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Scientific Molding and Adaptive Process Quality Control with External Sensors for Injection Molding Process

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Abstract: This study established a real-time measurement system to monitor the melt quality in an injection molding process using a pressure sensor installed on the nozzle and a strain gauge installed on the tie bar. Based on the sensing curves from these two external sensors, the characteristic values of nozzle pressure and clamping force were used to optimize parameters. This study defined product weight as a quality indicator and developed a scientific molding parameter setup process. The optimization sequence of parameters is injection speed, V/P switchover point, packing pressure, packing time, and clamping force. Finally, an adaptive process control system was established based on the online quality characteristic values to maintain product quality consistency. Continuous production experiments were conducted at two sites to verify the system's effectiveness. The results revealed that the optimized process parameters can ensure product weight stability during long-term production. Furthermore, using the adaptive process control system further enhanced product weight stability at both sites, reducing the standard deviation of product weight to 0.0289 g and 0.0148 g, and the coefficient of variation to 0.065% and 0.035%, respectively.

Keywords: injection molding process; external sensor; scientific molding parameter setup; online quality characteristic value; adaptive process control system

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1. Introduction

In the context of the continuous development of industrial automation, the concept of smart machines plays a pivotal role in driving forward Industry 4.0. The design of smart machines enables them to be connected, visible, transparent, predictable, and adaptively controllable. By connecting different equipment and systems, data are visualized, and the causes of machine or production abnormalities are made transparent. This allows for a clear understanding of the reasons behind the problems. Additionally, predictions can be made for the production process. When abnormalities occur in the product, the adaptive control system automatically adjusts process parameters to counteract external disturbances, improving production efficiency and maintaining product quality consistency.

In the injection molding process, the setting of process parameters significantly influences product quality. Different process parameter settings can result in varying pressure profile characteristics. Pressure profiles are highly related to product quality, can be used to optimize process parameters, and also serve as the foundation for establishing a scientific molding parameter setup.

To capture the changes in molten material during the injection molding process, previous studies have installed sensors on machines and molds to collect data such as temperature, pressure, and clamping force, analyzing the correlation between these data and product quality. Gao et al. [1] used sensors to monitor melt pressure, temperature, velocity, and viscosity and employed regression models to predict product quality, demonstrating that sensor-based in situ quality monitoring can significantly improve productivity and achieve quality control. Su et al. [2] utilized a nozzle pressure sensor and a tie-bar strain gauge to collect data, conducting experiments with materials of three different viscosities. The V/P switchover point was determined based on the nozzle peak pressure, while the appropriate clamping force was identified using the clamping force peak. Tsou et al. [3] used single and multiple pressure sensors to monitor changes in residual stress near the gate during different processes and conducted temperature disturbance experiments to verify the effectiveness of process variables, indicating that the process variables defined using multiple sensors were highly correlated with residual stress near the gate. Ke et al. [4] used the melt pressure curve to define quality indexes and examined the correlations of these quality indexes with the geometric width of the injection molded parts. The quality indexes were input into a multilayer perceptron model for learning, and the accuracy of the model's prediction was verified. The results indicated that the training and testing accuracy of the geometric width quality indexes exceeded 92%. Su et al. [5] installed strain sensors on the tie bars and defined an appropriate clamping force peak value as the control basis for clamping force through continuous production experiments, showing that the clamping force peak value not only optimized the clamping force but could also be used to predict product quality. Chang et al. [6] collected data using mold cavity pressure sensors and set different packing pressure methods for experiments, indicating that using multi-stage packing pressure could improve the tensile strength, total shrinkage and warpage of the product. Chen et al. [7] installed five sensors in the mold cavity and discovered through experiments with different process parameter settings that the pressure integral has a higher correlation with the product weight. Chen et al. [8] installed pressure sensors in the cavity, runner, and nozzle to measure pressure changes during the filling stage and used two different materials to study the melt flow behavior and melt quality indexes. The experiments revealed that the peak pressure had the highest correlation with product weight, while the pressure gradient showed the lowest correlation.

Some studies have utilized data to define online quality characteristic values, which are subsequently used to optimize process parameters to achieve the best product quality. Liou et al. [9] proposed a method for defining online quality characteristic values based on the nozzle pressure curve and tie-bar strain curve. They used these values to optimize process parameters for three materials of different viscosities. Lin [10] used relative viscosity to define the appropriate injection speed. The optimal injection speed is where the relative viscosity change stabilizes. Párizs et al. [11] applied cavity pressure sensors to a multi-cavity mold to optimize clamping force, V/P switchover point, and packing time. Nian et al. [12] established a parameter optimization process based on cavity pressure sensors, reducing product warpage defects by setting multiple stages of packing pressure. Huang et al. [13] analyzed the impact of multiple stage packing pressure and injection speed setups on product quality. Process parameters were optimized based on the pressure curve, improving product weight, dimensions, and warpage. Xu et al. [14] proposed a method to measure the clamping force before injection and during cooling. By calculating the difference, the appropriate clamping force setting can be determined.

In previous studies, adaptive process control methods have been used to stabilize product quality. This approach primarily utilizes information gathered by sensors to monitor changes in the product, including pressure, temperature, and strain values. Chen et al. [15]

used a tie-bar strain sensor to monitor the peak clamping force increment. When the peak clamping force increment exceeds the specified limits, the process can be successfully restored to stable production conditions by modifying the V/P switchover point and holding pressure. Krantz et al. [16] established an auto-viscosity control system to monitor the time taken for the melt to reach the sensor and thereby adjust the screw velocity to reduce the variability of recycled materials during the production process. Cheng et al. [17] used the adaptive process control method to confirm that the system can stabilize the weight of thin-walled parts during long-term production. Chen et al. [18] analyzed the impact of cavity pressure on tie-bar strain during the injection process, indicating a strong correlation between variations in clamping force and product weight, demonstrating that controlling the clamping force effectively stabilizes product weight during long-term production. Xu et al. [19] defined the pressure integral over time as the melt viscosity and utilized it as a control reference. By automatically adjusting the V/P switchover point and packing pressure in real time, the melt viscosity was successfully stabilized, and variations in product weight were controlled during long-term production, including experiments with both virgin and recycled materials. Chang et al. [20] demonstrated through experiments that there is a strong correlation between screw position and injection time, product weight, and clamping force peak. They further proved that adjusting process parameters based on changes in the clamping force peak can stabilize product weight during continuous production. Huang et al. [21] utilized cavity peak pressure as a monitoring characteristic for long-term production. In continuous injection experiments, increasing the barrel temperature increased cavity peak pressure and product weight, showing a high correlation. The study ultimately demonstrated that adjusting packing pressure could prevent excessive product quality deviations and maintain its consistency. Schiffers et al. [22] applied the viscosity index as an adaptive control method to adjust the V/P switchover point, showing that this method could reduce the part weight variation to 0.25%.

In this study, a nozzle pressure sensor and a tie-bar strain gauge were installed to capture sensing curves, and characteristic values were established based on these sensing curves. The sensing curve characteristic values could optimize the parameter settings of the injection, packing, and clamping stages to determine the optimal process parameters. Finally, this study established an adaptive control system to stabilize product quality. Continuous production experiments were conducted to verify the effectiveness of the scientific molding parameter setup and the adaptive process control system during long-term and multi-site production.

2. Methodology

2.1. P-V-T Relationship

The *P-V-T* relationship describes the interaction between pressure (P), specific volume (V), and temperature (T) for polymers. When temperature is held constant, an increase in pressure leads to a decrease in specific volume. Conversely, when pressure is constant, increasing the temperature leads to a rise in specific volume. The final specific volume after cooling significantly influences product quality, such as product dimensions, mechanical properties, and weight.

According to the *P-V-T* relationship, pressure variations during the injection process affect the material's specific volume or density, which in turn influences product quality. Many process parameters in injection molding are closely related to pressure. Therefore, setting appropriate process parameters to maintain consistent pressure profiles for each cycle and controlling specific volume can enhance the stability of product quality.

2.2. Viscosity Characteristics of Melt

The viscosity of plastic materials is a critical factor influencing the injection molding process. Plastic materials are shear-thinning non-Newtonian fluids, where the viscosity decreases as the shear rate increases [23].

At low shear rates, molecular chains are highly entangled and have low orientation, leading to high viscosity. As the shear rate increases, the chains begin to disentangle and align, resulting in a continuous decrease in viscosity. When the shear rate reaches a certain level, the alignment of the molecular chains stabilizes, reducing the sensitivity of viscosity to shear rate changes and leading to stable flowability, as shown in Figure 1. Therefore, modifying the shear rate by adjusting the injection speed not only improves the flowability of the molten material, but also increases its stability.

