C, where the injection pressure reached its lowest value of 10.40 MPa and the number of weldline defects was minimized. This trend is in agreement with the literature [15] reports that melt temperature directly governs the flow characteristics of thermoplastic materials and the resulting injection pressure in the molding process.

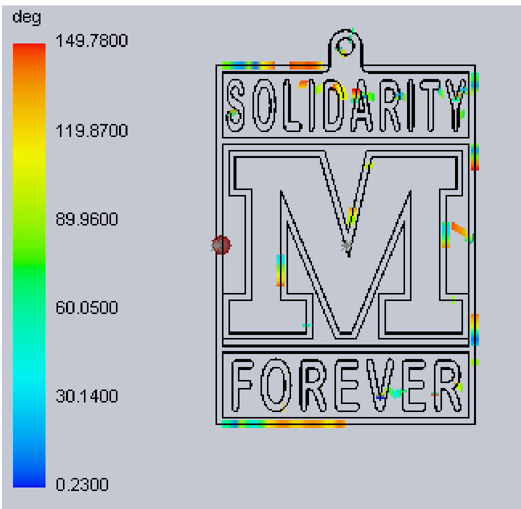

Figure 14. Simulation result at 240°C optimal injection condition

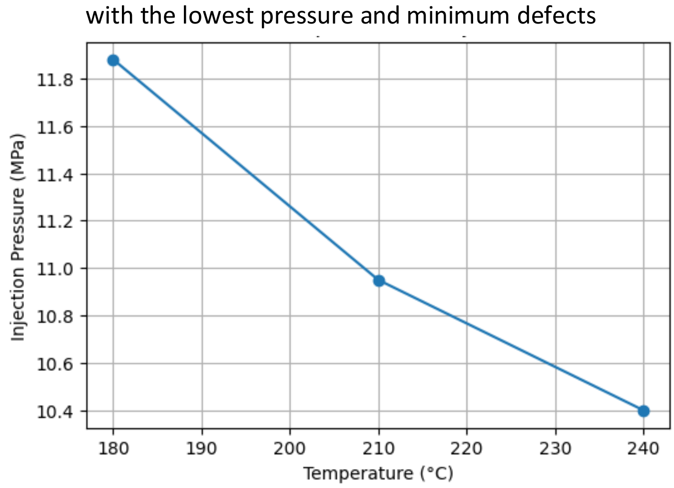

Figure 15. Relationship between melt temperature and injection pressure

Overall, the CAE simulation approach proved effective in predicting material flow behavior and potential product defects prior to the actual manufacturing process. The combination of Gate 1 and a melt temperature of 240°C was identified as the most optimal parameter setting, yielding the lowest injection pressure with the best cavity filling quality for the mini injection molding machine using recycled HDPE material.

4. CONCLUSION

This study successfully designed a mini injection molding machine for processing recycled HDPE plastic waste, utilizing a screw-based injection system and a ball screw clamping mechanism. The designed machine is capable of supporting stable melting and injection processes of HDPE material through the use of a screw with an L/D ratio of 20:1, a mechanical transmission system, and a three-zone heating system based on band heaters. The results of the injection process analysis using CAE software indicate that a gate position located at the center of the product provides a more uniform material flow distribution with fewer weldline defects compared to other positions. In addition, increasing the melt temperature leads to a reduction in injection pressure due to the decreased viscosity of HDPE material. Based on the simulation results, the optimal process parameters were obtained at a melt temperature of 240°C with an injection pressure of approximately 10 MPa. The integration of mini injection molding machine design and CAE analysis in this study demonstrates the potential for developing more economical and efficient small-scale plastic waste processing technologies, suitable for laboratory and small-to-medium enterprise (SME) applications.

AUTHORS' CONTRIBUTIONS

AZ, YM, and **NR** contributed to the conceptualization of the study, methodology development, supervision, formal analysis, data validation, writing of the original draft, and reviewing and editing the manuscript. **MY, NR,** and **AZ** were responsible for investigation, data curation, formal analysis, data visualization, and preparation of the original draft. Meanwhile, **AZ, NR,** and **YM** also contributed to conceptualization, methodology development, supervision, project administration, and manuscript review and editing.

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