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Advanced Cooling Fixture Implementation to Maintain Dimensional Stability in Silo Boot Parts for Plastic Injection Molding from PP Bapolene 5063C

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Abstract

This research paper presents the design and implementation of an advanced cooling fixture to address critical dimensional instability in Silo Boot parts molded with PP Bapolene 5063C material. The Silo Boot parts, being heavy and bulky, exhibited significant post-molding shrinkage, particularly at the rectangular openings. Traditional cooling methods, including belt conveyors, were inadequate to maintain dimensional specifications, leading to parts becoming oval-shaped and out of tolerance. This study introduces a novel cooling fixture connected to a constant chiller flow and exhaust system, ensuring effective cooling of the rectangular opening and stabilizing critical dimensions. The fixture was tested through DOE trials, and a finalized mass-production fixture was developed to enhance process efficiency while addressing floor space constraints and operator ergonomics. Results demonstrated a significant improvement in product quality, meeting the OD requirement of 17.400 +0.080/-0.020 inches and ensuring roundness.

Keywords: Plastic Injection Molding, Cooling Fixture, Dimensional Stability, Silo Boot, Smart Manufacturing, DOE Trial, PP Bapolene 5063C, Shrinkage Control

Introduction

Plastic injection molding remains the cornerstone of modern manufacturing due to its ability to produce complex parts with high precision, repeatability, and cost-efficiency. However, the process faces several challenges when dealing with bulky components made from semi-crystalline polymers like polypropylene (PP). In this study, we focus on PP Bapolene 5063C, a material widely known for its lightweight, high chemical resistance, and ease of processing. PP is a semi-crystalline thermoplastic that exhibits notable thermal shrinkage during cooling due to the crystalline regions' reorganization, making it a challenging material for maintaining tight dimensional tolerances.

The Silo Boot part, with a weight range of 5-7 lbs., presented significant post-molding shrinkage issues, particularly at its rectangular openings. The gating system, located in these critical regions, led to the accumulation of molten material, resulting in uneven shrinkage and deformation. Semi-crystalline materials like PP typically experience anisotropic shrinkage, where shrinkage along the flow direction differs from that perpendicular to the flow. This phenomenon was exacerbated by the part's design geometry, which combines a circular outer diameter with rectangular openings.

Moreover, the nature of PP Bapolene 5063C, with its melt flow index (MFI) and thermal expansion properties, contributes to its sensitivity to cooling rates. A rapid cooling process often leads to residual stresses, warpage, and uneven crystallization, particularly in areas with thick sections. These material behaviors required a targeted cooling solution to achieve consistent dimensions while maintaining mechanical integrity. Traditional belt conveyor systems, while effective for lightweight parts, failed to address the cooling needs of the Silo Boot.

This paper introduces a novel cooling fixture design that incorporates a controlled flow of chilled water and exhaust systems to stabilize the critical dimensions of Silo Boot parts. The proposed solution aligns with the principles of smart manufacturing by improving process consistency, reducing floor space utilization, and enhancing product quality. The study showcases the critical relationship between material science, thermal management, and process optimization in injection molding.

Problem Statement

In the plastic injection molding of Silo Boot parts using PP Bapolene 5063C, two significant challenges emerged during post-molding cooling:

1. **Dimensional Instability:** The Silo Boot's critical rectangular opening exhibited severe shrinkage and deformation post-molding. This issue arose from the material properties of PP Bapolene 5063C and the gating design, which led to an accumulation of molten plastic in the rectangular regions. Semi-crystalline polymers, such as PP, undergo non-uniform shrinkage due to the crystallization process during cooling. As the material transitions from molten to solid states, crystalline regions form, leading to differential shrinkage rates. In this case, the rectangular openings became deformed and failed to meet the required tolerance, often exceeding dimensions like 17.601 inches.

Figure 1 : the parts shrinks one side more than the other, ending up with oval shape

The OD (outer diameter) of the part also exhibited oval deformation instead of maintaining a perfectly round profile. This issue stemmed from uneven cooling across the part's geometry, where the circular ends cooled faster compared to the thicker rectangular regions. Without a targeted cooling strategy, the imbalance in cooling rates led to anisotropic shrinkage, introducing residual stresses and warpage.

