



EXPERIMENTAL INVESTIGATION OF THE EFFECTS OF PROCESS PARAMETERS ON PRODUCT GEOMETRY AND WEIGHT IN THE INJECTION MOLDING PROCESS WITH PE100 MATERIAL

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Abstract: This study investigates the influence of key process parameters on the geometric and physical properties of parts produced by injection molding using high-density polyethylene (PE100). The parameters include packing pressure, melt temperature, and cooling time which are systematically varied based on MoldFlow simulations. Samples are analyzed using an ATOS Q 3D scanning system and a high-precision digital scale. Results show that increasing packing pressure improves flatness and dimensional accuracy. While higher melt temperature enhances surface flatness, it also increases cylindrical deformations. Cooling time positively affects flatness but may lead to deformation in the upper cylinder. Regarding product weight, packing pressure has the most significant effect, followed by melt temperature, whereas cooling time shows minimal impact. The experimental findings offer practical and reliable insights for optimizing injection molding processes involving dense materials like PE100, providing meaningful contributions to both design and production strategies.

Keywords: PE100, Injection molding, Packing pressure, Melt temperature, Cooling time, Shrinkages

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1. Introduction

Plastic injection molding has long been a fundamental technology for the production of polymer-based components, owing to its versatile manufacturing capabilities, cost-effectiveness, and high repeatability. Today, the use of this method continues to grow in the production of plastic parts across a wide range of sectors, including consumer electronics, automotive, medical devices, and household appliances. This is largely due to the ability of injection molding to produce complex, multi-component parts with tight tolerances and well-controlled surface quality. However, achieving the desired part with minimal defects, minimal distortion, and optimal mechanical properties is not solely dependent on mold design but also requires precise control of process parameters. Traditionally, these parameters are selected based on experience or manufacturer guidelines, which do not always guarantee perfect results. In recent years, many academic studies have been conducted to understand, model, and improve the relationship between molding conditions and final part quality, leading to the development of interdisciplinary approaches ranging from numerical simulations to 3D optical scanning solutions.

The quality of products manufactured by plastic injection

molding depends on material selection, design, and process conditions. Among the most common problems encountered during the process is shrinkage. Some of the shrinkage-related defects stem from wall thickness variations, while others are caused by changes in mold surface temperature (Mathivanan et al., 2010; Mustafa et al., 2015). To avoid such defects, shrinkage issues must be addressed before mass production. Melt temperature, packing time, mold temperature, and packing pressure are all identified as significant parameters influencing shrinkage (Jansen and Titomanlio, 1996; Jafarian and Shakeri, 2005; Ahmad et al., 2009; Altan, 2010; Hussin et al., 2012; Mustafa et al., 2015). These factors contribute to solving shrinkage problems in the injection molding process. Postawa and Koszkuł examine the effects of processing conditions on shrinkage and weight variation (Postawa and Koszkuł, 2005), while Jansen et al. analyze shrinkage in different plastics, both highlighting the importance of packing pressure and melt temperature (Jansen et al., 1998). Kazmer and Barkan focus on pressure control in multi-cavity molds (Kazmer and Barkan, 1997), and Bushko and Stokes investigate the behavior of thermo-viscoelastic melts (Bushko and Stokes, 1996). Zhang's wireless sensor design presents an innovative approach to measuring cavity pressure



(Zhang et al., 2001), and Titomanlio studies the effects of in-mold shrinkage on the final product (Titomanlio and Jansen, 1996). Angstadt and Coulter emphasize the potential of cavity pressure as an indicator of part quality (Angstadt and Coulter, 1999). While various optimization tools and techniques exist for injection molding parameter studies, including Taguchi's Design of Experiments approach that has been widely used in the literature (Jansen and Titomanlio, 1996; Kazmer and Barkan, 1997; Zhang et al., 2001; Turng and Peić, 2002; Postawa and Koszkuł, 2005; Tang et al., 2006; García et al., 2003; Altan, 2010; Hussin et al., 2012), this study adopts a simulation-guided, single-parameter variation approach. In this approach, each process parameter (packing pressure, melt temperature, and cooling time) was varied individually within a range determined from MoldFlow simulations, while the remaining parameters were held constant, in order to clearly isolate and characterize the effect of each parameter on the geometric and physical properties of the product.