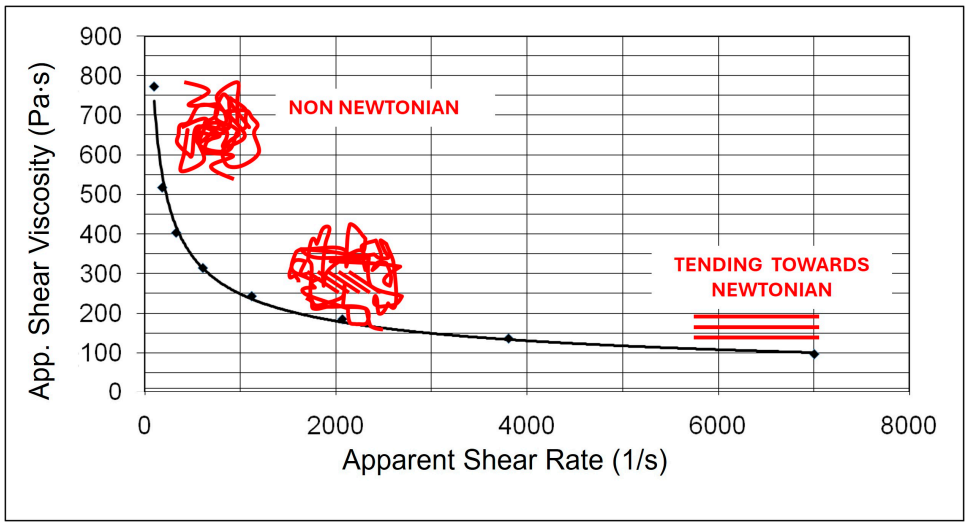


Figure 1. Changes in melt viscosity at various shear rates (Courtesy: Suhas Kulkarni, FIMMTECH INC).

2.3. Characteristics of Nozzle Pressure Profile

According to the *P-V-T* theory, pressure, specific volume, and temperature strongly correlate with product quality. Therefore, adjusting process parameters closely related to product quality can establish a standard pressure profile.

This study defined several online quality characteristic values from the nozzle pressure profile: nozzle peak pressure, timing of peak pressure, relative viscosity, nozzle pressure difference, and viscosity index. These online quality characteristic values were used to optimize process parameters at different stages and served as strategy indices for the adaptive process control system. Figure 2 shows the nozzle pressure characteristic values.

- Nozzle peak pressure (P_{peak}): This value represents the maximum pressure value in the nozzle pressure profile. It is used to optimize the injection speed and the V/P switchover point, serving as a key quality characteristic in adaptive process control.
- Timing of peak pressure (t_{peak}): The instant of time when the peak pressure occurs is used for optimizing injection speed.
- Relative viscosity ($\eta_{relative}$): Defined as the product of nozzle peak pressure and the timing of peak pressure, it is used for optimizing injection speed. The formula for the relative viscosity is shown in Equation (1).
- Nozzle pressure difference (ΔP): Defined as the rate of change in nozzle pressure per second, it is used for optimizing packing pressure and packing time. The formula for nozzle pressure difference is shown in Equation (2).

- Viscosity index (*VI*): The integral of pressure over time in the nozzle pressure profile, it is an online quality characteristic value for adaptive process control systems. The formula for the viscosity index is shown in Equation (3).

$$\eta_{relative} = P_{peak} \times t_{peak} \tag{1}$$

$$\Delta P = P_{time} - P_{time-1} \tag{2}$$

$$VI = \int_{t_{injection_start}}^{t_{packing_end}} P_{nozzle}(t)dt \tag{3}$$

where P_{time} represents the nozzle pressure at the specified time, P_{time-1} represents the nozzle pressure one second before P_{time}, $t_{injection_start}$ represents the timing of injection start, $t_{packing_end}$ represents the timing of packing end, and P_{nozzle} represents the nozzle pressure.

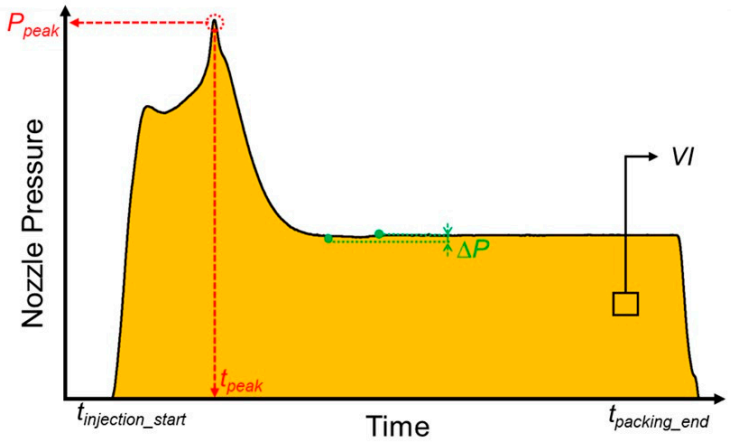


Figure 2. Nozzle pressure characteristic values.

2.4. Characteristics of Real-Time Clamping Force Value

Clamping force is the amount of force required to keep the mold closed during the injection-molding process. An appropriate clamping force can prevent the product from mold separation and make the product quality more stable. Initially, the rule of thumb for calculating the required tonnage for the part is used to determine the appropriate clamping force, as shown in Equation (4).

$$F = A \times P_M \tag{4}$$

where F represents the required clamping force, A represents the total projected area of the product, and P_M represents the tonnage required per square inch of material. Typically, crystalline materials require 3.5 to 4.5 tons of clamping force per square inch of projected area, while amorphous materials require 2.5 to 4.0 tons per square inch of projected area [24].

However, this method only provides an approximate clamping force. This study defines the clamping force difference value (ΔCF) as an online quality characteristic value to determine the optimal clamping force, as shown in Figure 3. If the ΔCF is too large, it indicates that mold separation occurred during the injection process. The formula for the clamping force difference value is shown in Equation (5).

$$\Delta CF = CF_{0.5packing_time} - CF_{set} \tag{5}$$

where $CF_{0.5packing_time}$ represents the clamping force at half of the packing time, while CF_{set} represents the set value of the clamping force.

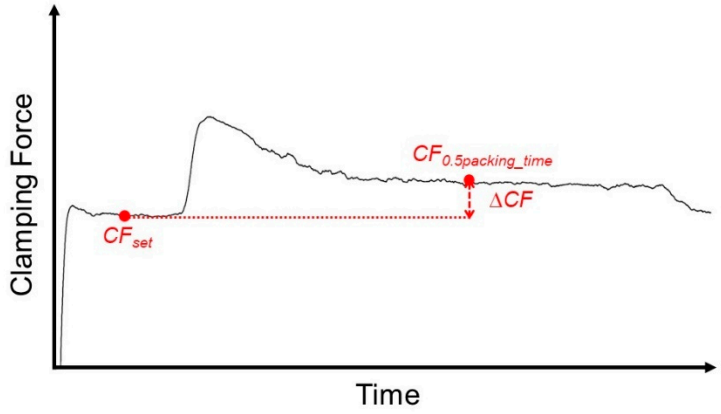


Figure 3. Clamping force difference value.

2.5. Adaptive Process Quality Control System

The online quality characteristic values defined in this study were the viscosity index, nozzle peak pressure, and clamping force difference value. An adaptive process quality control system was established using these characteristic values and a microcontroller unit.

Statistical Process Control (*SPC*) is a method used in quality control to monitor and control a process through statistical techniques. The Upper Control Limit (*UCL*) and Lower Control Limit (*LCL*) are the boundaries set on a control chart to identify acceptable variation in the process. An *SPC* strategy was used to reduce the impact of environmental noise on system judgment. The viscosity index and nozzle peak pressure must remain within the *UCL* and *LCL*. In this study, the results are assumed to follow a normal distribution. Based on a 95% confidence level, the *UCL* and *LCL* are set at ±2 standard deviations.

The adaptive process quality control system operates according to the following strategies:

(1) Viscosity index adjustment: If the viscosity index exceeds the *UCL* for two consecutive cycles, the injection speed increases by 1%. If it falls below the *LCL* for two consecutive cycles, the injection speed decreases by 1%.

(2) Nozzle peak pressure adjustment: If the nozzle peak pressure exceeds the *UCL* for two consecutive cycles, the *V*/*P* switchover point increases by 0.1 mm. If it falls below the *LCL* for two consecutive cycles, the *V*/*P* switchover point decreases by 0.1 mm.

(3) Clamping force difference monitoring: The clamping force difference value is continuously tracked to ensure it approaches zero, maintaining the stability of the injection process. Figure 4 shows the adaptive process control system flowchart.

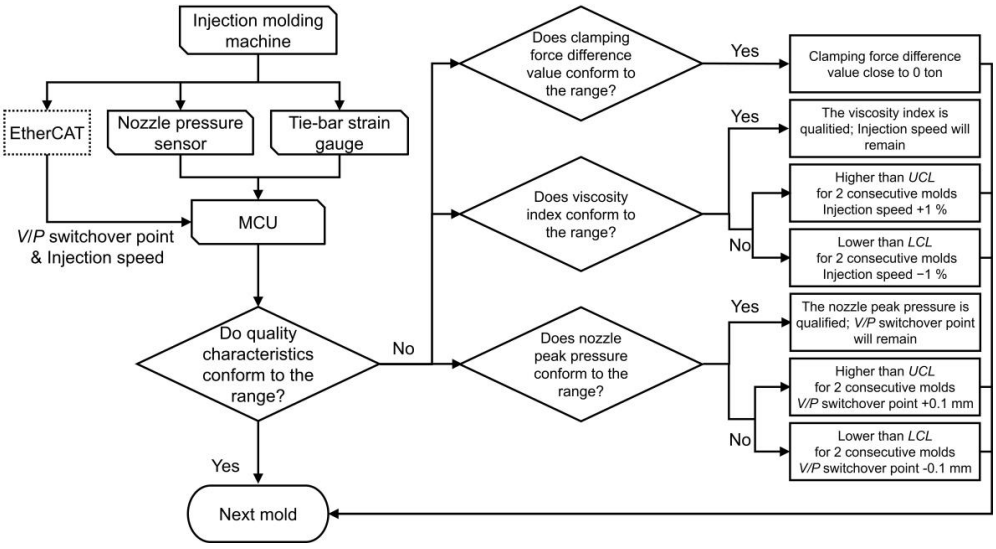


Figure 4. Adaptive process control system flowchart.

