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Process Optimization of Injection Molding for High-Precision Cosmetic Dispenser SealCaps: A Process Capability (Cp, Cpk) Analysis

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Abstract

The dimensional stability of the SealCap, a critical polymer component in cosmetic dispenser pumps, is crucial for ensuring consistent discharge volume and preventing functional defects. This study aimed to optimize the injection molding process for high-precision SealCaps by analyzing changes in machine type and processing conditions. We conducted a comparative analysis between a large 64-cavity high-speed machine and a small 12-cavity precision machine. For the precision machine, three conditions were tested by varying the holding pressure time (3.0–3.5 s), resulting in cycle times of 7.2–7.7 s. The dimensional stability of the SealCap's outer diameter and the discharge volume of assembled pumps were evaluated using process capability indices (Cp and Cpk). The results demonstrated that the small precision machine under condition C (7.7 s cycle time) achieved the highest process capability, with a dimensional Cpk of 1.91, significantly outperforming the large high-speed machine (Cpk = 0.53). Similarly, the discharge volume Cpk was highest under condition C at 1.31, indicating superior functional consistency. These findings indicate that a longer cycle time enhances process stability and reduces inter-cavity variation, leading to improved dimensional quality. Therefore, condition C was identified as the optimal manufacturing process, confirming that utilizing a precision injection molding machine with optimized parameters is a highly effective strategy for producing high-quality, high-precision polymer components.

Keywords: injection molding; process optimization; process capability index (Cpk); cosmetic dispenser; dimensional stability

1. Introduction

The demand for high-precision polymer components is paramount in various industries, where dimensional accuracy directly impacts functional performance and product reliability. In the cosmetics industry, dispenser pumps serve as a prime example, requiring consistent and reliable operation for customer satisfaction. These devices consist of several intricately assembled polymer parts, where the SealCap is a particularly critical internal component, as illustrated in Figure 1. The SealCap's primary function is to create the dynamic seal necessary for pressure generation. Achieving the required tolerances for this component often demands advanced micro-injection molding techniques[1]. Even minute dimensional deviations can compromise the integrity of the assembly, leading to significant failures such as inconsistent dosing or leakage.

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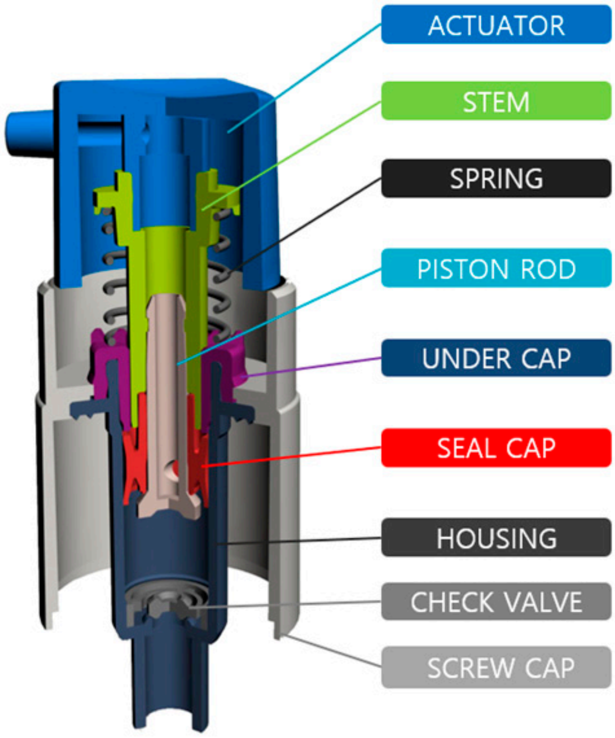


Figure 1. Schematic of the cosmetic dispenser pump assembly. This exploded, cross-sectional view illustrates the main components and their assembly order. The figure highlights the location and functional importance of the SealCap (the component of interest in this study), which is critical for creating the internal seal required for consistent product discharge.