An injection molding process is a complex procedure where many factors impact the quality of the final product. Significant research has been dedicated to understanding the influence of molding parameters such as cavity pressure and temperature. Studies have shown these parameters are crucial in determining properties like shrinkage, weight, residual stress, and dimensional accuracy. For example, Postawa and Koszkuł investigated the changes in shrinkage and weight as a function of processing conditions, while Jansen et al. studied shrinkage in various plastics. Both studies highlighted the importance of packing pressure and melting temperature. Kazmer and Barkan focused on pressure control in multi-cavity molds, and Bushko et al. analyzed the behavior of thermo-viscoelastic melts. Zhang's innovative wireless sensor design offered a new method for measuring cavity pressure, while Titomanlio concentrated on how in-mold shrinkage affects the final product. Angstadt and Coulter further emphasized that cavity pressure can serve as a strong indicator of part quality.

While the existing literature frequently addresses the effects of molding parameters like cavity pressure and temperature on part shrinkage and warpage, a comprehensive evaluation of a part's final quality should not be limited to these two variables alone. To achieve true dimensional accuracy, it's essential to consider both vertical and horizontal measurements of the part. This allows for a more comprehensive analysis of the relationship between molding conditions and the resulting measurements. A significant portion of current research relies heavily on numerical simulations (Turng and Peić, 2002; García et al., 2003; Tang et al., 2006). Although these methods can provide reliable results under specific conditions, they don't always align perfectly with real-world, experimentally obtained data. Experimental studies, while often high cost, can provide more precise results for these applications. In such

research, it is crucial to use high-precision measurement systems to accurately evaluate the effects of variable molding parameters on the final product. This approach enables the derivation of meaningful and reliable conclusions from experimental analyses. The literature review reveals that while many studies have focused on common plastics like polypropylene (PP) and acrylonitrile butadiene styrene (ABS), there is limited research on materials with high density and large volumes, such as high-density polyethylene (HDPE) like PE100.

This study addresses this gap by presenting an original experimental investigation into the geometric and physical effects of key processing parameters on products molded from PE100. In this research, molding parameters were systematically varied based on simulation data, and the influence of each parameter on product shrinkage was evaluated in detail.

The produced parts were analyzed using advanced measurement techniques to collect comprehensive data on geometric integrity, dimensional precision, and material behavior. This work contributes to the optimization of injection molding processes through both its unique design and the analytical methods employed.

2. Materials and Methods

The first step in the experimental molding process was the preparation of the full-scale sample design, as shown in Figure 1. The three-dimensional model of the plastic injection mold, including all its details, was designed using SolidWorks software (Figure 2). The four-cavity female and male plates of the plastic injection mold used in the study are shown in Figure 3.

The study focused on a fundamental component used to integrate PE100 pipes into flanged connection systems. Strict dimensional and positional tolerances were considered, as one end of this component was designed to be compatible with a PE100 (HDPE) pipe, while the other end was designed to be compatible with metal equipment requiring a flanged connection. Therefore, tolerance control was prioritized during the injection molding process.

Experimental applications were performed using a Haitian MA3800 model injection molding machine with an injection pressure of 183 MPa, a screw diameter of 70 mm, and a clamping force of 3800 kN. The initial molding parameters were determined based on literature data and industrial applications.

The PE100 material used in the study is a copolymer of high-density polyethylene (HDPE). PE100 has a wide spectrum of properties and is used in many applications in the pipe industry, such as water distribution, sewage systems, industrial applications, and natural gas transmission. The technical properties of the PE100 material are presented in Table 1.

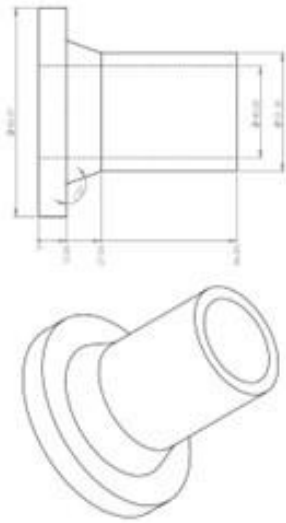


Figure 1. Sample geometry and dimensions.

