

## Design and Optimization of a 12-Cavity Injection Mold for Syringe Barrel Production

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### ABSTRACT

Injection molding is an efficient manufacturing method for mass-producing plastic components, including syringe barrels used in medical applications. The barrel must be manufactured with high precision and safety standards. Injection molding simulation is needed to evaluate material distribution and identify potential product defects before production. This study aims to design a mold and simulate the injection molding process for a 12-cavity syringe barrel by optimizing the runner system. The molten plastic flow was analyzed using flow analysis software. Two runner layout variations were tested in a three-plate mold construction. Simulation results showed that layout 1 provided better performance in terms of shorter cycle time and lower material waste, making it the preferred design.

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## INTRODUCTION

Disposable plastic syringes have replaced traditional reusable glass and metal syringes. The syringe barrel, as the main component of the syringe, features a thin-walled cylindrical tube design with a high-resistance profile that functions as a piston. The use of injection molding technology in medical device production enables cost efficiency and prevents contamination during disease diagnosis and treatment. Therefore, the development of more efficient mold designs is crucial to improving the quality of medical device production (Chun, 2017).

Injection molding is the primary manufacturing method for syringe barrel production due to its capability to produce large quantities with short cycle times and consistent quality. However, suboptimal mold design can lead to imbalanced plastic flow, increased injection pressure, and reduced production efficiency. The fishbone runner system, commonly used in multi-cavity molds, often experiences flow imbalances that can affect product quality (Lin et al., 2022). Therefore, optimizing the runner system using simulation tools is essential to enhance material flow balance, reduce injection pressure, and improve production efficiency (Abdullah et al., 2023; Nitnara & Tragangoon, 2023). Additionally, the implementation of a three-plate mold system allows for automatic runner separation, reducing the need for manual processing and increasing production effectiveness (Monkova et al., 2014; Mufid et al., 2017).

This study aims to design and optimize a 12-cavity injection molding mold with a three-plate mold system for syringe barrel production. Optimization is performed using Moldflow software to enhance plastic material flow balance, minimize time and pressure imbalances within cavities, and optimize cycle time to reduce shrinkage and improve production efficiency (Zhu et al., 2021). The performance evaluation of the mold design is conducted based on Moldflow simulation results to ensure production stability on an industrial scale.

## THEORETICAL REVIEW

### *Injection molding for medical plastic components.*

Injection molding is one of the most widely used manufacturing methods for polymer parts because it enables high productivity, dimensional repeatability, and the fabrication of complex geometries with short cycle times. The process consists of melting the polymer, filling the cavity under pressure, packing to compensate for volumetric shrinkage, cooling, and ejecting the solidified part. For medical products such as syringe barrels, these stages must be controlled carefully because dimensional error, residual stress, weld lines, air traps, and warpage can directly affect product function and safety (Czepiel et al., 2023).

### *Runner system balance in multi-cavity molds.*

In a multi-cavity mold, the runner system governs how molten polymer is distributed from the sprue to each cavity. A balanced runner design is essential because unequal pressure drop and unequal filling time can cause cavity-to-cavity variation in dimensions, internal stress, and part quality. Although symmetrical layouts are commonly used, geometrical symmetry alone does not always ensure balanced filling. Shear heating can reduce melt viscosity locally, causing some cavities to fill earlier than others. Therefore, runner dimensions,

branch arrangement, and gate design must be optimized simultaneously to achieve uniform melt flow and stable production. Full-round runners are also theoretically preferred because they provide lower pressure drop than less efficient runner cross-sections (Lin et al., 2022).

#### ***Material behavior of polypropylene in syringe barrel molding.***

Polypropylene is commonly selected for injection molding because of its favorable processability, low density, chemical resistance, and broad industrial applicability. In syringe-barrel applications, the selected PP grade must also provide sufficient melt flow for thin-walled filling, dimensional stability after cooling, and compatibility with medical-use requirements. During molding, viscosity, melt temperature, shear rate, and cooling history strongly influence filling behavior and final part quality. Since PP is shear-sensitive, the flow condition in the runner and gate region becomes an important factor in determining pressure requirement, flow balance, and defect risk in multi-cavity molds (Hossain et al., 2024).