2. **Production Inefficiency:** The standard belt conveyor cooling system proved inadequate for such heavy and bulky components. After exiting the molding machine, parts retained excessive heat, particularly in the rectangular areas where the gates were located. Operators could not handle the parts immediately due to high surface temperatures, requiring parts to be laid on the shop floor for prolonged cooling. This approach introduced two additional issues:
    - **Space Constraints:** Laying parts on the floor consumed significant production space, making it infeasible for mass production. The use of floor space as a cooling buffer created workflow bottlenecks and reduced operational efficiency.
    - **Inconsistent Cooling:** Floor cooling lacked uniformity, causing further dimensional instability. Parts that cooled for varying durations exhibited inconsistencies in shrinkage, leading to rejection rates.

PP Bapolene 5063C, despite its favorable MFI and mechanical properties, necessitates a precise cooling process to mitigate warpage and shrinkage. Its crystalline structure demands controlled thermal management to stabilize dimensions without compromising mechanical strength. To address these challenges, I proposed the development of a cooling fixture that ensures uniform cooling, stabilizes critical dimensions, and optimizes production workflows.

Root Cause Analysis

The dimensional instability and warpage issues observed in Silo Boot parts stem from the intrinsic properties of semi-crystalline polymers like PP Bapolene 5063C. These materials undergo a complex crystallization process during cooling, where molecular chains rearrange to form crystalline regions. This reorganization leads to anisotropic shrinkage, where the material shrinks more along the flow direction than perpendicular to it. For the Silo Boot part, the gate locations at the rectangular openings introduced further complexity.

The gates act as entry points for molten plastic, and being at the critical rectangular regions, they become the areas with the most concentrated and hottest plastic flow. As the plastic solidifies, the final areas to cool (end-of-fill regions) retain high heat for a prolonged duration. Inadequate cooling at these regions allowed the plastic molecules to shrink unevenly, leading to localized warpage. The imbalance in cooling exacerbated shrinkage along one axis, resulting in the rectangular regions deforming while the OD took on an oval shape. The mechanical property variations across thick and thin sections of the part further aggravated the issue.

The standard belt conveyor cooling method failed to address these challenges due to its reliance on air cooling and uncontrolled cooling rates. Semi-crystalline polymers like PP require a balance between rapid and uniform cooling to avoid excessive residual stresses. Without this balance, parts experience dimensional instability, warpage, and inconsistency in mechanical properties.

Proposed Solution: Cooling Fixture Design

To address the root causes identified, I designed a specialized cooling fixture to stabilize the rectangular openings and ensure uniform cooling throughout the part. The proposed fixture addresses the material properties and thermal behavior of PP Bapolene 5063C, aligning the cooling strategy with the crystallization process to minimize anisotropic shrinkage and residual stresses.

Key Design Features:

1. **Chilled Water System:** The fixture is connected to a chiller that provides a constant flow of cold water through channels built into the fixture. This ensures consistent cooling at the rectangular openings, where the highest thermal energy resides.
    - **Material Insight:** PP Bapolene 5063C requires cooling at a controlled rate to avoid rapid crystallization, which introduces warpage. By controlling water temperature and flow rate, the fixture promotes uniform shrinkage without compromising mechanical integrity.
2. **Exhaust System for Heated Water:** The fixture incorporates an exhaust mechanism to remove heated water, maintaining the chiller's effectiveness.
3. **Targeted Contact Points:** The fixture applies cooling specifically to the rectangular regions while supporting the circular OD to prevent oval deformation. This balances the cooling process across all critical areas.
4. **Cycle Optimization:** The fixture is designed to hold parts for 14-16 minutes, the optimal cooling duration identified during DOE trials. This ensures that the rectangular openings stabilize dimensionally before removal.

Initial Trial Results: The first manual fixture, shown in Figure 2, validated the feasibility of the design. The fixture provided precise cooling control, stabilizing the rectangular dimensions and reducing the oval deformation observed in the OD. By targeting high heat zones and aligning the cooling process with the material's thermal characteristics, the fixture mitigated anisotropic shrinkage effectively.