It is well-established that injection molding process parameters—such as holding pressure, cooling time, and mold temperature—critically influence the shrinkage and warpage of molded parts, and thus their final dimensional quality [2,3]. Research in this field is extensive, addressing these challenges not only through process optimization but also through the development of specialized equipment, for instance, to handle materials like recycled polymer waste [4]. Concurrently, recent advancements have moved towards integrating sophisticated analysis tools, such as multiscale modeling and in-situ characterization, to gain a deeper understanding of polymer behavior during the molding process [5,6].

While traditional optimization focuses on minimizing defects, recent trends emphasize statistical process control (SPC) to ensure long-term stability. The process capability index (Cpk) is an effective metric for this purpose, and it has been successfully applied as a target response for optimizing injection molding parameters. However, a critical challenge in mass production is the "cavity-to-cavity variation" in multi-cavity molds, which significantly degrades overall process capability. Achieving a balanced filling across all cavities is a complex problem influenced by runner and gate design, polymer viscosity, and process conditions [7]. Despite the proposal of theoretical models and systematic approaches, empirical research comparing the process stability of large-scale, high-speed systems against small-scale, precision-oriented systems remains limited. Furthermore, a quantitative correlation between the dimensional Cpk of a component and the functional performance consistency of the final assembled product has not been fully investigated.

This study aims to bridge this gap by conducting a systematic process optimization for a high-precision cosmetic dispenser SealCap. The primary objectives are: (1) to com-pare the process capability of a large 64-cavity high-speed injection molding system with that of a small 12-cavity precision system; (2) to investigate the effect of holding pressure time and cycle time on dimensional stability; and (3) to quantitatively correlate the di-mensional Cpk with the functional performance (discharge volume Cpk) of the assembled pump. By achieving these objectives, this research seeks to identify optimal manufactur-ing strategies for high-precision polymer components.

2. Materials and Methods

2.1. Materials

The SealCaps were manufactured using a blend of low-density polyethylene (LLDPE) and high-density polyethylene (HDPE). This material combination was selected for its excellent processability, flexibility, chemical resistance, and suitability for cosmetic packaging applications, being harmless to the human body and fully recyclable. The key physical properties of the LLDPE and HDPE used in this study are detailed in Table 1.

Table 1. Physical properties of the LLDPE and HDPE used in this study.

Property	Melt Index (MI) [1]	Tensile Strength at Yield	Density	Elongation at Break
Test Method	ASTM D1238	ASTM D638	ASTM D1505	ASTM D638
Unit	g/10 min	kgf/cm²	g/cm³	%
LLDPE	20	150	0.924	600
HDPE	5	260	0.965	500

[1] The test conditions for Melt Index were a load of 2.16 kg at a temperature of 190 °C.

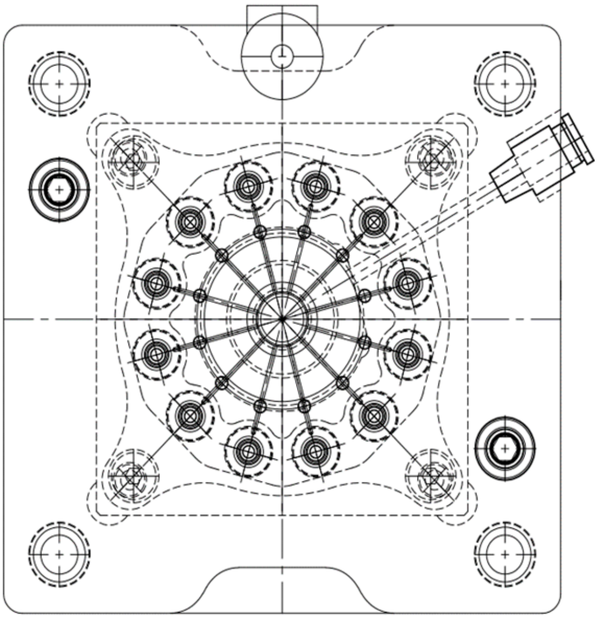
2.2. Injection Molding Equipment

Two distinct injection molding systems were used for a comparative analysis. The primary system was a small-scale, high-precision injection molding machine (MicroPower 15ton, Wittmann Battenfeld, Austria), the detailed specifications of which are provided in Table 2. This machine was equipped with a custom-designed 12-cavity mold (150 mm × 150 mm × 169 mm) utilizing a side-gate system. Figure 2 shows a schematic of the injection mold and the final molded SealCap part. For baseline comparison, a conventional large-scale, 64-cavity high-speed injection molding machine was used, representing a standard mass-production process.