#### ***Role of simulation in mold design optimization.***

Computer-aided engineering tools such as Moldflow are widely used to predict gate suitability, filling sequence, pressure distribution, temperature evolution, and possible defects before mold fabrication. From a theoretical standpoint, simulation reduces reliance on trial-and-error methods by linking mold geometry and processing conditions to polymer rheology and heat transfer behavior. For this reason, Moldflow analysis is highly relevant in evaluating alternative runner layouts and selecting the design with better filling balance, lower pressure demand, shorter cycle-related performance, and lower material waste (Lin et al., 2022).

Based on these theoretical considerations, the present study focuses on optimizing the runner layout of a 12-cavity three-plate mold for syringe barrel production, with attention to flow balance, pressure distribution, cycle efficiency, and material waste

## **METHODOLOGY**

The product used is a 50-cc syringe barrel with dimensions like those of a standard syringe. Figure 1 shows the syringe barrel product, while Table 1 presents its specifications.



**Figure 1. Syringe barrel**

Table 1. Product specification

Description	Specification
Appearance	Transparent
Material	Polypropylene
Weight	12 grams
Thickness	1 mm

The polypropylene plastic material (Polyflam RPP1058UHF) was selected as the syringe barrel material. Polyflam RPP1058UHF is a specialized polypropylene that meets biocompatibility standards for medical applications (Ishak et al., 2018). This material is non-toxic, does not react with drugs or medical fluids, and is safe for direct contact with the human body. Compliance with FDA (Food and Drug Administration) and ISO 10993 standards makes this material highly suitable for use in disposable medical products such as syringe barrels. It has high optical transparency, allowing users to clearly see the liquid volume inside the barrel. This feature is crucial in medical applications to prevent dosage errors and ensure that the liquid is free from air bubbles (Schulman, 2022). Polyflam RPP1058UHF has good flow properties and a melting temperature suitable for the injection molding process. This facilitates the production of complex barrel shapes with thin walls and smooth surfaces, resulting in precise and high-quality products. Additionally, this material exhibits minimal deformation and shrinkage, ensuring stability in mass production.

The design process began with a literature study to understand the fundamental concepts and technical specifications of the syringe barrel, which was designed using Autodesk Inventor Professional 2024 and Moldflow Plastic Insight. After identifying the product requirements and standards, the syringe barrel type, dimensions, and materials that are safe and compliant with medical standards were determined.

The product design was carried out using Autodesk Inventor Professional 2024 to create a 3D model of the syringe barrel according to the specified specifications. Once the model was completed, the design data was input into Moldflow Plastic Insight to simulate the injection molding process, including gate location analysis, material flow, and the cooling system to prevent product deformation.

The simulation results were evaluated to determine whether the design parameters and runner system layout were optimal. The next step was to establish the mold construction using a three-plate mold, selected based on the simulation analysis results.

The detailed mold specifications were determined, covering product shape, number of cavities, runner and gate arrangement, and cooling system (Kazmer, 2007). The mold design was then created using Autodesk Inventor Professional 2024. Once the mold design was completed, working drawings were prepared, and the working mechanism of the three-plate mold in the injection molding process was explained. The final stage involved drawing conclusions

from the design and simulation results, as well as providing recommendations for further development.

## RESULTS AND DISCUSSION

Figure 2 shows the gate location analysis results. The gate position significantly affects product quality (Kuang & Gu, 2011; Zhai et al., 2005). The colors in the image represent the distribution of plastic material flow from the gate position recommended by Moldflow. The color scale ranges from blue (best) to red (worst), indicating the quality of mold filling. Blue areas represent regions with optimal material flow, while red areas indicate potential defects such as weld lines or air traps.