2.6. Quality of Products

This study defined the product weight as a quality indicator. The standard deviation and coefficient of variation of the product weight were utilized to evaluate product quality stability during continuous production. The formula for standard deviation and coefficient of variation are shown in Equations (6) and (7).

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}(w_i - \overline{w})^2}{N}} \quad (6)$$

$$C_v = \frac{\sigma}{\overline{w}} \times 100\% \quad (7)$$

where σ represents the standard deviation of the product weight, w_i represents the weight of each molded product, $\overline{w}$ represents the average of product weight, N represents the total number of products, and C_v represents the coefficient of variation of the product weight.

3. Experiment Setups

3.1. Material

The material used in this study is Polypropylene (PP), with the material type PP-HNR100 (Sasol Limited, Sandton, South Africa) utilized for the scientific molding parameter setup experiments and adaptive process control experiments. Beta site verification experiments will be conducted at different locations using various materials to further validate the effectiveness of the established scientific molding parameters and adaptive process control system. The material type for Beta site experiments is PP-PD943 (LCY Chemical Corp., Taipei, Taiwan). Properties of polypropylene are shown in Table 1.

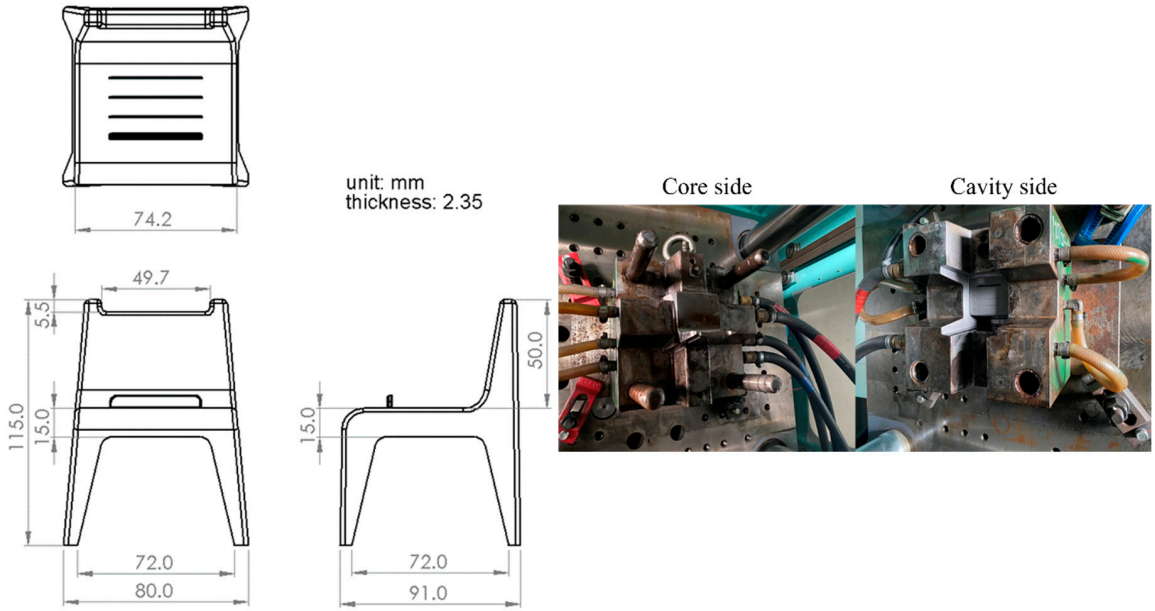
Table 1. Properties of polypropylene (HNR100/PD943).

	Unit	HNR100	PD943
Melt Flow Index	g/10 min	12	10.8
Density	g/cm^3	0.905	0.905
Shrinkage	%	1.3	41.3
Melt Temperature	°C	220–260	190–240
Mold Temperature	°C	15–50	20–60

3.2. Equipment

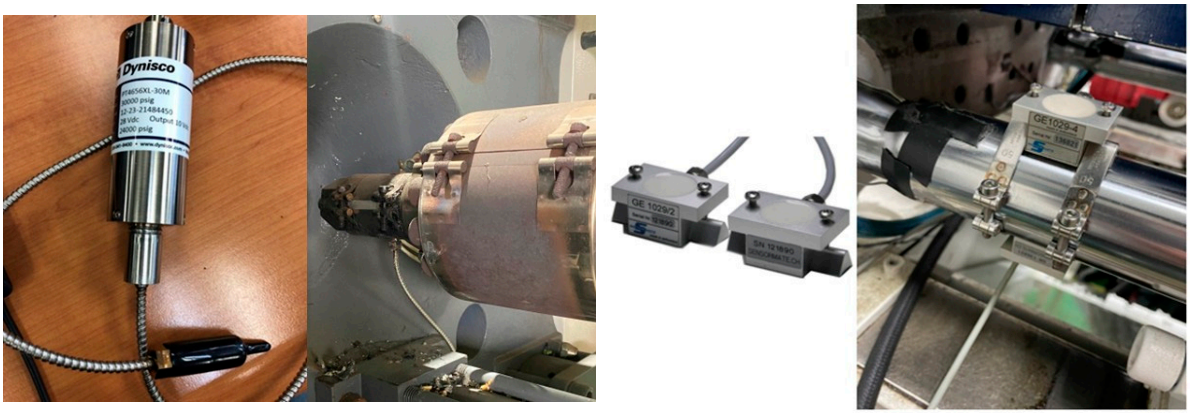
This study was conducted with an all-electric injection molding machine (CLF-230AE, Chuan Lih Fa Co., Ltd., Tainan, Taiwan), with a maximum clamping force of 230 tons, maximum injection rate of 398 cm^3/s, and maximum injection pressure of 1612 kg/cm^2. The experiments utilized a hot runner single-cavity mold to produce a phone stand sample, as shown in Figure 5.

Figure 6 shows the nozzle pressure senor and strain sensor. Figure 7 shows the experimental measurement system. To determine the flow behavior of the melt during the injection molding process, the pressure signal of the melt at the nozzle was measured by a nozzle pressure sensor (PT4656XL, Dynisco, Franklin, MA, USA). A strain sensor (GE1029, Gefran, Provaglio d'Iseo, Italy) was mounted on the tie bar and used to monitor the strain during production. A data acquisition system (DAQ USB-4716, Advantech Co., Ltd., Taipei, Taiwan) was connected to external sensors to capture data. The sampling rate used in this study was 1000 Hz. A microcontroller unit (AR-300T, ICP DAS Co., Ltd., Hsinchu, Taiwan) was used as the platform for subsequent adaptive control experiments.



(**a**) (**b**)

Figure 5. (**a**) The dimensions of the phone stand sample and (**b**) mold of the part.



(**a**) (**b**)

Figure 6. (**a**) The nozzle pressure sensor and (**b**) the strain sensor.

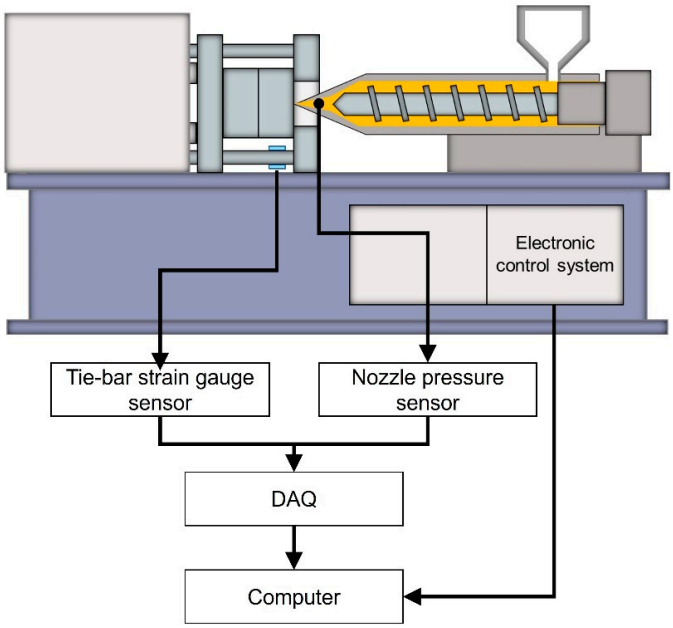


Figure 7. Experimental measurement system.

4. Experiment Results and Discussion

4.1. Scientific Molding Parameter Setup Experiments

Before the experiments began, fixed process parameters were established and maintained consistently throughout the study. Equation (4) calculated the initial clamping force for the mold, yielding an approximate value of 45 tons. To consider the use of more extreme process parameters during the experiment, a safety factor of 1.5 was applied to prevent mold separation, resulting in an initial clamping force setting of 70 tons. The melt and mold temperatures were set according to the material manufacturer's recommendations.