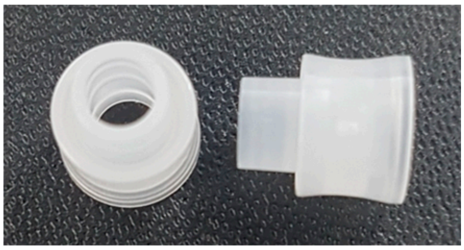
Table 2. Specifications of the high-precision injection molding machine (MicroPower 15ton).

Parameter	Unit	Specification
Clamping force	kN	150
Opening stroke / Opening force	mm/kN	100 / 15
Ejector stroke / Ejector force	mm/kN	40 / 5
Dosing screw diameter	mm	14
Screw L/D ratio	-	20
Specific injection pressure	Mpa	250
Injection plunger diameter	mm	8
Max. screw speed	rpm [1]	200
Nozzle stroke / Contact force	mm/kN	230 / 40
Injection speed	mm/s	750
Barrel heating power (nozzle incl.)	kW	2.45
Number of heating zones	-	4
Dimensions (Length × Width × Height)	m	2.6 × 1.3 × 2.2(2.52)
Net weight	kg	2400
Mold height (min. / max.)	mm	100 / 300

[1] revolutions per minute.



(2a)



(2b)

Figure 2. Schematic of the multi-cavity injection mold and the final molded part. (2a) Top-view schematic of the 12-cavity mold used with the high-precision injection molding machine, illustrating the radial arrangement of the cavities. (2b) Photograph of a single, as-molded polymer SealCap, which is the high-precision component investigated in this study.

2.3. Experimental Conditions

To investigate the effect of processing parameters on the dimensional stability of the SealCap, four distinct experimental conditions were established, as summarized in Table 3. Conditions #A, #B, and #C were performed on the small-scale precision machine, where the holding pressure time was systematically varied from 3.0 s to 3.5 s, resulting in cycle times of 7.2 s, 7.4 s, and 7.7 s, respectively. Other parameters, including a holding pressure of 385 bar, a coolant temperature of 15 °C, and a cylinder nozzle temperature of 170 °C, were kept constant. Condition #D was performed on the large-scale high-speed machine, with a cycle time of 13.0 s, a coolant temperature of 19 °C, and a nozzle temperature of 180 °C, serving as the benchmark for a conventional process.

Table 3. Summary of processing parameters for the four experimental conditions (#A, #B, #C, and #D).

Parameter	Unit	Condition #A	Condition #B	Condition #C	Condition #D
Machine Type	-	Small Precision	Small Precision	Small Precision	Large High-Speed
Holding Pressure Time	sec	3.0	3.2	3.5	-
Holding Pressure	Bar	385	385	385	-
Cycle Time	sec	7.2	7.4	7.7	13.0
Coolant Temperature	°C	15	15	15	19
Cylinder Nozzle Temp.	°C	170	170	170	180

[1] Not Applicable: These parameters were part of the standard benchmark process on the large-scale machine and were not varied as independent variables in this study's design.

2.4. Measurement and Analysis

The outer diameter of the molded SealCaps was measured using a non-contact image measurement system (IM-6225, Keyence, Japan) with a resolution of 0.001 mm. The target specification for the outer diameter was 7.30–7.35 mm. For conditions #A, #B, and #C, a total of 960 samples (12 cavities × 80 shots) were sampled for each condition. For condition #D, 1,152 samples (64 cavities × 18 shots) were collected.

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To assess functional performance, the molded SealCaps were assembled into complete cosmetic dispenser pumps. The discharge volume per actuation was measured by dispensing water onto a precision electronic balance (FX-200i, AND, Japan) with a resolution of 0.001 g. The quality specification for the discharge mass was 0.15 ± 0.02 g. A total of 1,008 assembled pumps were tested for each of the four conditions.