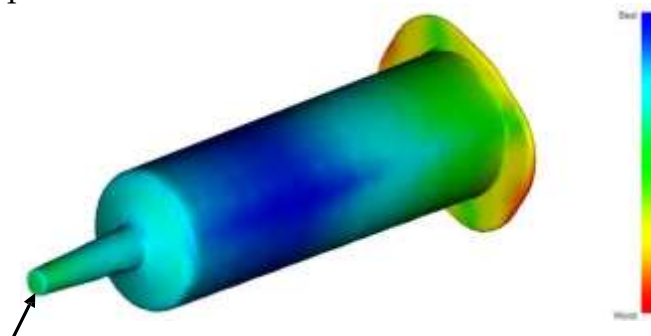
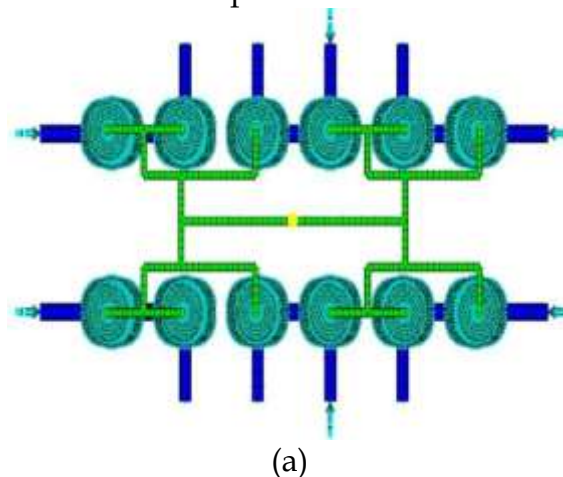
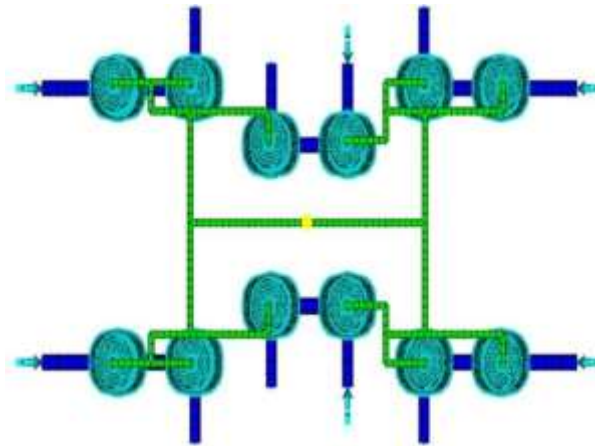


Figure 2. Gate location analysis

In this design, two runner system layouts are proposed, as shown in Figure 3. Layout 1 utilizes a symmetrical runner with a balanced runner system configuration. The plastic material flow is evenly distributed to each cavity through runners of equal length. Each cavity is connected to the runner using gates that are equidistant from the sprue.





(b)

**Figure 3. Runner layout: (a) Layout 1; (b) layout 2**

Layout 2 utilizes an asymmetrical runner with an indirect balancing approach. The main runner extends horizontally in the center, distributing the material asymmetrically to both sides of the cavities. Moldflow simulation was applied to both runner layout alternatives, followed by analysis and comparison. The analysis results are presented in Table 2.

Table 2. Runner layout analysis

Analysis	Layout 1	Layout 2
Fill Time	0.5577 s	0.5640 s
Pressure At V/P Switchover	49.50 Mpa	54.89 Mpa
Volumetric Shrinkage	13.90%	13.85%
Sink Index	2.653%	2.660%
Circuit Coolant Temperature	25.28 °C	25.32 °C
Time to Freeze Part	11.54 s	11.68 s
Time to Freeze Cold Runner	48.13 s	47.71 s
Circuit Heat Removal Efficiency	0.53	1
Maximum Temperature Part	71.68 °C	73.35 °C
Runner Waste	25.95 gram	30.80 gram

Based on the Moldflow simulation data in the table, Layout 1 is the best choice for the mold design due to the following considerations:

1. Layout 1 has a lower pressure (49.50 MPa) compared to Layout 2 (54.89 MPa). Lower pressure reduces the risk of flash and warpage.
2. Layout 1 has a volumetric shrinkage of 13.90% and a sink index of 2.653%, which is slightly better than Layout 2 (13.85% and 2.660%). Although the difference is small, Layout 1 demonstrates better dimensional stability.
3. The freezing time in Layout 1 (11.54 s for the part and 48.13 s for the cold runner) is slightly shorter than in Layout 2. This indicates more efficient cooling in Layout 1, allowing for a faster production cycle.