This study aims to establish a standardized setup for scientific molding parameters. The optimization experiments begin with injection speed and V/P switchover point, followed by packing pressure and packing time, and finally clamping force optimization. The optimized parameters from previous experiments are applied to subsequent experiments.

4.1.1. Injection Speed Optimization Experiments

During the injection molding process, as the injection speed increases, the viscosity of the melt gradually decreases as the shear rate increases. Given the critical influence of melt viscosity on product quality, this study selected injection speed as the first process parameter to optimize. Initially, a V/P switchover point that does not reach complete mold filling was set to prevent the melt from compressing after filling the cavity, which would cause a significant increase in nozzle pressure and affect the relative viscosity results. The experimental parameters are shown in Table 2.

Table 2. Injection speed optimization experimental parameters.

Fixed Parameters			
Injection pressure (bar)	1500	Melting temperature (°C)	235
Cooling time (s)	20	Mold temperature (°C)	25
Packing pressure (bar)	0	Clamping force (ton)	70
Packing time (s)	0	V/P switchover point (mm)	31
Varying Parameters			
Injection speed (mm/s)	10, 20, 30, . . ., 100, 110, 120		

According to the experimental results, increasing the injection speed at a lower speed effectively reduces the timing of peak pressure. However, it has a relatively small impact on the nozzle peak pressure. This result indicates that increasing the injection speed shortens the time required for the filling stage, as shown in Figures 8 and 9. At lower injection speeds, the shear rate is low, causing the molecular chains of the melt to remain entangled. As the injection speed increases, the higher shear rate causes the molecular chains to disentangle and align, gradually improving the flowability of the melt. Once the injection speed reaches around 80 mm/s, the change in relative viscosity drops to below 2%, indicating that viscosity has converged. Further increasing the injection speed offers limited improvement in melt flowability and instead increases the machine load, as shown in Figure 10. Therefore, the appropriate injection speed was set to 80 mm/s.

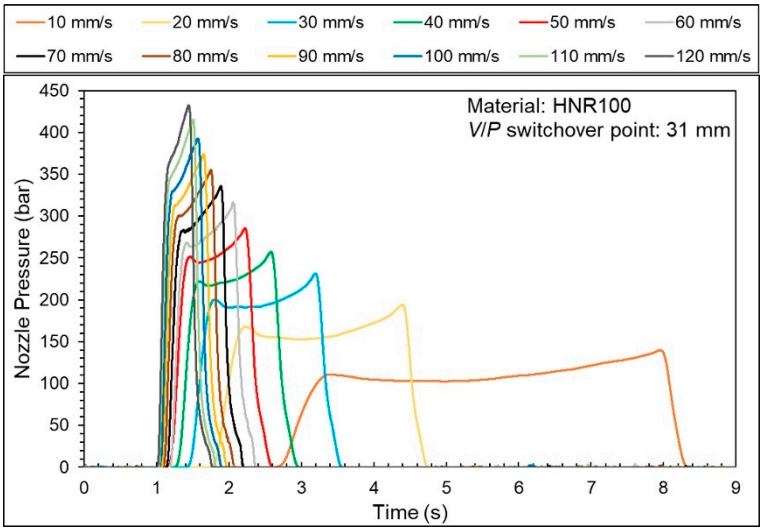


Figure 8. Nozzle pressure profile with various injection speeds.

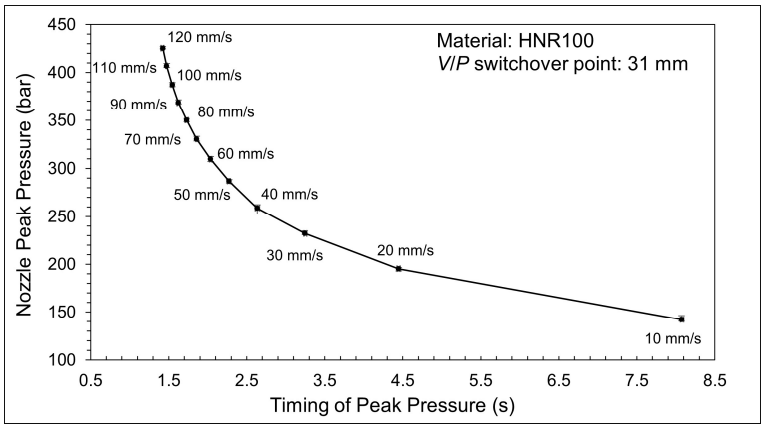


Figure 9. The relationship between nozzle peak pressure and timing of peak pressure.

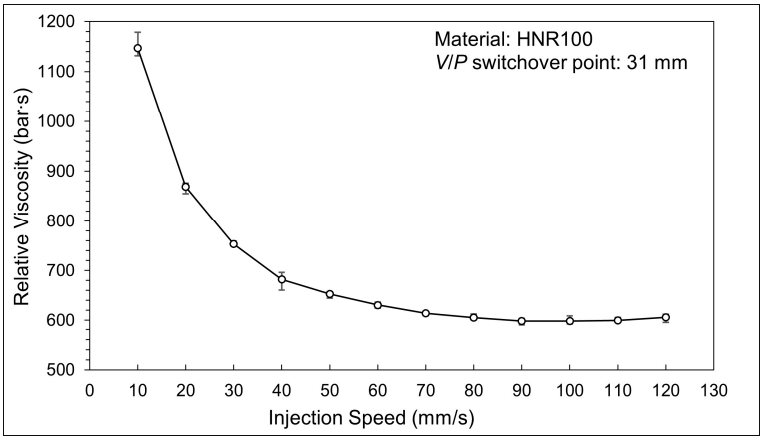


Figure 10. Relative viscosity with various injection speeds.

4.1.2. V/P Switchover Point Optimization Experiments

In the injection molding process, the ideal V/P switchover point is typically around 95% to 98% of the mold cavity volume being filled. When the melt approaches complete filling during the filling stage, it enters the compression stage, causing the pressure profile to rise significantly. Therefore, setting the V/P switchover point before the nozzle peak pressure increases rapidly is most appropriate. This experiment set various V/P switchover

points to observe the changes in nozzle peak pressure and product weight. The result of injection speed optimization experiments was used in V/P switchover point experiments. The experimental parameters are shown in Table 3.

Table 3. V/P switchover point optimization experimental parameters.

Fixed Parameters			
Injection pressure (bar)	1500	Melting temperature (°C)	235
Cooling time (s)	20	Mold temperature (°C)	25
Packing pressure (bar)	0	Clamping force (ton)	70
Packing time (s)	0	Injection speed (mm/s)	80
Varying Parameters			
V/P switchover point (mm)	25, 26, 27, 28, 29, 30, 31		

The results indicate that the nozzle peak pressure increases significantly when the V/P switchover point is between 25 and 27 mm. This suggests that the mold cavity is filled, but the screw continues to advance, causing a sharp rise in nozzle pressure. Conversely, when the V/P switchover point is between 28 and 31 mm, the nozzle pressure change is insignificant, indicating that the melt is still in the flow phase and has not yet filled the cavity, as shown in Figure 11. Based on the phenomenon of a sharp rise in the nozzle peak pressure, the transition point from the filling to the compression stage appears at the V/P switchover point of 28 mm. The product weight gradually converges, as shown in Figure 12. However, due to factors such as machine and material variations, this transition point may be unstable. Therefore, the appropriate V/P switchover point was set to 29 mm.

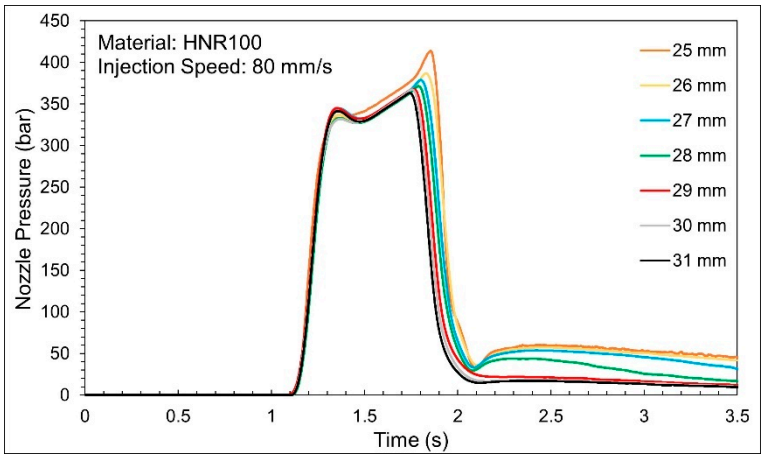


Figure 11. Nozzle pressure profile with various V/P switchover points.

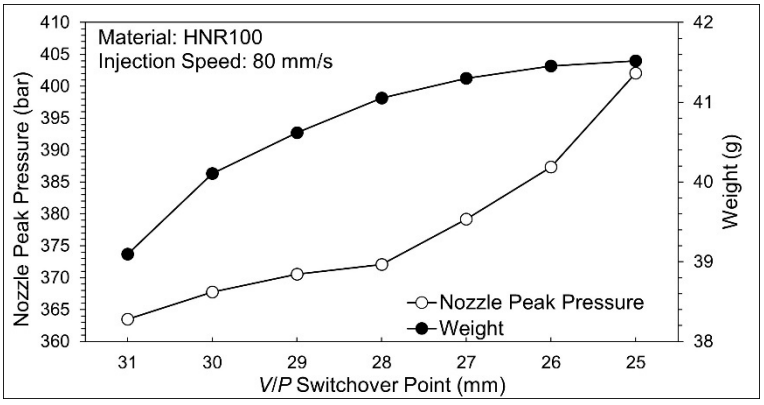


Figure 12. The relationship between nozzle peak pressure and product weight.