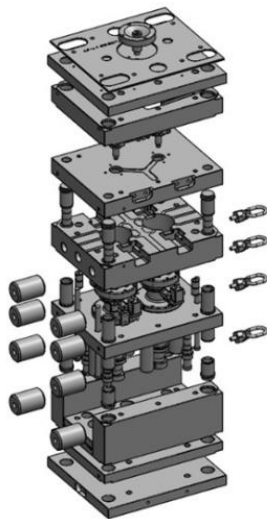


Figure 2. Plastic injection mold model.

Table 1. Mechanical properties of PE100 raw material

Properties	Density	Tensile modulus	Tensile strain	Vicat softening temperature	Melt flow rate
Condition	23°C	23°C	23°C	10N	190°C/5 kg
Method	ISO 1183/A	ISO 527 -2/1	ISO 527 -2/50	ISO 306/A	ISO 1133
Unit	g/cm ³	MPa	%	°C	g/10 min
General purpose	0.9590	1100.0000	>350.0000	128.0000	0.4500



Figure 4. Mesh structure used in MoldFlow analysis.



Figure 3. Plastic injection mold female and male plates.

Before the experimental applications were initiated, it was necessary to define the appropriate processing parameters for the injection molding process. As a first step, modeling of the flanged adapter was carried out using the SolidWorks CAD software. The resulting design was then transferred to MoldFlow software for flow analysis and molding optimization. Figure 4 visualizes the generated base structure and mesh model. A 3D mesh was used in the mesh structure, with a mesh count of 767618. A mesh independence (convergence) study was performed prior to the final analyses by comparing the simulation outputs obtained at progressively refined mesh densities; the 767618-element mesh was adopted as it provided results that no longer changed appreciably with further refinement, while keeping the computational cost reasonable.

MoldFlow is a commercial simulation tool that provides numerical solutions combining finite element and finite difference methods to analyze the molding process from thermal and mechanical perspectives. As shown in Figure 5, this software analyzes various variables of the injection process, especially by focusing on the mold filling phase, to determine the ideal processing conditions.

Within the scope of this analysis, key variables such as the melted temperature inside the mold, the applied packing pressure, packing time, and part cooling time were evaluated. Based on the simulation outputs, experimental studies were conducted with packing pressures ranging from 20 to 100 MPa, packing times from 3 to 20 seconds, melt temperatures from 200 °C to 310 °C, and cooling times from 20 to 100 seconds.

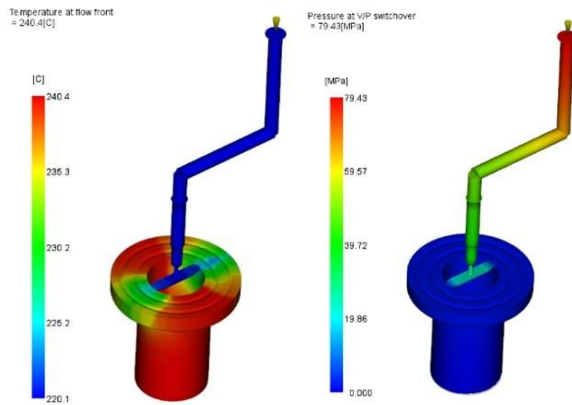


Figure 5. Example of molding process simulation.

To determine the deformation of the parts, an ATOS Q (Advanced Topometric Sensor) system was used. This three-dimensional optical 3D scanner can automatically scan the entire surface of a part without the need for special fixtures or reference markers during the scanning process, as shown in Figure 6. When the scan is complete, the system automatically creates a high-quality mesh. In addition, the CAD data obtained with SolidWorks software is transferred to the ATOS Q system. In the final step, the scanned data set is aligned with the CAD using GOM software, as seen in Figure 7, and the deviations between the two data sets are calculated and displayed graphically. The measured quality criteria, which are the average deviation of the top and bottom cylinders and the flatness of the skirt plane, are shown in Figure 8.

