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Metrological Characterization of Shrinkage in Precision Injection Moulded Polypropylene Plates through Experimental Measurements and Process Simulation

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Abstract

This study assesses the potential of numerical simulations to accurately predict the dimensional shrinkage behaviour of polypropylene (PP) injection-moulded plates. A set of manufacturing experiments was conducted on an ARBURG Allrounder 370 A machine using SABIC PP 579S polypropylene. Mould cavity and moulded part specimens were characterised using a Coordinate Measuring Machine (CMM), an analytical balance and a micrometre. The data was employed as an input for the process simulations in Moldex3D.

The experimental data showed shrinkage of 1.18% and 1.24% in length (along the flow direction) and width (across the flow direction), respectively. Furthermore, numerical simulations predicted values of 1.00% and 1.02%, respectively, within a deviation of 0.22% in each direction. In contrast, the thickness direction exhibited a negative shrinkage (expansion) of −1.47%, whereas simulations predicted a contraction of 2.53%. Short-term experiments showed a clear dependence of thickness on injection volume, indicating that the discrepancy is influenced by pressure-dependent tooling and consequent material behaviour. Factors such as melt compressibility, elastic mould deformation, release of residual compressive stresses, and incomplete mould sealing under high packing pressure are not fully accounted for in conventional simulation boundary conditions, limiting the accuracy of thickness-direction shrinkage predictions.

Overall, results confirm the capability of the injection moulding simulations to accurately predict shrinkage in planar dimensions, while highlighting the sensitivity of thickness behaviour to processing and tooling conditions. This study demonstrates the importance of integrating precise experimental measurements with numerical simulations to improve the reliability of shrinkage prediction in polymer injection moulding.

Keywords: Injection moulding, Shrinkage characterization, Polypropylene (PP), Dimensional metrology, Simulation validation.

1. Introduction

Injection molding is one of the most widely used manufacturing processes for polymer components production, particularly in automotive, medical, and consumer goods applications, due to its ability to produce complex geometries with high repeatability and efficiency [1,2]. However, achieving precise dimensional accuracy remains a significant challenge, primarily due to material shrinkage during cooling and solidification [3-5].

Shrinkage arises from the volumetric contraction of polymers as they transition from the molten to the solid state and can lead to dimensional deviations, residual stresses, and warpage, which negatively affect the part quality and functionality [4,6].

The magnitude and direction of shrinkage depend on both material properties and processing conditions; thus, understanding and predicting shrinkage behaviour is critical for optimizing mold design, processing parameters, and material selection [3,7].

Process simulation tools such as Moldex3D, Autodesk Moldflow or Cadmould, are widely used to predict shrinkage and support mold design and process optimization. Nevertheless, the accuracy of these predictions strongly depends on the quality of the input data, material models, and boundary conditions, making experimental validation essential [5,8].Previous studies have investigated the shrinkage behaviour in polypropylene (PP) under various injection molding conditions; however, the strong dependency on material grade, tooling, and processing parameters limits the generalizability of existing results [9].

In this study, the shrinkage behaviour of precision injection moulded polypropylene plates is experimentally characterized using high accuracy dimensional metrology and systematically compared with numerical process simulations.

Particular attention is given to differences between planar (length and width) and thickness shrinkage, providing insight into the limitations of current simulation approaches and the influence of tooling and process related effects. The resulting dataset serves as a reliable benchmark for validating shrinkage predictions in polymer injection molding.

2. Materials and Methods

A moulding including two flat rectangular PP plates was produced using a two-cavity injection mould (Figure 1). This relatively simple geometry enabled the evaluation of the shrinkage behaviour along the flow (length), transverse to the flow (width), and thickness directions.

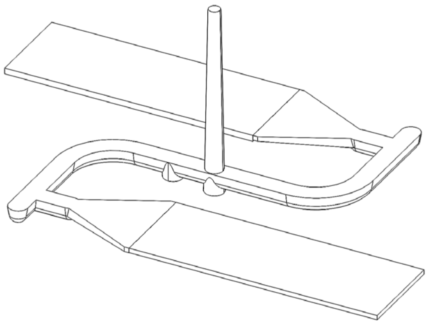

Figure 1. Geometry of the injection-moulded PP plates.