4.1.3. Packing Pressure Optimization Experiments

The primary purpose of the packing pressure is to prevent the backflow of the melt within the cavity and to avoid shrinkage and warpage of the product during cooling. This experiment found the appropriate packing pressure by observing the relationships between the nozzle pressure curve, screw position, and product weight. In order to ensure that the gate fully solidifies during each experiment and to prevent any impact on the product weight, a longer packing time was set. The previous process parameter optimization results were used in packing pressure experiments. The experimental parameters are shown in Table 4.

Table 4. Packing pressure optimization experimental parameters.

Fixed Parameters			
Injection pressure (bar)	1500	Melting temperature (°C)	235
Cooling time (s)	20	Mold temperature (°C)	25
Packing time (s)	30	Clamping force (ton)	70
Injection speed (mm/s)	80	*V*/*P* switchover point (mm)	29
Varying Parameters			
Packing pressure (bar)		0, 25, 50, . . ., 250, 275, 300	

Figure 13 shows the nozzle pressure profiles with various packing pressures. When the packing pressure is insufficient, the melt cannot smoothly enter the mold cavity because the screw has difficulty advancing steadily during the packing stage, as shown in Figure 14a. However, as the packing pressure increases, there is a tendency for the nozzle pressure to rise, and the screw advances more smoothly. This indicates that higher packing pressure effectively facilitates the compensation of the melt into the mold cavity, as shown in Figure 14b,c. Observing the changes in product weight reveals that as the packing pressure increases, the product weight gradually rises. At a packing pressure of 200 bar, the change in product weight noticeably converges, with the variation in weight difference between adjacent parameters being within 0.2%. The packing pressure sufficiently fills the mold cavity completely, as shown in Figure 15. Therefore, the appropriate packing pressure was set to 200 bar.

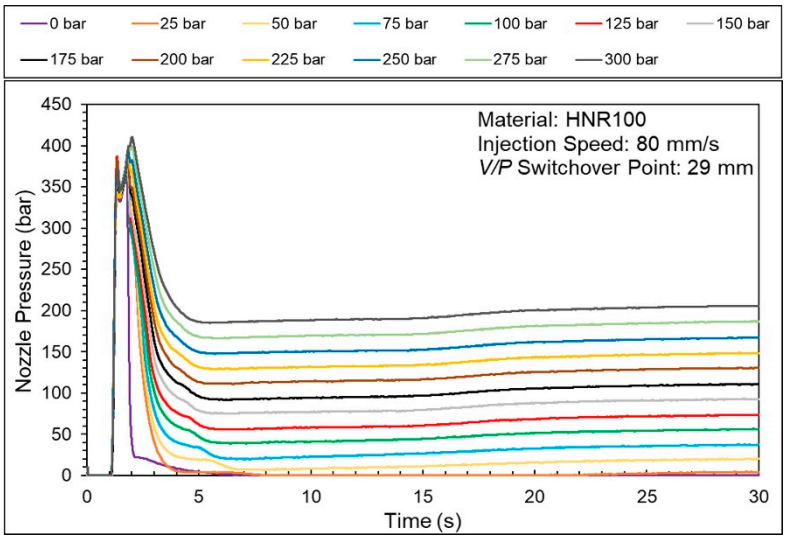


Figure 13. Nozzle pressure profiles with various packing pressures.

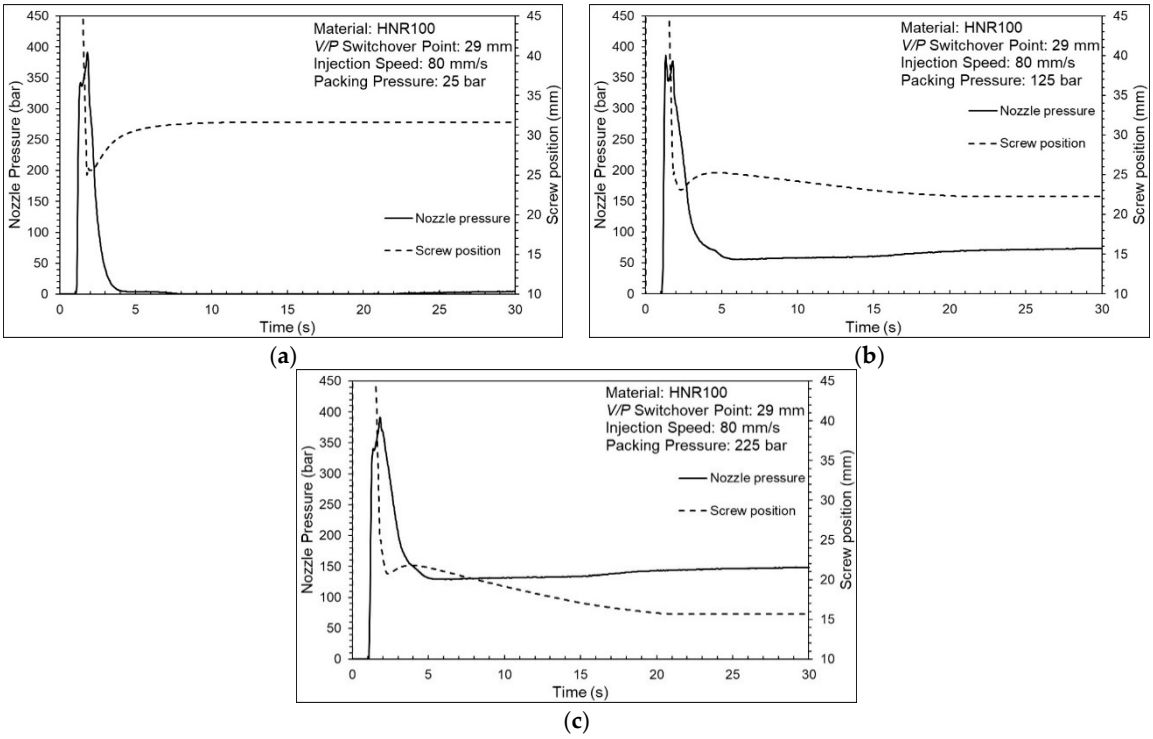


Figure 14. Nozzle pressure profiles and screw positions for packing pressures of (**a**) 25 bar, (**b**) 125 bar, and (**c**) 225 bar.

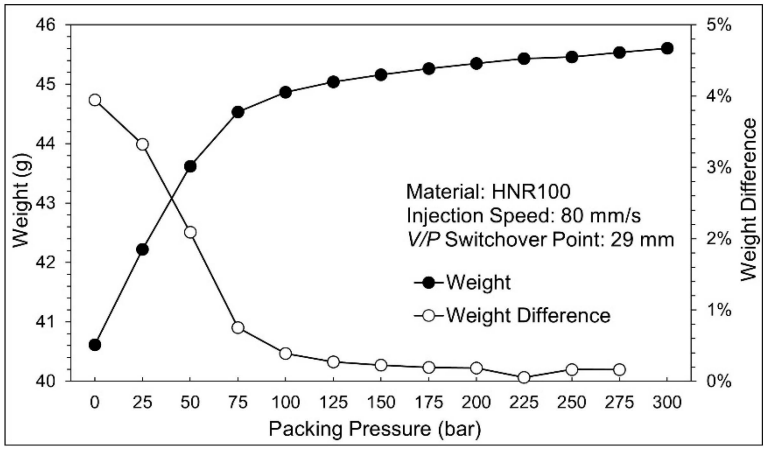


Figure 15. Product weights and weight difference with various packing pressures.

4.1.4. Packing Time Optimization Experiments

The packing time optimization experiment set different packing times to observe their influence on product weight and the nozzle pressure difference. The previous process parameter optimization results were used in packing time experiments. The experimental parameters are shown in Table 5.

Observing the nozzle pressure difference during the packing stage can identify the time when nozzle pressure changes most clearly. Setting a longer packing time causes the nozzle pressure to rise rapidly at 16 s, and this turning point shows the maximum nozzle pressure difference. This phenomenon may occur because the screw continues to advance at the set packing pressure even after the gate has solidified. The melt is compressed in the hot runner and nozzle, which causes the pressure to increase, as shown in Figure 16.

Table 5. Packing time optimization experimental parameters.

