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Determination of packing parameters influence on the accuracy of precision moulded components by coordinate metrology

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Abstract
High-volume manufacturing of polymer components increasingly demands micrometric dimensional tolerances and stable geometric quality across multi-cavity moulds. We report a metrology-driven experimental study on a six-cavity tool and precision injection moulding process for polypropylene moulded rings, where a tactile coordinate measuring machine (CMM) and analytical weighing were used to quantify the effect of holding pressure (200–600 bar applied for 6 s) and holding time (1–4 s at 400 bar of packing pressure) on product dimensions (inner/outer diameters) and roundness, and part mass. A Design of Experiments (DOE)-based analysis shows that measurement repeatability is negligible compared with process-induced variation; expanded measurement uncertainties for the main dimensional responses are 0.6-0.7 µm, confirming capability for sub-micrometric discrimination. Across 10 cycles per setting (producing 60 parts per cycle), holding pressure/time significantly increases part mass and characteristic dimensions while decreasing roundness error up to an over-packing threshold. Cavity-dependent three-lobed deformation is mitigated as pressure approaches 500 bar, yet material inefficiency emerges beyond this level as sprue weight increases disproportionately versus product weight, consistent with gate-limited feeding. The results establish a practicable framework for advanced product and process control in precision injection moulding using coordinate metrology and provide actionable set-up recommendations balancing quality and sustainability.

Keywords: Precision injection moulding; Coordinate metrology; CMM; Multi-cavity moulds; DOE; Roundness; Process control.

1. Introduction

Precision injection moulding (IM) has evolved to deliver geometries with tolerances down to 10-20 µm over 10–100 mm characteristic lengths (i.e., 0.01-0.20%), driven by stringent functional and assembly requirements in medical, energy, mobility and consumer devices [1,2]. Achieving such performance at scale (i.e. 10^6-10^8 parts/year) hinges on robust product and process control across the full moulding cycle and all cavities within the mould [3].

Coordinate metrology – especially with tactile coordinate measuring machines (CMMs) probing – provides traceable dimensional and form measurements with sub-µm resolution and single-digit micrometric accuracy, enabling discrimination of small process-induced variations that might otherwise be buried by process as well as measurement noise [2]. These measurements provide reliable data for process optimisation and associated economic benefits [4].

Packing pressure and packing time are among the strongest levers for minimizing shrinkage/warpage in conventional parts, often through statistical optimization (e.g., design of experiments) or data-driven techniques (e.g., machine learning) [5–6].

Multi-cavity variation studies have shown that cavity-dependent mechanics and thermal fields produce substantial dimensional scatter. Instrumentation and modelling link these aspects to mould compliance and imbalance [7], as well as to differential shrinkage between external and internal geometrical characteristics, e.g., in micro rings [8].

This work develops and validates a metrology-centric methodology for mapping and controlling relationships between process parameters of the moulding cycle packing phase (holding pressure and holding time) and product characteristics (diameters, height, roundness, mass) for a thermoplastic mechanical part produced in a six-cavity two-plate cold-runner mould. In the study, measurement planning, part fixturing, CMM program design and uncertainty estimation are combined with factorial design of experiments (DOE) and effect screening.

The study uncovers how holding pressure and time drive part dimensions and form, identifies cavity-specific deformation modes, and quantifies an over-packing regime where further pressure and time primarily increase sprue mass rather than part mass. Control levers (parameter set-points, cavity-specific corrective actions, gate/runner improvements) to optimize quality and material efficiency are recommended.

2. Methodology

2.1. Part, material and moulding setup

The target product is a polypropylene (PP) ring-shaped mechanical part with thin sections (see Figure 1, left), manufactured on an Arburg 420C Golden Edition machine (equipped with a Ø25 mm diameter screw) using Total PPC 5660 (PP YA42-006). Production uses a six-cavity two-plate cold-runner mould (see Figure 1, right).

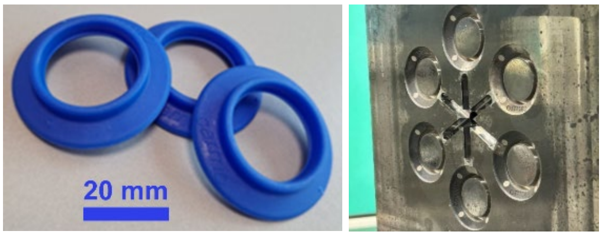

Figure 1. Precision moulded polypropylene ring (left); six-cavity two-plates cold-runner mould (left).

During the experiments, two groups of parameters were varied: (i) holding pressure at 200, 300, 400, 500, 600 bar (holding time fixed at 6 s); (ii) holding time at 1, 2, 3, 4 s (holding pressure fixed at 400 bar). For each setting, 10 cycles were targeted for process monitoring, so 60 parts were produced for each experiment to be measured.