- Layout 1 shows a lower maximum temperature ( $71.68^{\circ}\text{C}$ ) compared to Layout 2 ( $73.35^{\circ}\text{C}$ ). A lower temperature reduces the risk of thermal deformation and thermal stress on the final product.
- Layout 1 generates less runner waste (25.95 grams) than Layout 2 (30.80 grams). This means higher material efficiency in Layout 1, making it more economical and environmentally friendly.

Based on the analysis of these parameters, Layout 1 provides lower pressure, more consistent dimensional stability, and less material waste compared to Layout 2. Therefore, Layout 1 is recommended as the optimal runner layout for the mold design in this study.

The initial stage in the basic mold design is to ensure the foundation dimensions of the mold. The product design and measurements are used to determine the fundamental mold dimensions (Goodship, 2004). After defining the dimensional requirements for the Syringe Barrel product and configuring the runner system in the Moldflow Insight application, the Cavity and Core Plate Futaba DA-S-IH 400 mm x 700 mm was selected (FUTABA, 2015). The choice of this series is related to the product analysis characteristics, which utilize the three-mold plate technique.

The primary material used in the Futaba mold foundation is S 55 C, a type of carbon steel known for its high strength, ease of machining, and excellent weldability (Pedroso et al., 2024). Additionally, this material exhibits high strength and impact resistance under both standard and elevated temperatures.

Figure 4 presents the injection mold assembly, while Table 3 describes the mold components and the materials used.

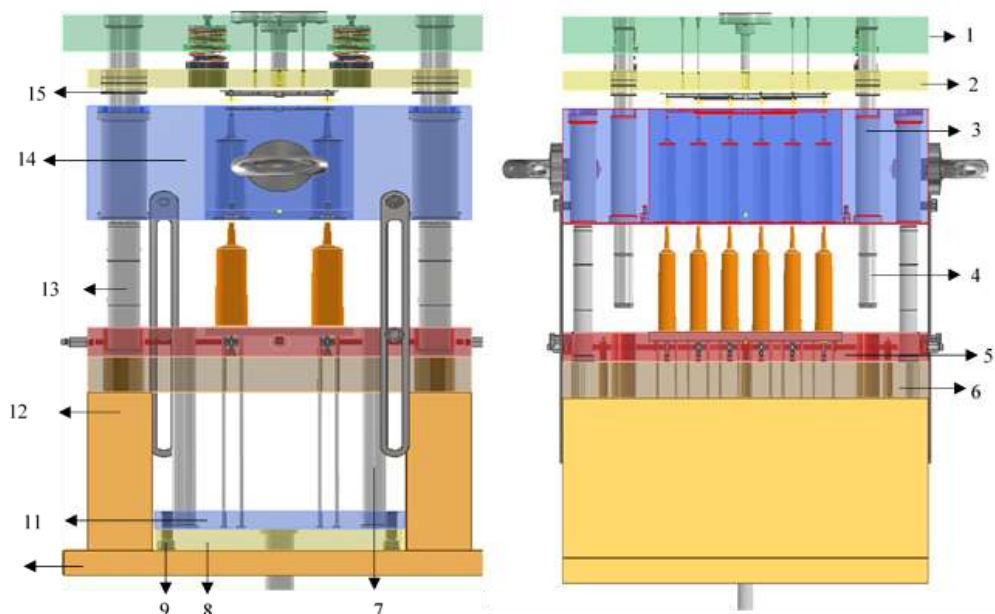


Figure 4. Mold assembly

Table 3. Mold components

No	Part Name	Material
1	Top Clamping Plate	SUJ 2
2	Runner Stripper Plate	SUJ 2
3	Guide Bush	SUJ 2
4	Support Pin	SUJ 2
5	Core Plate	S 55 C
6	Support Plate	S 55 C
7	Return Pin	SUJ 2
8	Ejector Retainer Plate	S 55 C
9	Cylinder Headcaps Screw	S 55 C
10	Bottom Clamping Plate	S 55 C
11	Core Plate	S 55 C
12	Spacer Block	SUJ 2
13	Guide Pin	S 55 C
14	Cavity Plate	S 55 C
15	Guide Bush	SUJ 2

Based on Table 3, the selection of materials for the Three Mold Plate components utilizes two main types of materials: SUJ 2 and S 55 C.