Fixed Parameters			
Injection pressure (bar)	1500	Melting temperature (°C)	235
Cooling time (s)	20	Mold temperature (°C)	25
Packing pressure (bar)	200	Clamping force (ton)	70
Injection speed (mm/s)	80	V/P switchover point (mm)	29
Varying Parameters			
Packing time (s)	0, 2, 4, . . ., 18, 20, 22		

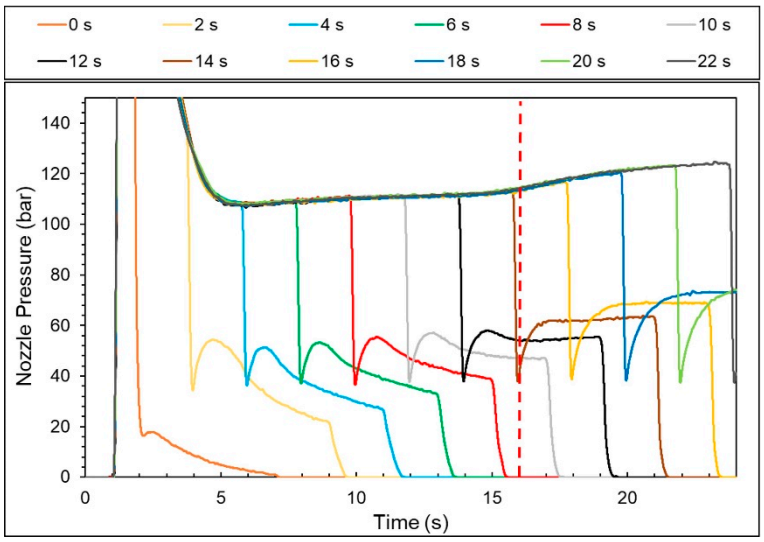


Figure 16. Nozzle pressure profiles with various packing times.

The nozzle pressure at 16 s of total time corresponds to approximately 14 s of packing time, as the filling stage takes about 2 s. As the packing time increases, the product weight shows an upward trend. After 14 s of packing time, the increase in product weight begins to slow down. This indicates that the area near the gate is solidified, causing melt compensation to become limited, as shown in Figure 17. Therefore, the appropriate packing time was set to 14 s.

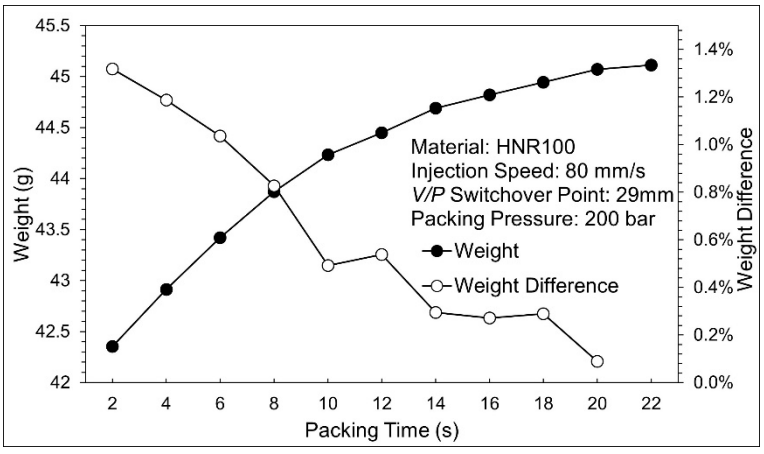


Figure 17. Product weights and weight difference with various packing times.

4.1.5. Clamping Force Optimization Experiments

To optimize the clamping force and stabilize product weight, this study used a tie-bar strain gauge to measure the real-time clamping force data and thereby calculate the

clamping force difference value. The previous process parameter optimization results were used in the clamping force experiments. The experimental parameters are shown in Table 6.

Table 6. Clamping force optimization experimental parameters.

Fixed Parameters			
Injection pressure (bar)	1500	Melting temperature (°C)	235
Cooling time (s)	20	Mold temperature (°C)	25
Packing time (s)	14	Packing pressure (bar)	200
Injection speed (mm/s)	80	*V*/*P* switchover point (mm)	29
Varying Parameters			
Clamping force (ton)		10, 15, 20, 25, 30, 35, 40, 45	

Figure 18 shows the clamping force profiles with various clamping force settings, and Figure 19 presents the clamping force difference values and product weights with various clamping force settings. As the clamping force increases, both the clamping force difference value and product weight show a downward trend, indicating that the flash issue is gradually improving. When the clamping force gradually increases to 35 tons, the product weight stabilizes, and the clamping force difference value approaches zero. Considering environmental noises such as temperature, machine variability, and material batch differences, this study multiplies the optimal clamping force of 35 tons by a safety factor of 1.2. This adjustment helps mitigate the risk of flash during continuous production. Therefore, the appropriate clamping force was set to 42 tons.

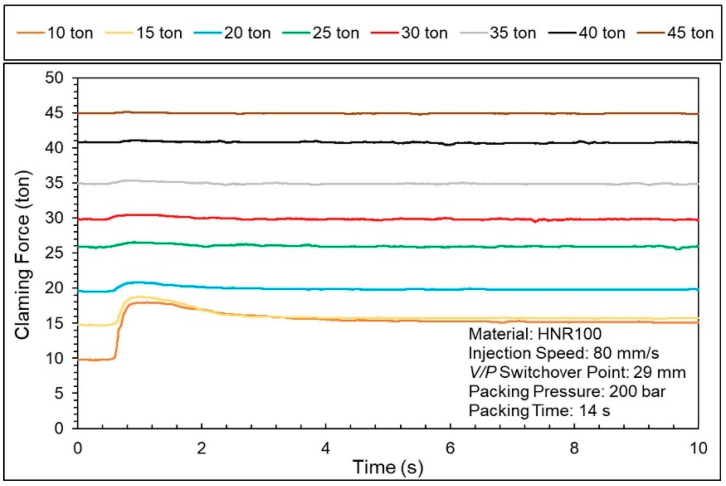


Figure 18. Clamping force profiles with various clamping force settings.

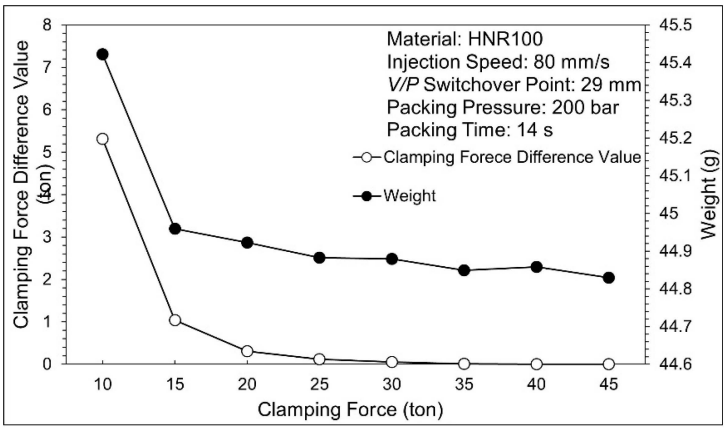


Figure 19. Clamping force difference value and product weights with various clamping force settings.

4.2. Adaptive Process Quality Control Experiments

During long-term continuous injection molding production, product quality is affected by environmental noise as the number of production cycles increases. To maintain stability during injection molding production, this study established an adaptive process control system based on the characteristic values of the nozzle pressure curve. The viscosity index and nozzle peak pressure were defined as online quality characteristic values for the adaptive process control system. If the characteristic values exceed the control limits, the system adjusts the injection speed or the V/P switchover point in the next mold to stabilize the product quality. The system also monitors the clamping force difference value to prevent mold separation and flash during production. All experiments were conducted with and without the adaptive process control system for 120 cycles. The quality standard was defined by a product weight standard deviation below 0.09 g and a coefficient of variation below 0.2% to observe whether the results met the set criteria.

4.2.1. Adaptive Process Control Experiments

The adaptive process control experiments utilized the optimal process parameters identified through the scientific molding parameter setup experiments. Adaptive process control system experimental parameters are shown in Table 7.

Table 7. Adaptive process control system experimental parameters.

Experimental Parameters			
Injection pressure (bar)	1500	Injection speed (mm/s)	80
Melt temperature (°C)	235	V/P switchover point (mm)	29
Mold temperature (°C)	25	Packing pressure (bar)	200
Clamping force (ton)	42	Packing time (s)	14
Cooling time (s)	20	Material	HNR100

Figure 20 shows the product weight control results of the adaptive process control system. The results indicate that the product quality met the required standards during continuous production. However, using the control system increases product weight stability during continuous production. The standard deviation of product weight decreased from 0.0414 g to 0.0289 g, and the coefficient of variation decreased from 0.093% to 0.065%.

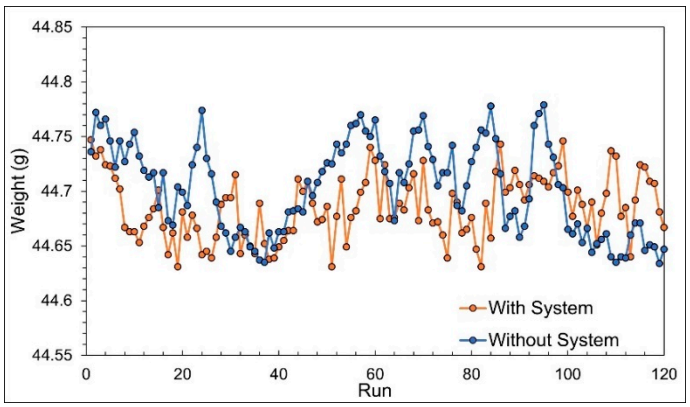


Figure 20. Product weight control results of the adaptive process control system.

Figure 21 shows the results of parameter adjustment, and Figure 22 shows the results of nozzle peak pressure and viscosity index with and without the system. The system monitored the online quality characteristic values for each cycle in real-time. If the online quality characteristic values exceed the defined control limits, the system immediately

adjusts the process parameters for the next cycle to reduce product quality variability. Finally, the clamping force difference value remained close to zero throughout the process, indicating that no flash occurred. This confirms that the clamping force setting determined from the scientific molding parameter setup experiments is appropriate, as shown in Figure 23.