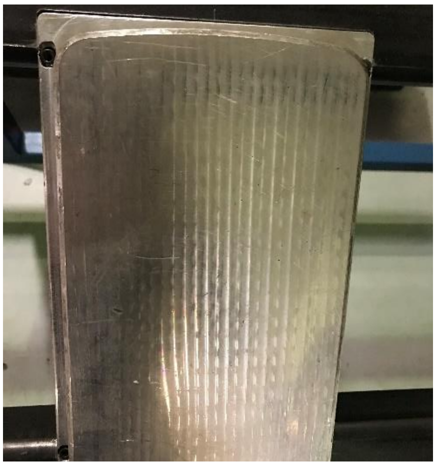

Figure 2. Initial cooling fixture used for trials

DOE Trials and Results

To validate the proposed fixture design, I conducted a detailed series of Design of Experiments (DOE) trials to determine the optimal cooling time, temperature, and fixture efficiency. The goal was to evaluate dimensional stability, particularly at the critical rectangular openings and the outer diameter (OD), while minimizing shrinkage and residual stresses. The DOE included multiple cooling durations, flow rates, and part positioning strategies to ensure the most efficient and repeatable process.

DOE Setup:

The trials were carefully structured around three key parameters:

1. **Cooling Duration:** Tested intervals of 6, 8, 10, and 12 minutes to evaluate the impact on shrinkage stabilization.
2. **Water Flow Rate:** Constant water flow rates of 2.5, 3.5, and 4.5 liters per minute were tested to determine the optimal heat dissipation capacity.
3. **Fixture Contact Points:** Evaluating configurations where cooling was concentrated only at the rectangular openings versus a combination of openings and OD support.

Data Collection:

Dimensional measurements were taken using calibrated digital calipers, Pi-tape and a CMM (Coordinate Measuring Machine) for precision. The following critical dimensions were tracked:

- **Rectangular Opening:** Tolerance target of critical dimensions.
- **Outer Diameter (OD):** Target OD of 17.400 +0.080/-0.020 inches.
- **Roundness and Warpage:** Measured ovality and any asymmetry.

Results Analysis:

The DOE trials provided clear insights into the impact of cooling duration and water flow rate on part stability:

1. **Without Fixture Cooling (Baseline):**
   - Parts exhibited severe dimensional instability, with the rectangular openings significantly deformed. The OD consistently measured above tolerance at values such as 17.520 - 17.601 inches, and ovality issues were prevalent. Manual floor cooling proved inconsistent, with variations observed across parts.
2. **With Cooling Fixture at 10-12 Minutes:**
   - The parts showed moderate improvement but remained slightly out of spec. Residual heat in thicker rectangular sections was not completely dissipated, leading to localized shrinkage.
3. **With Cooling Fixture at 12-14 Minutes (Optimal):**

- The rectangular openings stabilized within specified tolerances, and the OD consistently met the target of 17.400 inches.
- Warpage and ovality were virtually eliminated, and uniform cooling across critical regions was achieved.
- The combination of targeted cooling at the rectangular openings and support at the OD resulted in the most consistent results.

4. **At Extended Durations (16 Minutes):**
   - Marginal improvements were observed, but cycle efficiency suffered, so does Operator was missing the FIFO making it impractical for mass production.

Key Findings:

The DOE results demonstrated that the optimal cooling duration for the proposed fixture was 12-14 minutes at a water flow rate of 3.5 liters per minute. This configuration effectively stabilized the dimensions of the rectangular openings while maintaining OD roundness. The fixture successfully addressed the inherent material shrinkage challenges posed by PP Bapolene 5063C, aligning with both mechanical and production efficiency requirements.

Figure 3. Vertically in-spec part using the cooling fixture

Figure 4. Horizontally in-spec part showing OD roundness improvement

Final Fixture Design for Mass Production

Based on the DOE results, a robust and ergonomic fixture design was finalized for mass production. The design focused on maintaining efficiency, ensuring repeatability, and improving operator usability. The following features were integrated into the final fixture table:

Design Features:

1. **Capacity for Multiple Parts:** The fixture accommodates 8 parts simultaneously, arranged in a way that optimizes space usage and cooling efficiency. This multi-part capability significantly enhances production throughput compared to single-part manual fixtures used in initial trials.
2. **First-In-First-Out (FIFO) Cooling System:** To ensure consistency, a FIFO sequence was implemented for loading and unloading parts. Operators follow a sequential pattern, loading parts in rows while leaving one position vacant to identify the most cooled part for removal. This system minimizes operator errors and ensures maximum cooling duration for each part.
3. **Optimized Cooling Channels:** The fixture integrates precise cooling channels that direct chilled water flow to the rectangular openings while simultaneously providing support for the circular OD. The water flow maintains a temperature of 15°C-20°C, optimized to match PP Bapolene 5063C's thermal properties and minimize residual stresses.
4. **Exhaust Mechanism**: Heated water is continuously exhausted from the fixture to maintain a consistent cooling effect. This design prevents heat accumulation, ensuring uniform cooling for all 8 parts.
5. **Operator Ergonomics:** The fixture was designed with operator ergonomics in mind, incorporating an adjustable table height and easy part placement/removal. The rows are angled to reduce strain during handling while maintaining clear visibility of part positioning.

Mass Production Implementation:

The finalized fixture, shown in Figure 5, was deployed on the production floor. Operators were trained to load and unload parts in the designated FIFO sequence, ensuring streamlined workflow. The fixture's capacity to stabilize dimensions while cooling 7 parts simultaneously addressed the earlier production inefficiencies and space constraints.

Figure 5. Final mass-production fixture developed for Silo Boot cooling

Results in Production:

Following the implementation of the final cooling fixture:

- **Dimensional Stability:** The rectangular openings remained within specified tolerances, and the OD consistently measured 17.400 +0.080/-0.020 inches.
- **Improved Throughput:** Cooling 7 parts simultaneously reduced the overall cycle time, enabling higher production rates.
- **Enhanced Product Quality:** Warpage and ovality issues were eliminated, ensuring customer satisfaction and improved part performance.

The design and implementation of the mass-production cooling fixture represent a significant advancement in managing thermal behavior and shrinkage in semi-crystalline polymers like PP Bapolene 5063C. This solution aligned perfectly with smart manufacturing principles by combining process optimization, material science understanding, and ergonomic considerations.

Results and Discussion

The results of this study confirmed the success of the advanced cooling fixture in addressing the previously observed challenges of shrinkage, warpage, and dimensional instability in Silo Boot parts. By integrating targeted cooling for the rectangular openings and support for the outer diameter (OD), the fixture achieved a balance between material behavior and process optimization.

Key Improvements:

1. **Dimensional Accuracy:**

- Before using the fixture, parts exhibited dimensions significantly out of tolerance, with OD values reaching 17.601 inches due to anisotropic shrinkage.
- Post-implementation, the OD consistently met the required tolerance of 17.400 +0.080/-0.020 inches, stabilizing the critical rectangular openings and eliminating warpage.

2. **Roundness and Warpage Elimination:**
   - The cooling fixture ensured uniform shrinkage across all critical regions, maintaining OD roundness and eliminating ovality issues.
3. **Operational Efficiency:**
   - Cooling 7 parts simultaneously optimized the cycle time, leading to a significant reduction in overall production time.
4. **Material Behavior:**
   - PP Bapolene 5063C exhibited predictable shrinkage characteristics when cooled under controlled conditions, aligning with its semi-crystalline molecular behavior.
5. **Customer Satisfaction:**
   - The improved part quality, including dimensional stability and roundness, resulted in higher acceptance rates and customer satisfaction.

Conclusion

The successful design and implementation of the advanced cooling fixture for Silo Boot parts represent a breakthrough in addressing post-molding dimensional instability challenges in the plastic injection molding industry. By combining in-depth material science insights with process engineering principles, the fixture effectively stabilized critical rectangular openings and ensured OD roundness.

The key achievements of this study include:

- **Dimensional Accuracy:** Consistent compliance with required tolerances.
- **Production Efficiency:** Optimized cycle times by cooling 7 parts simultaneously.
- **Customer Acceptance:** Enhanced product quality and reduced rejection rates.

This project demonstrates the importance of integrating smart manufacturing solutions with material behavior considerations to address complex production challenges. The fixture design sets a new benchmark for managing shrinkage and warpage in semi-crystalline polymers like PP Bapolene 5063C, further reinforcing the value of innovation in plastic injection molding processes.

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