The stability and capability of the injection molding process under each condition were quantitatively evaluated using Minitab® statistical software. The process capability indices, Cp and Cpk, were calculated for both the dimensional (outer diameter) and functional (discharge volume) data. Cp represents the potential process capability assuming the process is centered, while Cpk accounts for any shift in the process mean relative to the specification limits, thus reflecting the actual process performance.

3. Results and Discussion

3.1. Effect of Molding Conditions on Dimensional Stability

The dimensional stability of the molded SealCaps, a critical factor for their functional performance, was quantitatively evaluated using the process capability indices Cp and Cpk. Table 4 summarizes the statistical outcomes for the outer diameter measurements under the four experimental conditions, with the process capability results graphically represented in Figure 3.

A clear trend emerged from the analysis. Condition #C, which utilized the small precision machine with the longest cycle time (7.7 s), exhibited the highest process capability. It achieved a Cp value of 2.00 and, more importantly, a Cpk value of 1.91. This Cpk value significantly exceeds the industry standard of 1.67 for high-precision manufacturing (often associated with Six Sigma quality levels), indicating a highly capable and centered process. In contrast, condition #D, representing the large-scale high-speed manufacturing process, yielded the lowest capability with a Cpk of just 0.53, which is well below the generally accepted minimum of 1.33 for a capable process. Conditions #A (Cpk = 1.15) and #B (Cpk = 1.24) on the precision machine showed acceptable but lower capabilities compared to condition #C.

The discussion of these results highlights two key engineering insights. Firstly, within the precision molding setup (conditions #A, #B, #C), a longer cycle time, directly resulting from an increased holding pressure time, led to a substantial improvement in process capability. This is attributed to a more effective packing stage, where the extended holding pressure compensates for volumetric shrinkage more completely, and a more stable cooling phase, which reduces thermal variations. Secondly, the stark difference between condition #C (Cpk=1.91) and #D (Cpk=0.53) underscores the inherent challenge of maintaining dimensional consistency across a large number of cavities (64 vs. 12). The increased variability in the large-scale system likely stems from non-uniformities in melt flow, pressure distribution, and thermal gradients across the expansive mold, which ultimately compromises the dimensional precision of individual parts.

Table 4. Statistical summary and process capability indices (Cp and Cpk) for the outer diameter of the SealCaps under the four experimental conditions.

Parameter	Unit	Condition #A	Condition #B	Condition #C	Condition #D
Machine Type	-	Small Precision	Small Precision	Small Precision	Large High-Speed
Sample Mean	mm	7.33222	7.32831	7.32612	7.31236
Sample Size	ea	960	960	960	1,152
Standard Deviation	-	0.00517131	0.00583075	0.00416017	0.00773477
Process Capability	Cp	1.61	1.43	2.00	1.08
Process Capability	Cpk	1.15	1.24	1.91	0.53