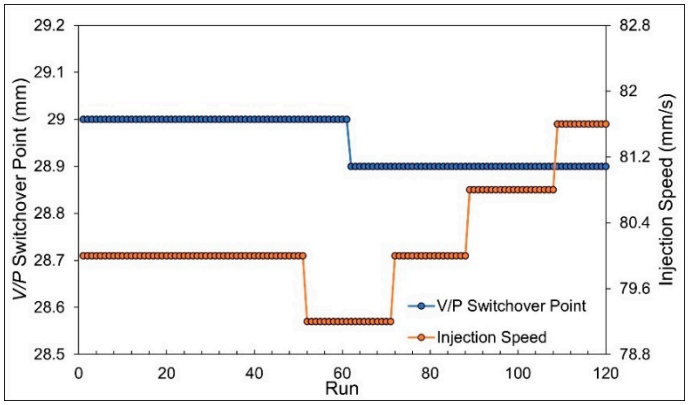
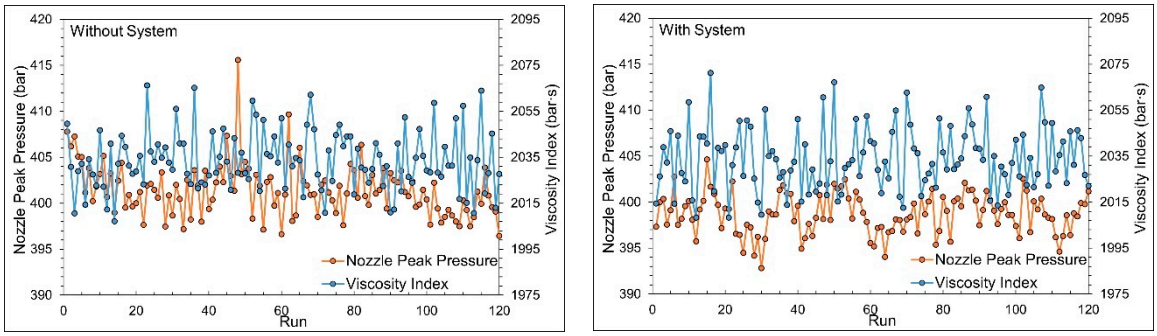
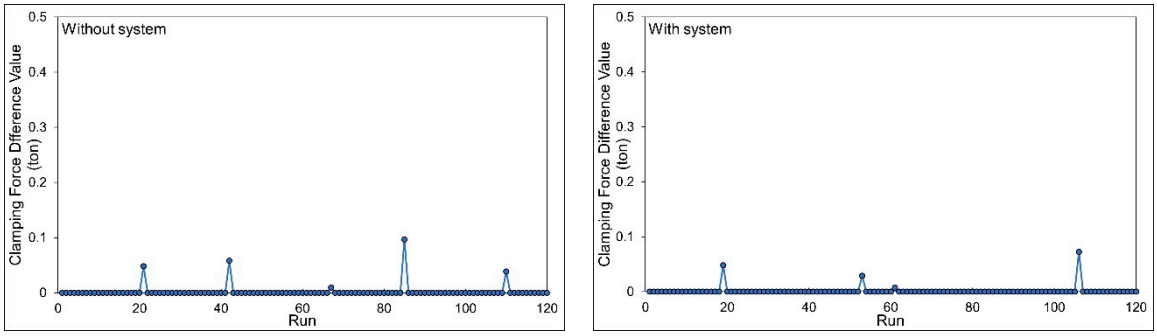


Figure 21. Results of parameter adjustment.



(**a**) (**b**)

Figure 22. The results of nozzle peak pressure and viscosity index (**a**) without system, and (**b**) with system.



(**a**) (**b**)

Figure 23. The results of clamping force difference value (**a**) without system, and (**b**) with system.

4.2.2. Beta Site Verification Experiments

To validate the effectiveness of the adaptive process control system, this study conducted Beta site verification experiments using the same machine and mold, but in different production environments and with different materials. The experimental parameters were determined based on the scientific molding parameter setup. The parameters for the Beta site verification experiments are shown in Table 8.

Table 8. Beta site verification experimental parameters.

Experimental Parameters			
Injection pressure (bar)	1500	Injection speed (mm/s)	40
Melt temperature (°C)	220	*V*/*P* switchover point (mm)	25
Mold temperature (°C)	25	Packing pressure (bar)	200
Clamping force (ton)	50	Packing time (s)	5
Cooling time (s)	20	Material	PD943

Figure 24 shows the product weight control results of the adaptive process control system at the Beta site. The adaptive process control system can make the product weight more stable during continuous production. The standard deviation of product weight decreased from 0.0153 g to 0.0148 g, and the coefficient of variation decreased from 0.036% to 0.035%.

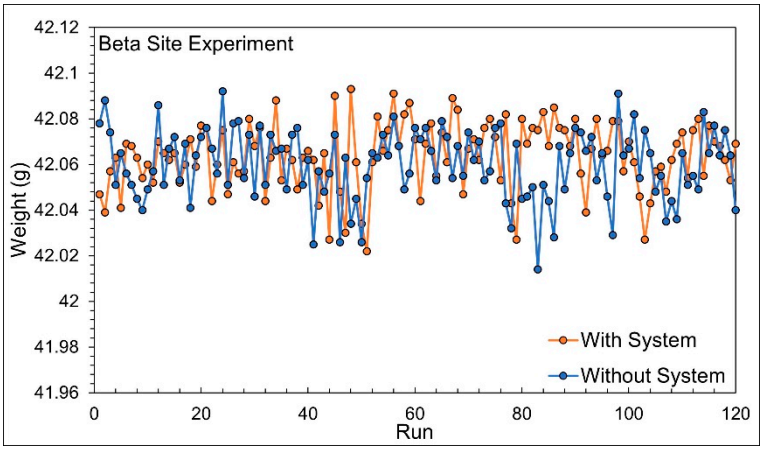


Figure 24. Product weight control results of the adaptive process control system at the Beta site.

Figure 25 shows the results of parameter adjustment at the Beta site, and Figure 26 shows the results of nozzle peak pressure and viscosity index at the Beta site. The clamping force difference value in the experiments remained close to zero, indicating that no flash occurred during production, as shown in Figure 27.

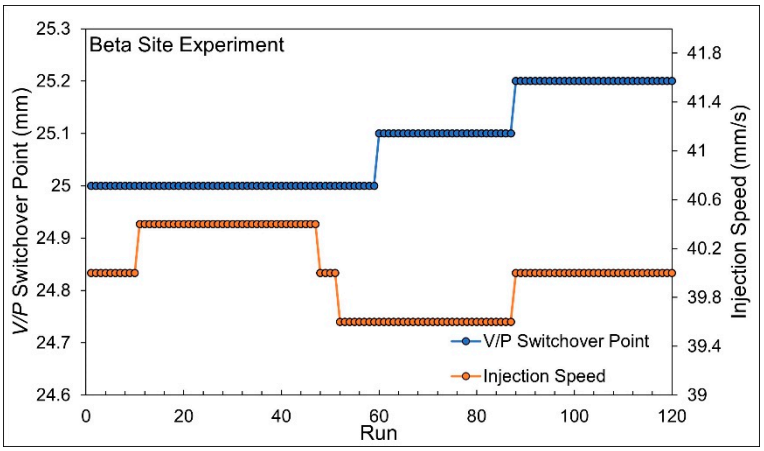
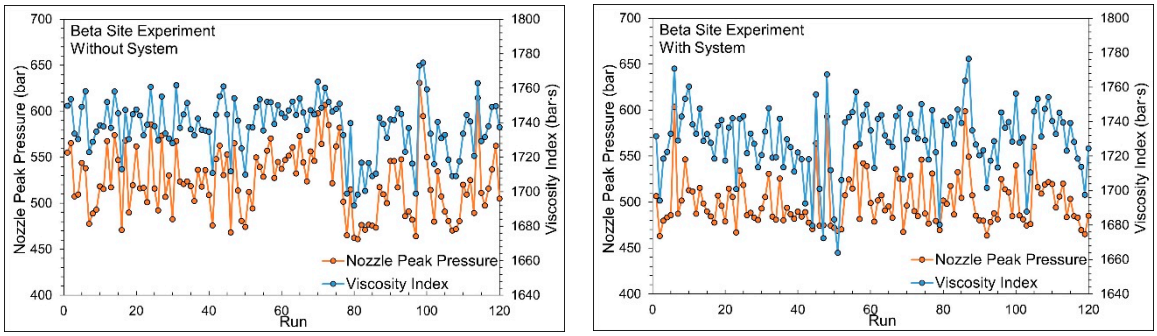
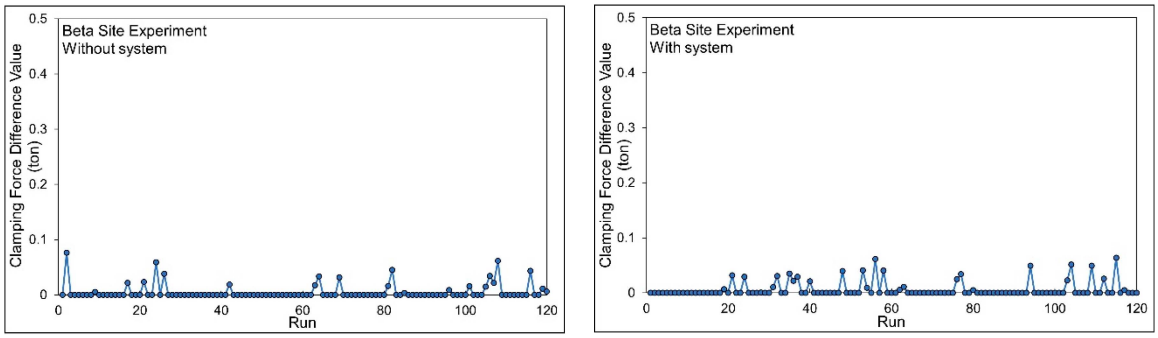


Figure 25. Results of parameter adjustment at the Beta site.