2.1. Measurement Uncertainty and Repeatability

To ensure statistically valid results, a preliminary analysis was conducted to assess the variability in the subsequent measurements and determine the minimum number of measurements per sample needed for reliable shrinkage evaluation. A sequential measurement strategy was followed: multiples measurements were taken incrementally in one single part, and the evolution of the mean and standard deviation for each measurement was tracked. The goal was to identify the point at which the relative standard deviation (RSD) defined as the ratio between the standard deviation (σ) and the mean (μ) stabilized, indicating that further measurements would not significantly change the estimated variability.

$$RSD = \frac{\sigma}{\mu} \tag{1}$$

RSD stabilization was observed after approximately six to eight measurements for all variables (length, width, thickness, and weight). Based on this result, ten measurements per dimension and condition were selected to ensure repeatability while keeping the workload manageable.

2.2. Mold Measurements

Mold cavity dimensions were measured using a ZEISS PRISMO CMM equipped with a tactile probing system [10]. All measurements were conducted under controlled laboratory conditions, with the mould rigidly fixed and aligned prior to measurement. Length (flow direction) and width (transverse direction) were selected as reference dimensions for the evaluation of planar shrinkage.

Each dimension was measured at three locations within the cavity using six probing points per axis to capture local dimensional variations (Figure 2). The resulting mean values and standard deviations were used as reference dimensions for the shrinkage analysis.

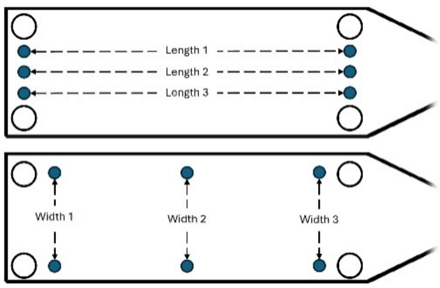

Figure 2. Distribution of probing points used for cavity dimension measurements.

2.3. Part Production

Injection molding trials were carried out using an ARBURG Allrounder 370 A 600–70 All Drive injection molding machine, designed for high-precision applications [11], and SABIC PP 579S [12]. A parametric variation of injection volume was introduced to produce short-shot and fully filled parts with evaluated volumes of 7, 9, 11, 13, 15, 16, and 17 cm³. All other process parameters- including filling time, melt and mold temperatures, packing time and pressure, cooling time, and total cycle time- were kept constant across all experimental runs. The complete set of processing parameters is summarized in Table 1.

Table 1. Filling, packing and cooling injection parameters.

Parameter	**Value**	**Unit**
Filling		
Filling time	0.83	s
Melt temperature	225	°C
Mold temperature	35	°C
Max injection pressure	250	MPa
Packing		
Packing time	9.00	s
Max packing pressure	250	MPa
Cooling and Cycle		
Cooling time	10.00	s
Mold open time	5.00	s
Ejection temperature	90	°C
Ambient air temperature	25	°C
Total cycle time	24.83	s

2.4. Dimensional and Mass Measurement of Parts

After molding, all parts were allowed to stabilize at room temperature under controlled environmental conditions (20±1°C and 35-50% relative humidity). The length and width of fully filled parts were measured using a DeMeet 400 optical CMM [13], whereas short-shot parts were measured using a Mitutoyo digital calliper due to their incomplete geometry.

For complete parts, six reference points were defined along both the length and width edges, following the same coordinate pattern used for mold measurements (Figure 2). Ten parts from each cavity were evaluated. Each dimension was measured ten times per part at the same defined locations.

For short shots, ten samples from each cavity were considered. Each part was measured ten times using the Mitutoyo digital calliper. Due the incomplete condition of the short shots, the measurement strategy was limited to the length dimension, defined as the distance from the gate edge to the most distal point of the part contour, as illustrated in Figure 3.

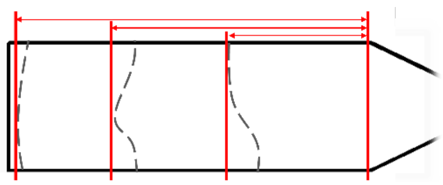

Figure 3. Reference for short shot length measurements.

Thickness measurements were performed using a Mitutoyo digital micrometre with a resolution of 0.001 mm [14]. Ten parts per cavity were evaluated, and each part was measured ten times at nine consistent reference locations, as illustrated in Figure 4.

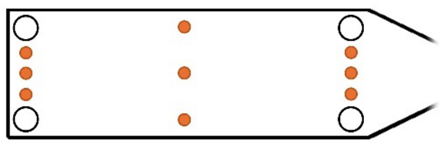

Figure 4. Distribution of reference probing points used for thickness measurements.

Mass was measured using an OHAUS DV215CD precision balance with a resolution of 0.0001 g [15]. A total of ten parts were weighed, with each part measured ten times. Parts were handled using a clean tissue to avoid any contamination. Measurements were recorded only after stabilization of balance reading within the draft shield, to minimize variability due to airflow, handling, and surface contamination.