2.2. Dimensional metrology planning and measurands

A tactile CMM (ZEISS PRISMO [9], maximum permissible error for length measurement MPE(E150) = 0.9 + L/400 µm, L in mm [10] and scanning single stylus form probing error P(FTU) = 1.0 µm [11]) measurement procedure was designed to maximize repeatability on irregularly shaped, flexible polymer parts lacking reference planes. The probe diameter was 3 mm, scanning speed was 5 mm/s, and probing force was 50 mN. The principal measurands considered were: inner diameter D1 (at a specific axial height of z6=6 mm from the top surface), outer diameter D2 (at z6), and roundness of D1 and D2 (both measured to z6) (see Figure 2). The coordinate features were built from point clouds acquired with controlled probing strategies on the selected planes. Roundness profile plots (consisting of 400 points collected around its circumference) were recorded for each cavity and setting.

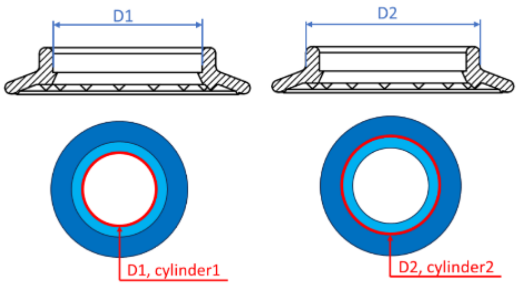

Figure 2. Measurands of the precision moulded polypropylene rings.

2.3. CMM part fixturing

The fixturing adopted a mechanical clamping concept with two spring clips and an optical flat (flatness 0.2 µm) to improve datum stability while avoiding part deformation (see Figure 3). The alignment was performed via a well-defined base alignment sequence and feature referencing at each run. Programmed strategies used a combination of discrete points, arcs and circular scan paths, with careful avoidance of clamp interference on bottom planes.

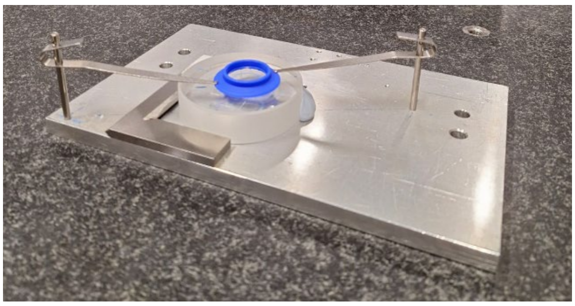

Figure 3. Ring fixturing on the CMM granite plane.

2.4. Mass measurements

The dataset also includes part mass from an analytical balance. Mass was measured on an OHAUS Discovery semi-micro analytical scale (declared repeatability 0.1 mg). The weighing step preceded CMM inspection and employed compressed-air cleaning to eliminate debris.

2.5. DOE design and analysis workflow

Two DOEs were executed in this work:

• DOE-1 (holding pressure 200-300-400-500-600 bar, 6 s holding time) to estimate the main effects of holding pressure along with cavity and cycle factors on D1, D2, roundness plots and mass partition between parts and sprue.

• DOE-2 (holding time 1-2-3-4 s hold at 400 bar holding pressure) to estimate the main effects of holding time along with cavity and cycle factors on D1, D2, roundness plots and mass partition between parts and sprue.

2.6. CMM measurement uncertainty and capability

An expanded uncertainty budget was estimated using the PUMA simplification of GUM [12], aggregating instrument resolution, reference standards, and a combined term for workpiece/fixturing/environment/procedure derived from five repeated measurements with re-clamping and re-alignment after each cycle. The resulting expanded uncertainties (k≈2) were: U(D1) = 0.7 µm and U(D2) = 0.6 µm, confirming that the measurement system is capable of discriminating process effects at the micrometric level, with sub-µm resolution.

3. Results

3.1. DOE-1: main effects of holding pressure

Holding pressure dominates cavity and cycle effects across all dimensional responses and part mass. Cavity differences exceed cycle-to-cycle differences, reflecting robust machine stability yet non-uniform cavity behaviour.

As pressure increases from 200 bar to 500 bar, both mass and characteristic diameters/height increase, while roundness error decreases, indicating enhanced packing that offsets material shrinkage and partially stabilizes shape. The improvement plateaus and can reverse at 600 bar for some features due to material over-packing (see Figure 4).