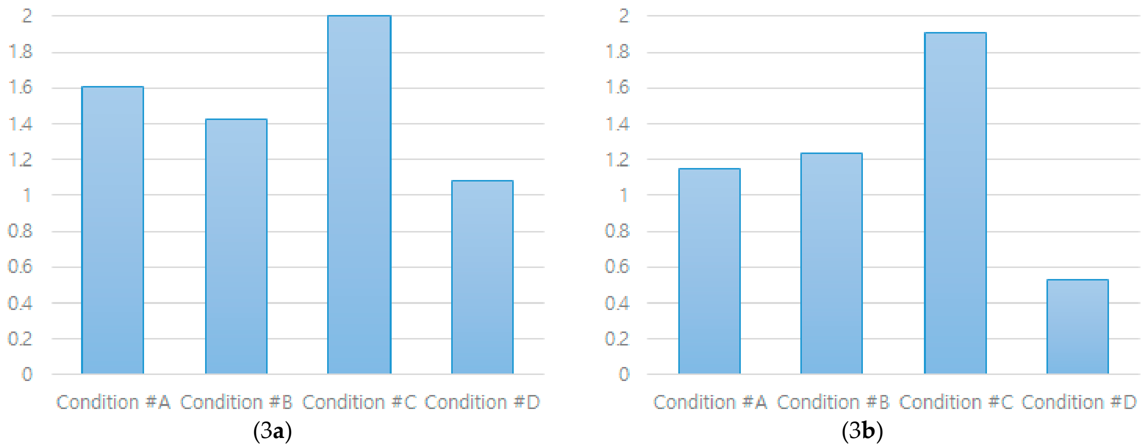

Figure 3. Process capability analysis for the outer diameter of the SealCaps under four different molding conditions (#A, #B, #C, and #D). (3a) Comparison of the potential process capability index (Cp). (3b) Comparison of the actual process capability index (Cpk), which accounts for the process mean shift. Condition #C (small precision machine, 7.7 s cycle time) demonstrates significantly superior capability in both indices compared to the other conditions, especially the conventional high-speed process (Condition #D).

3.2. Analysis of Inter-Cavity Variation

To further investigate process stability, the variation in dimensional quality among the different cavities of the 12-cavity mold was analyzed. Figure 4 provides a schematic layout of the mold, indicating the numbering and spatial position of each cavity, which serves as a reference for the subsequent analysis. Figure 5 illustrates the Cpk values for each of the 12 cavities as a function of cycle time. The results reveal a significant trend: as the cycle time increased from 7.2 s (Condition #A) to 7.7 s (Condition #C), the variability of Cpk values across the cavities markedly decreased. In Condition #A, there was a considerable spread in process capability between cavities, indicating inconsistent part quality. This variation was progressively reduced in Condition #B and became most uniform in Condition #C, where all cavities demonstrated a consistently high Cpk.

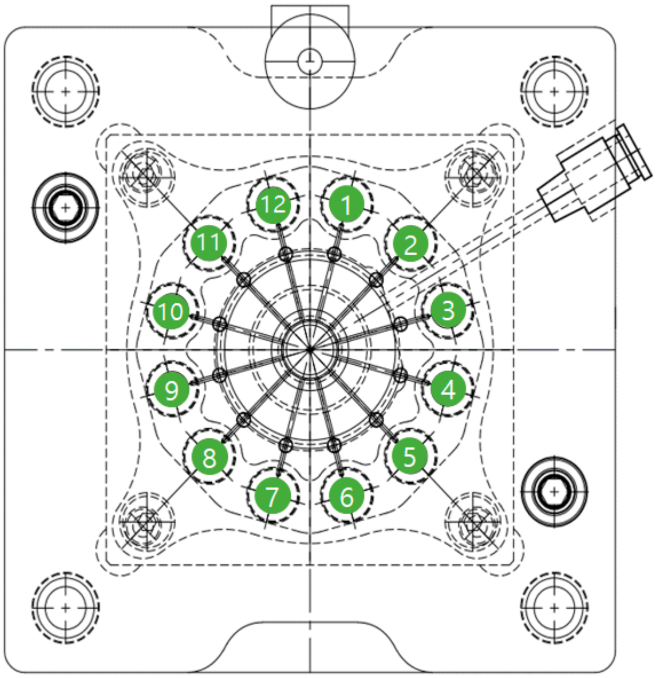

Figure 4. Schematic layout of the 12-cavity mold used in the precision injection molding process. The numbers indicate the specific designation and radial arrangement of each cavity. This map provides a spatial reference for the inter-cavity variation analysis presented in Figure 5.