(**a**) (**b**)

Figure 26. Results of nozzle peak pressure and viscosity index at the Beta site (**a**) without system, and (**b**) with system.



(**a**) (**b**)

Figure 27. Results of clamping force difference value at the Beta site (**a**) without system, and (**b**) with system.

5. Conclusions

This study installed two external sensors to collect data, establishing a standardized scientific molding parameter setup. The scientific molding parameter setup sequentially optimizes injection speed, V/P switchover point, packing pressure, packing time, and clamping force. As the injection speed increases, the relative viscosity of melts gradually stabilizes, and the appropriate injection speed can be determined by relative viscosity. The appropriate V/P switchover point occurs just before the nozzle peak pressure rises rapidly, while a late V/P switchover point leads to excessive melt compression in the mold cavity. In the packing pressure experiments, when the nozzle pressure stabilizes and the screw continues to advance, it indicates that the melt is effectively compensating into the mold cavity, resulting in a gradually stabilized product weight. Setting a longer packing time allows for the observation of a noticeable pressure difference during the packing phase. This phenomenon occurs because the screw continues to advance at the set packing pressure even after the gate has solidified, compressing the melt in the hot runner and nozzle. The appropriate packing time can be determined by the gate solidification time. The clamping force difference value closely corresponds to the product weight trend, which can detect mold separation issues. Thus, the appropriate clamping force has been defined as the point where the clamping force difference value reaches zero.

An adaptive process control system was established based on the optimal parameters and online quality characteristic values. Continuous production experiments were conducted in different environments to validate the effectiveness of the adaptive process control system by minimizing the standard deviation and coefficient of variation in product weight. In the adaptive process quality control experiments, the system successfully stabilizes the product weight, with the standard deviation of product weight decreasing to 0.0289 g and 0.0148 g, and the coefficient of variation decreasing to 0.065% and 0.035%, respectively.

The proposed external sensors monitoring method in industrial manufacturing can reduce sensor installation and maintenance costs while using a scientific approach to optimize process parameters. Additionally, this study establishes an adaptive control system that automatically adjusts parameters to maintain product quality consistency, laying a good foundation for the development of intelligent injection molding systems.

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References

1. Gao, R.X.; Tang, X.; Gordon, G.; Kazmer, D.O. Online product quality monitoring through in-process measurement. *CIRP Ann.* **2014**, *63*, 493–496. [CrossRef]
2. Su, C.W.; Su, W.J.; Cheng, F.J.; Liou, G.Y.; Hwang, S.J.; Peng, H.S.; Chu, H.Y. Optimization process parameters and adaptive quality monitoring injection molding process for materials with different viscosity. *Polym. Test.* **2022**, *109*, 107526. [CrossRef]
3. Tsou, H.H.; Huang, C.C.; Chen, Y.C.; Shih, S.Y. Online detection of residual stress near the gate using cavity pressure for injection molding. *J. Polym. Eng.* **2023**, *43*, 89–99. [CrossRef]
4. Ke, K.C.; Huang, M.S. Quality prediction for injection molding by using a multilayer perceptron neural network. *Polymers* **2020**, *12*, 1812. [CrossRef]
5. Su, W.J.; Peng, H.S. A real-time clamping force measurement eigenvalue for prediction, adjustment, and control of injection product quality. *Polym. Eng. Sci.* **2020**, *61*, 420–431. [CrossRef]
6. Chang, Y.H.; Chen, S.C.; Ting, Y.H.; Feng, C.T.; Hsu, C.C. The Investigation of Novel Dynamic Packing Technology for Injection Molded Part Quality Control and Its Production Stability by Using Real-Time PVT Control Method. *Polymers* **2022**, *14*, 2720. [CrossRef] [PubMed]
7. Chen, J.Y.; Wong, L.C.; Huang, M.S. Quality monitoring and control for plasticization of acrylonitrile-butadiene-styrene regrind polymer in injection molding. *Polym. Eng. Sci.* **2024**, *64*, 1057–1070. [CrossRef]
8. Chen, J.Y.; Yang, K.J.; Huang, M.S. Online quality monitoring of molten resin in injection molding. *Int. J. Heat Mass Transf.* **2018**, *122*, 681–693. [CrossRef]
9. Liou, G.Y.; Su, W.J.; Cheng, F.J.; Chang, C.H.; Tseng, R.H.; Hwang, S.J.; Peng, H.S.; Chu, H.Y. Optimize Injection-Molding Process Parameters and Build an Adaptive Process Control System Based on Nozzle Pressure Profile and Clamping Force. *Polymers* **2023**, *15*, 610. [CrossRef]
10. Lin, C.C. Influence of injection velocity and joint geometry on quality of insert molding. *Polym. Eng. Sci.* **2011**, *52*, 268–276. [CrossRef]
11. Párizs, R.D.; Török, D.; Ageyeva, T.; Kovács, J.G. Multiple In-Mold Sensors for Quality and Process Control in Injection Molding. *Sensors* **2023**, *23*, 1735. [CrossRef] [PubMed]
12. Nian, S.C.; Fang, Y.C.; Huang, M.S. In-mold and Machine Sensing and Feature Extraction for Optimized IC-tray Manufacturing. *Polymers* **2019**, *11*, 1348. [CrossRef] [PubMed]
13. Huang, M.S.; Nian, S.C.; Lin, G.T. Influence of V/P switchover point, injection speed, and holding pressure on quality consistency of injection-molded parts. *J. Appl. Polym. Sci.* **2021**, *138*, 51223. [CrossRef]
14. Xu, Y.; Liu, G.; Dang, K.; Fu, N.; Jiao, X.; Wang, J.; Xie, P.; Yang, W. A novel strategy to determine the optimal clamping force based on the clamping force change during injection molding. *Polym. Eng. Sci.* **2021**, *61*, 3170–3178. [CrossRef]
15. Chen, J.Y.; Zhuang, J.X.; Huang, M.S. Enhancing the quality stability of injection molded parts by adjusting V/P switchover point and holding pressure. *Polymer* **2021**, *213*, 123332. [CrossRef]

16. Krantz, J.; Nieduzak, Z.; Licata, J.; O'Meara, S.; Gao, P.; Masato, D. In-mold rheology and automated process control for injection molding of recycled polypropylene. *Polym. Eng. Sci.* **2024**, *64*, 4112–4127. [CrossRef]
17. Cheng, F.J.; Chang, C.H.; Wen, C.H.; Hwang, S.J.; Peng, H.S.; Chu, H.Y. Out-of-Mold Sensor-Based Process Parameter Optimization and Adaptive Process Quality Control for Hot Runner Thin-Walled Injection-Molded Parts. *Polymers* **2024**, *16*, 1057. [CrossRef] [PubMed]
18. Chen, J.Y.; Zhuang, J.X.; Huang, M.S. Monitoring, prediction and control of injection molding quality based on tie-bar elongation. *J. Manuf. Process.* **2019**, *46*, 159–169. [CrossRef]
19. Xu, Y.; Xie, P.; Fu, N.; Jiao, X.; Wang, J.; Liu, G.; Dou, X.; Zha, Y.; Dang, K.; Yang, W. Self-optimization of the V/P switchover and packing pressure for online viscosity compensation during injection molding. *Polym. Eng. Sci.* **2022**, *62*, 1114–1123. [CrossRef]
20. Chang, H.; Su, Z.; Lu, S.; Zhang, G. Intelligent Predicting of Product Quality of Injection Molding Recycled Materials Based on Tie-Bar Elongation. *Polymers* **2022**, *14*, 679. [CrossRef]
21. Huang, M.S.; Ke, K.C.; Liu, C.Y. Cavity pressure-based holding pressure adjustment for enhancing the consistency of injection molding quality. *J. Appl. Polym. Sci.* **2020**, *138*, 50357. [CrossRef]
22. Schiffers, R.; Kruppa, S.; Moser, S. The right changeover point for each shot. *J. Kunststoffe* **2014**, *11*, 26–29.
23. Beaumont, J.P. *Runner and Gating Design Handbook: Tools for Successful Injection Molding*; Carl Hanser Verlag GmbH Co. KG: Munich, Germany, 2019.
24. Kulkarni, S. *Robust Process Development and Scientific Molding: Theory and Practice*; Carl Hanser Verlag GmbH Co. KG: Munich, Germany, 2017.

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