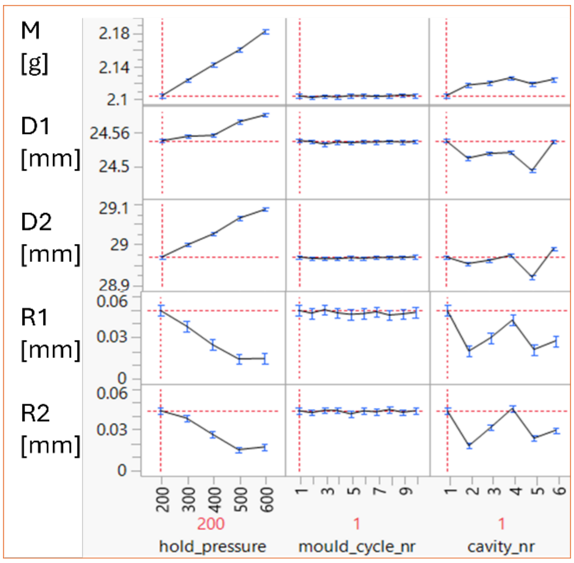

Figure 4. Influence of holding pressure, moulding cycle, cavity number on mass (M), ring internal diameter (D1), ring external diameter (D2), and their respective roundness (R1, R2).

Roundness plots reveal a three-lobed mode predominantly in cavities 1 and 4 for D1 and D2, which diminishes with pressure and is largely resolved near 500 bar (see Figure 5). Since inner and outer sections share the mode and respond similarly to pressure, the cause is attributed to flow-induced deformation rather than geometric errors in individual cavity inserts.

Averaging part mass across six cavities per cycle and pairing with the corresponding sprue mass reveals a nonlinear shift between 500 bar and 600 bar (see Figure 6). Sprue mass increases markedly more than product mass, indicating gate bottlenecking during the holding phase, with material accumulating in the runner system rather than feeding the cavities. This behaviour aligns with increasing thermos-viscous effects in the gate as it cools and solidifies under extended high pressure. The practical consequence is diminishing returns and material inefficiency above 500 bar for this geometry and tooling.

Although the best roundness is achieved near 500 bar, 400 bar is selected as a balanced set-point considering marginal quality gains vs. increased energy use, potential mould fatigue, and higher sprue mass at elevated pressures.

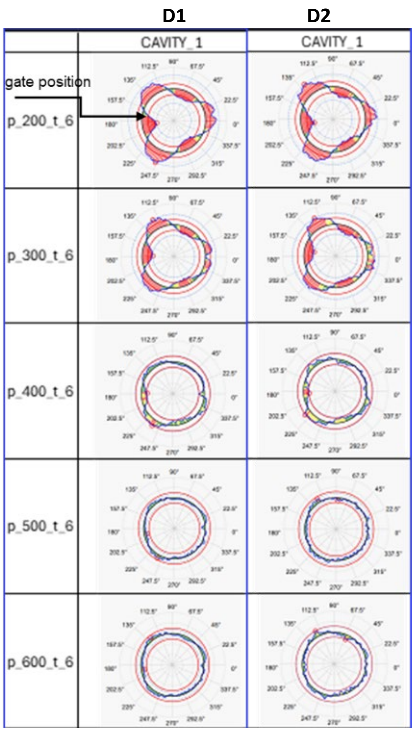

Figure 5. Influence of holding pressure on roundness R1 profile of the internal diameter (D1) and on roundness R2 of the external diameter D2.

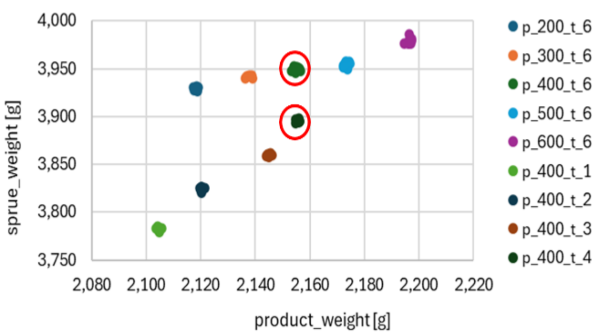

Figure 6. Influence of holding pressure and holding time on the moulded ring mass roundness and the sprue mass. An increase of packing time from 4 s to 6 s with a packing pressure of 400 bar cause an increase of sprue mass while the moulded product mass remains constant (see details in the red circles).

3.2. DOE-2: main effects of holding time

Holding time dominates cavity and cycle effects, echoing DOE-1: process parameters ≫ cavity ≫ cycle.

Mass and characteristic dimensions increase with holding time (from 1 s to 4 s), confirming slight improved shrinkage compensation under extended packing. Roundness decreases modestly but exhibits limited benefit beyond 3 s (see Figure 7).

Three-lobed deformation in cavities 1 and 4 remains the dominant mode and is not fully eliminated by longer holding times, reinforcing a flow/temporal imbalance rather than static cavity geometry error (see Figure 8). A recurring protrusion at 180° (gate location) is observed in roundness plots, compatible with differential local shrinkage because the gate region cools last.

Both sprue and product mass increase with time, but product gains saturate earlier than sprue gains: for some pairs of settings with equal pressure but different times, longer time yields a heavier sprue with negligible product mass benefit (see Figure 6). This suggests a wasteful holding regime and reinforcing the selection of shorter holding times.