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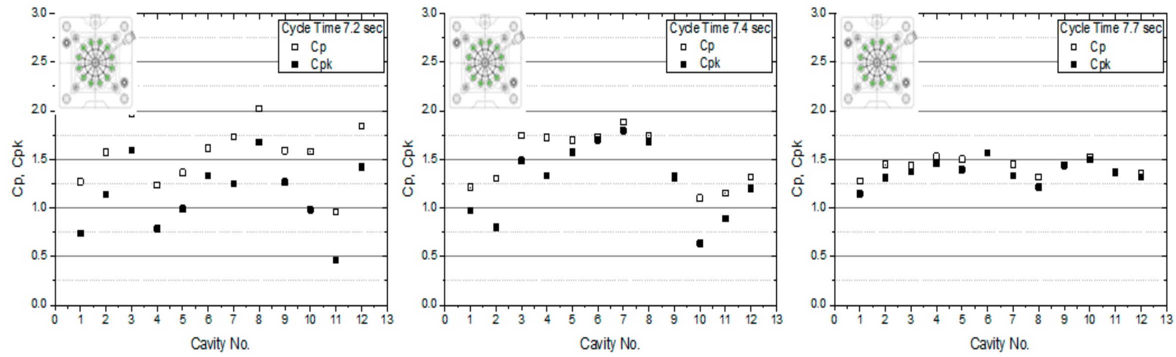
This finding suggests that a longer cycle time is crucial for achieving thermal and rheological homogeneity within a multi-cavity mold. A shorter cycle time may result in incomplete or non-uniform packing and cooling, particularly in cavities located further from the sprue, leading to greater dimensional discrepancies. By extending the cycle time, the pressure and temperature distributions across all cavities are allowed to equalize more effectively before part ejection. This ensures that each cavity produces a dimensionally consistent SealCap, which is a critical requirement for high-precision, multi-cavity injection molding.



(5**a**) (5**b**) (5c)

Figure 5. Analysis of inter-cavity variation in dimensional stability for the 12-cavity precision injection molding process. The plots show the process capability indices (Cp and Cpk) for each individual cavity under three different cycle times: (5a) 7.2 s (Condition #A), (5b) 7.4 s (Condition #B), and (5c) 7.7 s (Condition #C). A clear trend of reduced variability in Cpk values across the cavities is observed as the cycle time increases, indicating enhanced process homogeneity and part-to-part consistency.

3.3. Correlation Between Dimensional Stability and Functional Performance

The ultimate goal of enhancing dimensional stability is to improve the functional performance of the final product. To validate this relationship, the discharge volume of assembled dispenser pumps was measured, and its process capability was analyzed, as summarized in Table 5 and Figure 6.

Table 5. Statistical summary and process capability indices (Cp and Cpk) for the discharge volume of assembled pumps under the four experimental conditions.

Parameter	Unit	Condition #A	Condition #B	Condition #C	Condition #D
Machine Type	-	Small Precision	Small Precision	Small Precision	Large High-Speed
Sample Mean	g	0.151353	0.151567	0.149978	0.152234
Sample Size	ea	1,008	1,008	1,008	1,008
Standard Deviation	-	0.0061661	0.00535689	0.00506526	0.00603378
Process Capability	Cp	1.08	1.24	1.32	1.10
Process Capability	Cpk	1.01	1.15	1.31	0.98

The functional performance results directly mirrored the dimensional stability trends. Condition #C, which yielded the highest dimensional Cpk, also demonstrated the highest process capability for discharge volume, with a Cpk of 1.31. This value meets the general industry requirement for a capable process (Cpk ≥ 1.33). Conversely, condition #D, with the lowest dimensional stability, also showed the poorest functional consistency (Cpk = 0.98), failing to meet the capability standard.

This strong positive correlation confirms the initial hypothesis of the study: the precise dimensional control of the SealCap is directly linked to the reliable performance of the dispenser pump. The discussion points to the underlying mechanism: a highly consistent outer diameter on the SealCap ensures a uniform and reliable seal within the pump housing during actuation. This consistent sealing action leads to stable pressure generation and, consequently, a highly repeatable