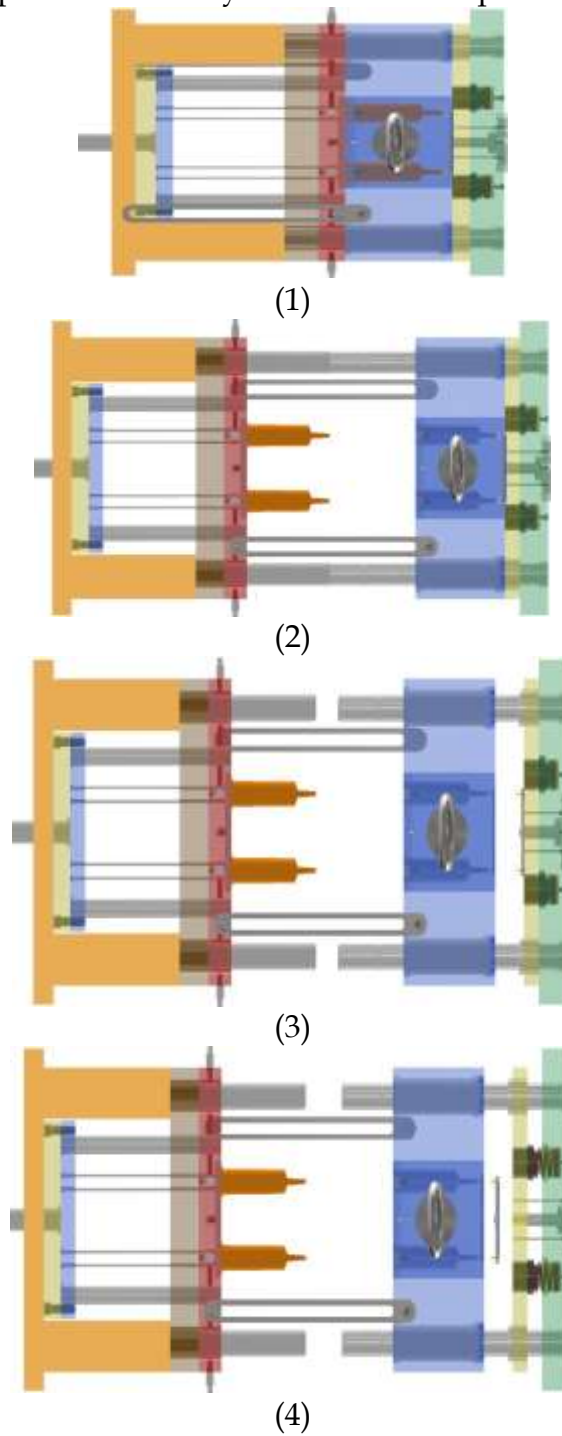
SUJ 2 is a bearing steel known for its high hardness and excellent wear resistance. This is crucial for moving components that experience high friction, such as guide bush, guide pin, and support pin, which ensure the smooth movement of the mold plates. The Top Clamping Plate and Runner Stripper Plate require high mechanical strength to withstand pressure during the injection molding process, making SUJ 2 an ideal choice.