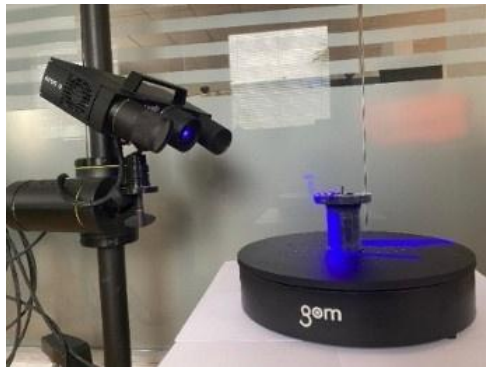


Figure 6. Three-dimensional scanning process.



Figure 7. Alignment of the model with the scanned data.

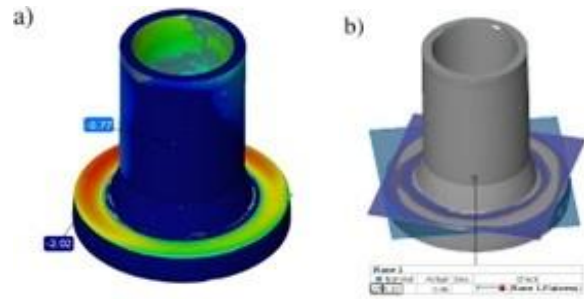


Figure 8. a) Deviation graph of the model and scanned data. b) Flatness measurement of the model with the scanned data.

The mass evaluations of the plastic samples produced in the experimental study were carried out to determine the fill rate and material volume changes associated with mold shrinkage. For this purpose, the weight of each sample was measured using a Huake brand digital scale with a sensitivity of 0.01 g, as shown in Figure 9, which operates at an analytical level of precision. The measurements were performed in a laboratory environment with stable ambient conditions, and an average value was recorded from three repeated measurements for each sample.

The weight data obtained were analyzed to evaluate the effect of different injection parameters on the part volume and, consequently, on mold shrinkage during molding.



Figure 9. Sample weight measurement.

3. Results and Discussion

Shrinkage behavior in injection-molded plastic parts has been a significant topic of discussion for many years. While a certain degree of shrinkage occurs in all plastic parts, dimensional errors in diameter and flatness are also unavoidable in parts with two different cylindrical geometries, such as flanges, due to various reasons. The key issue here is identifying under which conditions these defects can be minimized and which parameters have the most significant impact on the process. Therefore, it is crucial to understand the cause-and-effect relationship of these defects and to be able to analyze them effectively. Current research provides important findings in revealing the relationship between these variables. This section also addresses flatness, another measurable property of the molded parts. To better

understand the shrinkage tendencies, numerous experiments were conducted under different molding conditions. These experiments specifically focused on the effect of post-filling compression (packing) pressure on the amount of shrinkage and flatness error.

The shrinkage behavior of the parts was measured as the average deviation on separate selected surfaces, and the values were reported (Figure 8). This allowed for a clearer observation of the effects of the process parameters on the part geometry. Figure 10 shows the deviations in the upper cylinder, lower cylinder, and overall flatness values under packing pressures ranging from 2 to 100 MPa. The data obtained reveals that increasing packing pressure significantly improves structural stability and surface flatness.

At the lowest pressure level of 2 MPa, the deviation of the lower cylinder was measured as -2.52 mm, which decreased to -1.75 mm at 100 MPa. Similarly, the deviation in the upper cylinder decreased from -1.05 mm to -0.58 mm. These results indicate that the deformations of both the upper and lower cylinders decreased with increasing pressure, but the lower cylinder, which initially showed more deformation, improved at a higher rate. The flatness value, an indicator of surface smoothness, decreased from 0.87 mm at 2 MPa to 0.32 mm at 100 MPa. This demonstrates that increasing packing pressure has positive effects on the dimensional stability and surface quality of the product. Particularly in the 2–40 MPa range, noticeable improvements were observed in deviation and flatness values, while after 60 MPa, this change was seen to slow down. This suggests that after a certain threshold, the improving effect of increased pressure becomes limited, and the process enters a saturation trend.