2.5. Process Simulation

To complement the experimental study, a numerical process simulation was performed in Moldex3D Studio 2025R1OR, including filling, packing, cooling, and warpage analyses.

The CAD geometry based on CMM measurements was imported into Moldex3D in STEP format. A three-dimensional solid mesh was generated. The mesh resolution was set for 1 mm for the hole geometry and locally refined with a minimum element size of 0.23 mm in the gate and connector regions to improve simulation accuracy (Figure 5).

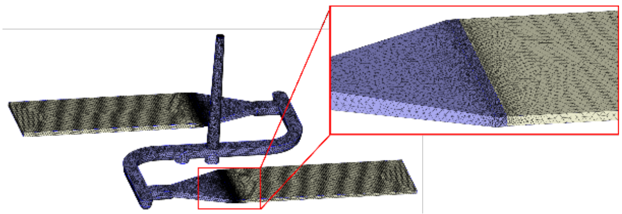

Figure 5. Mesh configuration used Moldex3D. A finer resolution was applied in the connector areas.

The SABIC PP 579S material model and the ARBURG Allrounder 370 A 600–70–18 machine were selected directly from the Moldex3D databases. Process parameters were defined and were matched to the experimental conditions used for the fully filled parts.

2.6. Shrinkage Calculation

Shrinkage was calculated by comparing reference dimensions to the corresponding dimensions of the evaluated part, whether physical or simulated. Shrinkage percentage S was calculated as:

$$\%S = \frac{D_{ref} - D_{evaluated}}{D_{ref}} \times 100 \quad (2)$$

Where D_{ref} corresponds to the nominal CAD or the mold cavity dimension obtained via CMM measurements, and $D_{evaluated}$ describes either measured part dimensions or simulation output dimensions. Positive values indicate dimensional contraction, while negative values correspond to dimensional expansion.

3. Results

3.1. Dimensional Analysis

Table 2 presents the measured mould cavity dimensions together with the nominal CAD values. Length and width deviations in both cavities were below 0.04 mm, whereas substantial deviations were observed in the thickness direction. Cavity 1 exhibited a thickness reduction of approximately 1.1 mm relative to the nominal geometry, while Cavity 2 showed a larger reduction of nearly 1.6 mm, indicating a significant discrepancy between the nominal and manufactured mould geometries.

Table 2. Comparison of nominal values and measured mould dimensions for both cavities (mean ± standard deviation).

Dimension	Nominal [mm]	Mold Cavity 1 [mm]	Mold Cavity 2 [mm]
Length	78.000	78.039 ± 0.003	78.015 ± 0.001
Width	28.000	28.035 ± 0.001	28.021 ± 0.007
Thickness	(1) 1.900 (2) 1.400	1.914 ± 0.034	1.420 ± 0.013

Based on these findings, the CAD geometry was corrected to reflect the measured cavity dimensions prior to performing the Moldex3D simulations, as illustrated in Figure 6. Based on these findings, the CAD geometry was corrected to reflect the measured cavity dimensions prior to performing the Moldex3D simulations, as illustrated in Figure 6.

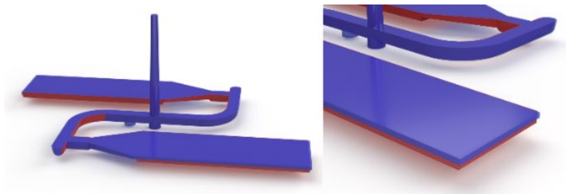

Figure 6. Comparison between the nominal CAD (red) and the corrected CAD model (blue) used for simulation.

Subsequently, fully filled parts were measured to characterize geometry and repeatability across both mould cavities. These measurements form the basis for the shrinkage analysis. Table 3 reports the mean values and standard deviations for length, width, and thickness.

Table 3. Measured dimensions of complete parts (mean ± standard deviation).

Dimension	Cavity 1 [mm]	Cavity 2 [mm]
Length	77.143 ± 0.078	77.067 ± 0.101
Width	27.701 ± 0.114	27.660 ± 0.049
Thickness	1.940 ± 0.022	1.443 ± 0.020

To examine the origin of the negative thickness shrinkage, short-shot parts were measured as a function of injection volume. Table 4 summarizes the thickness results.

Table 4. Measured thickness of short-shot parts as a function of injection volume for both mold cavities (mean ± standard deviation).