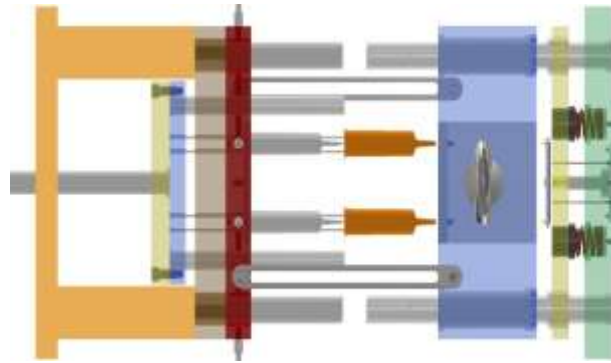
S 55 C is a carbon steel with high mechanical strength and good toughness. It is suitable for core plate, cavity plate, and bottom clamping plate components that need high durability against injection pressure. S 55 C has good machinability and can be polished to a smooth surface, making it ideal for cavity plates that influence the surface quality of the final product (Aiso & Matsumura, 2021). Compared to more expensive tool steel, S 55 C is more economical and readily available in the market, reducing the overall mold production cost.

Next, the working principle of the three-mold plate system for producing the syringe barrel is explained. The Three Mold Plates is a type of mold consisting of three main parts: The Cavity Plate, Core Plate, and Runner Stripper Plate. Its working principle aims to efficiently separate the runner and the product while facilitating the ejection process (Belcher, 2011). Figure 5 illustrates the working principle of the mold.

Figure 5.1 shows the mold in a fully closed condition, where the cavity plate is in contact with the core plate, forming a cavity space that matches the desired product shape. Molten plastic is injected through the sprue and flows through the runner located on the runner stripper plate before entering the cavity through the gate. During this process, injection pressure is applied to ensure the plastic completely and evenly fills the cavity.

Cooling occurs through cooling channels within the cavity plate and core plate, allowing the plastic to solidify into the desired product shape.





(5)

**Figure 5. Working principle of three-mold plates**

After the plastic has sufficiently cooled and solidified, the mold begins to open, as shown in Figure 5.2. At this stage, the runner stripper plate moves away from the core plate, while the cavity plate remains in its initial position. This movement separates the runner from the gate, keeping the runner attached to the runner stripper plate while the product remains on the core plate. This design allows for automatic runner separation without the need for manual cutting.

Next, in Figure 5.3, the cavity plate moves away from the core plate. This action fully opens the cavity, revealing the product still attached to the core plate. At this stage, the product has not yet detached from the core plate because the ejector system has not been activated. The separation between the cavity plate and the core plate also facilitates airflow, reducing vacuum effects that could cause product deformation.

Once the mold is fully open, the ejection mechanism is activated, as shown in Figure 5.4. The ejector pins attached to the ejector plate begin to push the product out of the core plate. This movement is supported by return pins, which ensure balance and uniformity in the ejector motion. The ejector pins are designed to prevent damage or marks on the product, maintaining surface quality.

In Figure 5.5, the product detaches from the core plate and automatically falls through a prepared chute. The ejector plate then returns to its original position with the help of return pins, making the mold ready for the next production cycle.

## **CONCLUSIONS AND RECOMMENDATIONS**

The conclusion of the Three Mold Plates mold design study for the syringe barrel indicates that using Layout 1 in the runner system provides more optimal results compared to Layout 2. Layout 1 offers lower injection pressure, more efficient cooling time, and reduced material waste. These factors contribute to more consistent product dimensions and minimize defects such as warpage and sink marks.

The selection of SUJ 2 for high-precision components and S 55 C for structural components has proven effective in meeting mechanical strength and wear resistance requirements. The mold design with a Three Mold Plates configuration successfully optimizes material flow and shortens the production cycle time, thereby improving the efficiency of the injection molding process.

## FURTHER STUDY

Future work should investigate the influence of processing parameters such as melt temperature, mold temperature, injection speed, packing pressure, and cooling time on the quality of syringe barrel products. These variables may affect shrinkage, sink marks, warpage, and cycle stability in mass production. Third, optimization may be extended to gate dimensions, cooling channel design, and cavity balancing in order to further improve product uniformity and production efficiency. In addition, dimensional, mechanical, and visual quality evaluation of the molded syringe barrels should be conducted to ensure that the final products satisfy medical-use requirements. Since this study used polypropylene medical-grade material and a three-plate mold system for automatic runner separation, further research may also evaluate long-term manufacturability, maintenance performance, and overall production cost under industrial operating conditions.

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