In conclusion, it has been confirmed that increasing the packing pressure within the studied range reduces both structural deformation and improves surface smoothness. However, the 60–80 MPa range can be recommended as a balanced processing window that ensures dimensional accuracy while also being mindful of production cost and safety.

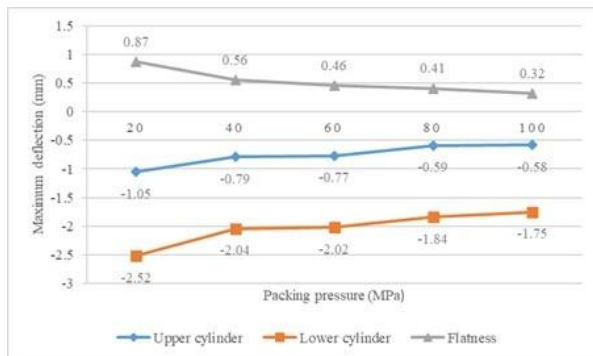


Figure 10. Effect of packing pressure on the total average shrinkage value and flatness error on cylindrical surfaces.

Figure 11 shows the deviations in the upper cylinder, lower cylinder, and flatness values under melt temperatures ranging from 200 °C to 310 °C. The findings indicate that increasing the melt temperature has a positive effect on flatness but a negative effect on cylinder deformations. The deviation of the lower cylinder reached -2.27 mm at 310 °C, up from -1.89 mm at 200 °C. Similarly, the deviation in the upper cylinder increased from -0.67 mm to -0.99 mm, showing greater deformation. This suggests that the increase in melt temperature creates effects that increase structural deformation through thermal expansion and changes in material flow behavior.

On the other hand, a significant improvement in the flatness value was observed. Flatness, which was 0.37 mm at 200 °C, increased to 0.88 mm at 310 °C, and this increase suggests that the melt temperature can play a role in improving the surface quality of the product. While the temperature showed a more limited change up to 270 °C, the increase in flatness gained momentum in the 270–310 °C range. This indicates that once a certain temperature threshold is exceeded, the process moves into a region where surface smoothness improves more rapidly.

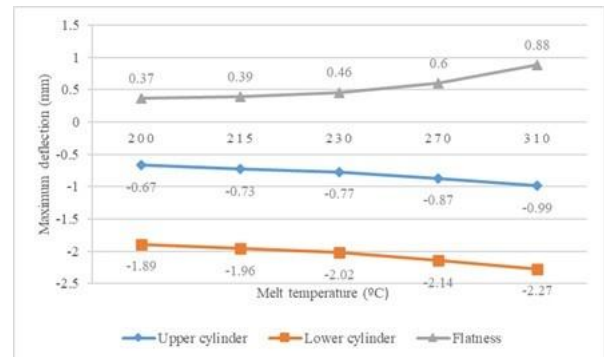


Figure 11. Effect of melt temperature on the total average shrinkage value and flatness error on cylindrical surfaces.

Figure 12 shows the deviation values in the upper cylinder, lower cylinder, and flatness parameters under cooling times ranging from 20 to 100 seconds. The data reveals that increasing the cooling time has a positive effect on surface quality but affects the lower- and upper-cylinder deformations at different rates. The deviation of the lower cylinder decreased from -2.11 mm at 20 seconds to -1.92 mm at 100 seconds. This reduction indicates that the structural deformation in the lower cylinder steadily decreases with longer cooling times. In the upper cylinder, however, an inverse trend is observed; the deviation value increased from -0.69 mm to -0.96 mm. This suggests that a longer cooling time may lead to thermally induced stress deformations in the upper cylinder. The flatness value, on the other hand, showed a regular increase with longer cooling times. The flatness value, which was 0.38 mm at 20 seconds,

reached 0.51 mm at 100 seconds. This trend indicates that longer cooling periods improve surface smoothness and have a positive effect on dimensional stability. While the increase in flatness was more pronounced in the 20–60 second range, the improvement curve flattens after 80 seconds, suggesting that the process is entering a saturation trend. Similarly, the deformation reduction effect in the lower cylinder occurred at a higher rate in this range.