Setting [cm³]	Cavity 1 [mm]	Cavity 2 [mm]
7	1.910 ± 0.004	1.431 ± 0.011
9	1.920 ± 0.003	1.436 ± 0.010
11	1.924 ± 0.017	1.437 ± 0.012
13	1.923 ± 0.019	1.439 ± 0.010
15	1.928 ± 0.023	1.438 ± 0.011

In addition, progressive filling behavior was confirmed through short-shot trials over the evaluated injection volume range (7–17 cm³). Measured part length increased steadily with injection volume during short-shot trials, converging to final values of approximately 77.1 mm for both cavities in complete parts, with standard deviation average below 0.24 mm.

Part weight increased monotonically with injection volume, ranging from 8.67 g for the lowest short-shot condition to approximately 12.10 g for complete parts, with a standard deviation below 0.04 g. These results indicate consistent volumetric filling and stable processing conditions, supporting the use of short-shot experiments as a reliable basis for the subsequent shrinkage analysis.

3.2. Shrinkage Analysis

Dimensional shrinkage was calculated for each cavity using the corrected mold dimensions as reference. Shrinkage was computed following Eq. (2). Table 5 compares the experimentally measured shrinkage of complete parts with the corresponding Moldex3D simulation results for length, width, and thickness.

Table 5. Comparison of experimental and simulated shrinkage for both cavities.

	Cavity 1		Cavity 2	
Dimension	Experimental [%]	Simulation [%]	Experimental [%]	Simulation [%]
Length	1.148	1.012	1.215	0.986
Width	1.191	1.036	1.288	1.000
Thickness	-1.365	3.646	-1.572	1.408

The results show good agreement between experiment and simulation for length and width in both cavities, with comparable shrinkage magnitudes. In contrast, a pronounced discrepancy was observed in the thickness direction. Experimental measurements revealed negative shrinkage (expansion), whereas the simulation predicted significant positive shrinkage.

Thickness shrinkage was evaluated on short-shot parts as a function of injection volume. Figure 7 shows the resulting trends for both cavities, including the transition to fully filled parts. This is due to elevated mould compliance.

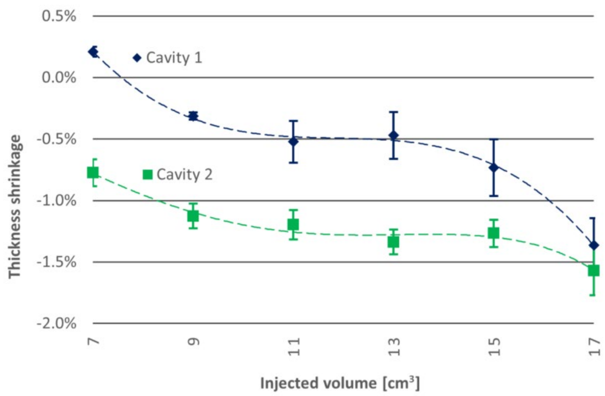

Figure 7. Thickness shrinkage relative to mould cavity dimensions as a function of injected volume for short-shot and fully filled parts in both cavities; negative values indicate expansion.

The results in Figure 7 show meaningful trends. In Cavity 1, thickness expansion increased with injection volume, suggesting that higher cavity pressure may promote slight mold opening, leading to apparent expansion in the thickness direction. In Cavity 2, the trend was less pronounced during short-shot conditions. However, both cavities exhibited a consistent decrease in thickness shrinkage with increasing injection volume. This behaviour supports the hypothesis that process effects, rather than material shrinkage alone, play a significant role in the observed thickness expansion.

In summary, although shrinkage in length and width aligns well with simulation, the behaviour in thickness is not adequately captured by the model and appears to be strongly influenced by experimental limitations.

4. Conclusions

This paper presents an experimental evaluation of shrinkage behaviour in polypropylene (PP) injection-moulded plates and a comparison with numerical simulation results. The conclusions are as follows:

(i) Experimental measurements showed consistent planar shrinkage in both cavities, with average values of approximately 1.2% in length and width. Moldex3D simulations accurately predicted this in-plane shrinkage, with deviations below 0.25% relative to experimental results, confirming the suitability of the simulation framework for planar dimensional prediction.

(ii) In contrast, a pronounced discrepancy was observed in the thickness direction: simulations predicted positive shrinkage, whereas experiments consistently exhibited negative shrinkage (expansion). Short-shot analysis revealed a clear dependence of thickness behaviour on injection volume, indicating that tooling- and process-related effects, such as imperfect mould sealing during filling and packing, significantly influence the measured thickness.

(iii) Overall, the study confirms the capability of Moldex3D simulations to predict planar shrinkage in polypropylene injection-moulded parts, while highlighting the need for careful experimental validation when assessing out-of-plane dimensional behaviour.

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