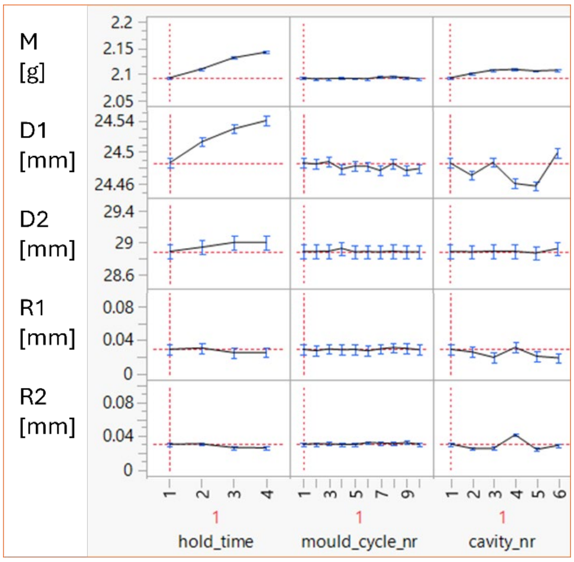

Figure 7. Influence of holding time, moulding cycle, cavity number on mass (M), ring internal diameter (D1), ring external diameter (D2), and the respective roundness (R1, R2).

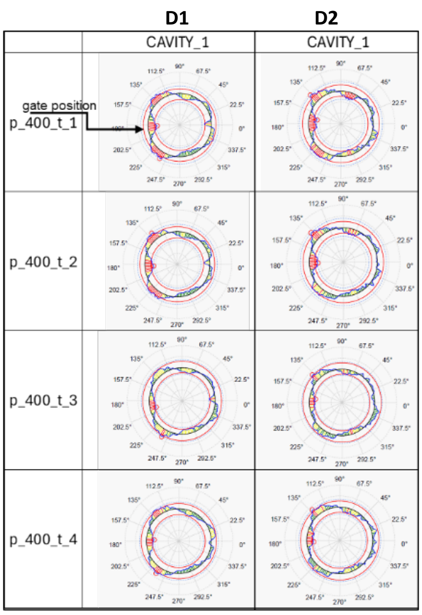

Figure 8. Influence of holding time on roundness R1 profile of the internal diameter (D1) and on roundness R2 of the external diameter D2.

4. Discussion

4.1. Cavity influence on part for error

The consistent three-lobed mode in cavities 1 and 4 across inner and outer sections indicates a global deformation mechanism (e.g., asymmetric flow front, local thermal gradient, or runner balancing) rather than localized cavity machining defects. Its mitigation under higher pressure suggests that improved local packing and more uniform pressure transmission can counteract the deformation, yet long-term elimination should focus on runner/gate balance and, potentially, local temperature control near the problematic cavities.

4.2. Overpacking and material efficiency

Material allocation between parts and sprue provides a sustainability perspective on process parameters setting selection. Beyond ≈500 bar or long holding times, the gate becomes a dominant restriction as viscosity increases during cooling, so additional energy predominantly packs the runner/sprue rather than the parts. In production, this raises scrap (sprue regrind) and energy use without proportional quality gains. The data support moderate pressure levels (e.g., 400 bar) and short holding times (e.g., 1 s) for the studied geometry/material/tooling combination, achieving robust dimensional targets while minimizing waste and energy consumption.

5. Conclusion and Future work

An advanced product and process control framework for precision injection moulding based on high-accuracy coordinate metrology and designed experiments has been demonstrated. Key outcomes are:

1. A CMM-based measurement strategy with robust fixturing and program design can deliver sub-µm expanded uncertainties on critical dimensions, enabling clear discrimination of process, cavity, and moulding reproducibility effects.
2. Holding pressure and holding time are dominant factors during the packing phase. Their increase raises part mass and characteristic dimensions while reducing roundness error up to an over-packing threshold.
3. Cavity-dependent lobing reflects flow-induced deformation and is mitigated near 500 bar. Addressing runner/gate balance is recommended for full elimination.
4. Sprue vs product mass analysis reveals diminishing returns beyond 500 bar or prolonged holding, supporting moderate pressure (~400 bar) and short holding time (~1 s) to balance quality, energy and material efficiency.

The results are specific to the considered PP moulded ring, a particular six-cavity mould and a defined machine. The study intentionally focused on the holding phase (i.e., pressure and time). Future work should integrate melt and mould temperatures, injection velocity, and switchover position to complete the factor space (i.e., including also the filling phase). Finally, only tactile CMMs were used for measurements in this study. Optical CMMs and X-ray computed tomography systems may be considered for speed and full 3D representation capabilities respectively. However, uncertainty of these systems should be carefully considered and verified if they are sufficient for precision moulding applications with multi-cavity moulds.

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