In conclusion, although increasing the cooling time offers positive results in terms of flatness and lower cylinder stability, a careful balance must be struck considering the increase in upper cylinder deformation. In this context, a cooling time range of 60–80 seconds can be proposed as an ideal processing window that balances surface quality with structural integrity.

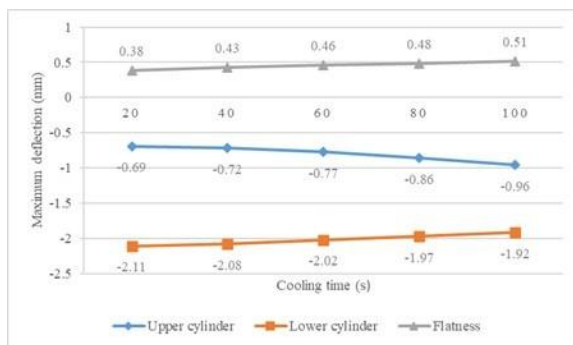


Figure 12. Effect of cooling time on the total average shrinkage value and flatness error on cylindrical surfaces.

Figure 13 compares the effects of packing pressure, melting temperature, and cooling time on product weight during the injection molding process. Increasing the packing pressure from 20 MPa to 100 MPa caused a significant increase in product weight, indicating that this parameter has the highest impact. This can be explained by the fact that high pressure ensures better filling of the mold cavity, thereby increasing material density. In contrast, increasing the melt temperature from 200 °C to 310 °C decreased the product weight, which may be related to backflow and potential material loss due to reduced viscosity at high temperatures. No significant change in product weight was observed when the cooling time was increased from 20 to 100 seconds. These findings reveal that the most critical parameter for optimizing product weight is packing pressure, melting temperature is of secondary importance, and cooling time has a limited effect.

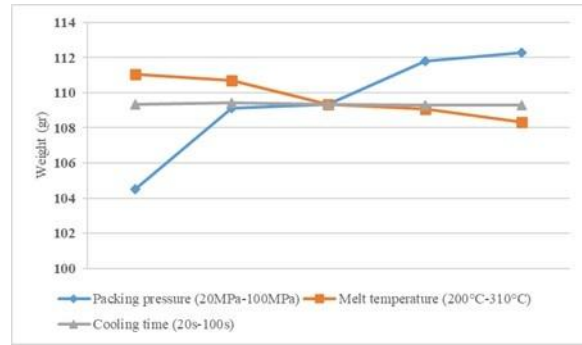


Figure 13. Effect of packing pressure, melt temperature and cooling time on product weight.

4. Conclusion

In this study, the injection molding process of PE100 material was comprehensively evaluated using high-precision experimental measurement techniques and simulation-supported analyses. Using an ATOS Q 3D scanning system and precise weight measurement devices, the effects of process parameters on the final product were revealed in detail. The findings showed that packing pressure is the primary determinant affecting both the mold fill condition and surface quality. High pressure reduced deformation and improved flatness values. While the melt temperature had positive effects on flatness, it increased deformation in the cylindrical regions, which demonstrated the effect of thermal flow and expansion behaviors on structural stability. The cooling time improved flatness while reducing deformation, especially in the lower cylindrical regions; however, it increased the risk of deformation due to thermal stresses in the upper cylinder. Packing pressure had the most significant effect on product weight, while melt temperature had an inverse effect, and cooling time resulted in limited change. These findings reveal that the correct selection of initial molding parameters directly affects both geometric defects and production quality. Specifically, the range of 60–80 MPa for packing pressure and 60–80 seconds for cooling time offers an optimal processing window that balances dimensional accuracy, productivity, and quality.

Author Contributions

The percentages of the authors' contributions are presented below. All authors reviewed and approved the final version of the manuscript.

	Y.T.	İ.K.
C	50	50
D	60	40
S	50	50
DCP	50	50
DAI	50	50
L	50	50
W	40	60
CR	50	50
SR	50	50
PM	50	50
FA	50	50

C= concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The authors declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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