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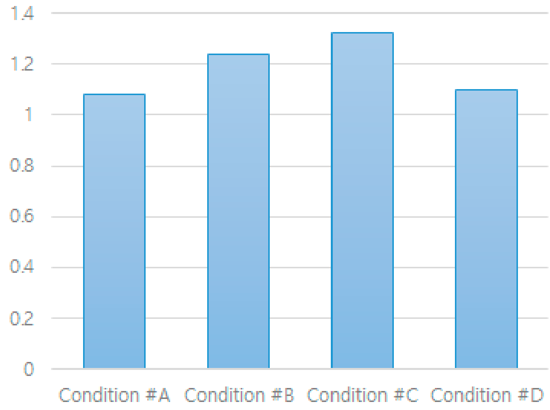
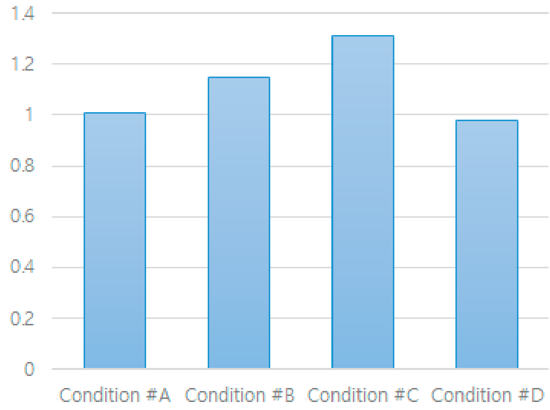
discharge volume. This result empirically establishes that optimizing for dimensional process capability is an effective and predictive strategy for achieving high functional quality in assembled mechanical products like cosmetic dispensers.



(6a)



(6b)

Figure 6. Process capability analysis for the functional performance (discharge volume) of assembled pumps fabricated under the four molding conditions. (6a) Comparison of the potential process capability index (Cp). (6b) Comparison of the actual process capability index (Cpk). The results show a strong correlation with the dimensional stability trends observed in Figure 3, with Condition #C achieving the highest Cpk value of 1.31, indicating the most consistent functional performance.

4. Conclusions

In this study, we systematically investigated the optimization of the injection molding process for high-precision polymer SealCaps, a critical component for cosmetic dispenser pumps, by comparing different manufacturing systems and process parameters. The dimensional stability of the SealCaps and the functional performance (discharge volume) of the assembled pumps were quantitatively evaluated using process capability indices (Cp and Cpk). The key findings of this research are as follows:

A significant performance gap was identified between the small-scale, 12-cavity precision molding machine and the large-scale, 64-cavity high-speed machine. The optimized process on the precision machine (Condition #C) achieved a dimensional Cpk of 1.91, which was vastly superior to the 0.53 Cpk obtained from the conventional high-speed process, highlighting the critical impact of machine selection and scale on process stability.

Within the precision molding process, a longer cycle time (7.7 s), resulting from an extended holding pressure time (3.5 s), was proven to be the most critical factor for enhancing both dimensional stability and inter-cavity consistency. This condition effectively minimized process variability, leading to the highest and most uniform quality across all cavities.

A strong positive correlation between the dimensional precision of the SealCap and the functional consistency of the final pump assembly was empirically established. The process condition that yielded the highest dimensional Cpk also produced the most stable discharge volume, with a Cpk of 1.31, confirming that precise dimensional control is a direct and effective pathway to ensuring high functional reliability.

In conclusion, this study demonstrates that for manufacturing high-precision polymer components where functional performance is critical, a strategy focused on enhancing process stability via optimized cycle times on a precision machine is more effective than a conventional high-speed, mass-production approach. The optimal condition identified (Condition #C) provides a robust and reliable manufacturing process that meets the stringent quality demands of the cosmetics industry, offering a practical solution for reducing defect rates and improving overall product value.

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Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org, Table S1: Raw measurement data for the outer diameter of all SealCap samples under conditions #A, #B, #C, and #D; Table S2: Raw measurement data for the discharge volume of all assembled pump samples under conditions #A, #B, #C, and #D.

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Data Availability Statement: The data presented in this study are available in the article and the associated Supplementary Material.

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Abbreviations

The following abbreviations are used in this manuscript:

ASTM	American Society for Testing and Materials
Cp	Process Capability Index
Cpk	Process Capability Index (Adjusted for Process Centering)
HDPE	High-Density Polyethylene
LLDPE	Low-Density Polyethylene
MI	Melt Index
SPC	Statistical Process Control

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