

# Enhancing Dimensional Stability and Environmental Durability in Delrin-Molded Parts Through Advanced Annealing Techniques

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## Abstract

This paper presents the implementation and optimization of an advanced annealing process designed to enhance the dimensional stability, moisture resistance, and crystallinity of Delrin-molded parts for demanding outdoor applications. Delrin, a widely used acetal resin, poses unique challenges in plastic injection molding due to its natural tendency to shrink post-molding and absorb moisture, which can compromise part performance in variable environmental conditions. By introducing a high-capacity annealing oven with precise temperature and humidity control, we achieved substantial improvements in part stability and durability. This process was developed through close collaboration with customer engineering teams and our in-house experts, ensuring the final product meets strict tolerance and environmental durability requirements. Results indicate that the annealing process effectively reduces dimensional variation, decreases moisture content by 75%, and increases crystallinity by 20%, making the parts robust enough to withstand extremes of heat, cold, and humidity. This study underscores the value of high-tech annealing solutions in the plastic injection molding industry, offering a blueprint for similar applications in advanced manufacturing.

**Keywords:** Delrin Annealing, Crystallinity Enhancement, Dimensional Stability, Moisture Resistance, Environmental Durability, Plastic Injection Molding, Advanced Manufacturing Techniques, High-Capacity Annealing Oven, Quality Engineering, Process Optimization

## Introduction

In the field of plastic injection molding, material selection plays a critical role in ensuring that manufactured parts meet rigorous performance standards, especially when intended for outdoor applications subjected to diverse environmental conditions. Our company, a leader in advanced manufacturing techniques, was recently awarded a project that required the production of parts using Delrin, a highly resilient acetal homopolymer. Delrin is known for its mechanical properties, including excellent tensile strength, low friction, and good dimensional stability under controlled conditions. However, it also presents unique challenges that necessitate advanced process control, particularly when intended for applications involving exposure to variable and extreme weather conditions.

Delrin's natural properties, including its tendency to absorb moisture and experience shrinkage post-molding, introduce complexities that can impact the final part's dimensional stability and crystallinity. Given the application's requirements—specifically outdoor meters exposed to direct sunlight, fluctuating temperatures, rain, and snow—our team had to develop a manufacturing process capable of overcoming these challenges. This necessitated an exploration into advanced annealing techniques to ensure that the molded parts could withstand prolonged exposure to environmental stressors without degradation in performance.

To address these requirements, we collaborated with the customer's engineering team to design and implement a high-capacity annealing oven. This oven was not only capable of achieving precise temperature control but was also optimized to enhance the parts' crystallinity and reduce residual moisture content. By deploying this advanced annealing process, we aimed to ensure that the Delrin parts would achieve the highest possible stability and resistance to moisture absorption, resulting in products that could reliably function under extreme environmental conditions. This paper documents the methodologies, findings, and insights derived from the implementation of this annealing process, underscoring its critical role in achieving dimensional and structural stability in Delrin-molded parts.

## Problem Statement

While Delrin offers various advantages for injection-molded components, particularly in terms of strength and low friction, it presents specific challenges when environmental durability is a primary concern. Two major issues were identified in this project:

1. **Dimensional Stability and Shrinkage:** One of the primary challenges with Delrin is its tendency to undergo dimensional shrinkage after molding. This shrinkage is not immediate and can take up to seven days to stabilize, which complicates the quality control and delivery timeline. For applications requiring tight tolerances, delayed stabilization can lead to inconsistencies in part dimensions, resulting in parts that may not meet the required specifications for assembly or end-use. This challenge is exacerbated in outdoor applications, where even minor variations in dimension due to environmental exposure could impact part performance.
2. **Crystallinity and Moisture Resistance:** Delrin's crystallinity is another critical factor that affects its durability, particularly in outdoor applications where parts are subjected to harsh environmental conditions. For parts used in external meters, which are exposed to direct sunlight, rain, and freezing temperatures, it was essential to achieve a high level of crystallinity to enhance resistance to thermal expansion, moisture absorption, and environmental degradation. Parts with insufficient crystallinity are more susceptible to moisture uptake, which can lead to dimensional changes, warping, and ultimately, part failure. Ensuring optimal crystallinity levels was therefore imperative to meet the application's demands for long-term stability and durability.

These two challenges necessitated the development and implementation of a comprehensive annealing process. Through this process, we aimed to enhance Delrin's structural and dimensional stability by promoting crystallinity and reducing moisture retention. The annealing oven setup, specifically configured to achieve precise temperature control and moisture extraction, was designed to address these issues by providing consistent heating to remove internal stresses, align polymer chains, and achieve a stable crystalline structure. This process not only improves dimensional accuracy but also extends the part's usable life in environments characterized by wide temperature fluctuations and humidity variations.

## Methodology

To address the challenges presented by Delrin's natural properties—specifically, its tendency to shrink post-molding and absorb moisture—we decided to implement a high-capacity annealing oven. This oven was selected for its precision in temperature control and its ability to maintain consistent conditions required for enhancing the parts' crystallinity and moisture resistance. The annealing process was meticulously designed, considering multiple

parameters that are critical for ensuring optimal results. The collaboration with the customer's engineering and quality control teams allowed us to tailor the process specifically to meet the demanding environmental conditions the parts would face.



**Figure 1:** High-capacity annealing oven purchased and used to enhance crystallinity and moisture resistance in Delrin-molded parts, ensuring dimensional stability and durability for outdoor applications.

### Oven Configuration and Parameters

The annealing oven was configured with advanced settings to provide precise temperature regulation and dehumidification. The following parameters were critical for achieving our objectives:

- **Temperature Control:** The oven was programmed to ramp-up to 320°F. This temperature range was chosen based on empirical testing and Delrin's material properties, as it allows for effective stress relief without compromising the material's structural integrity. The selected temperature promotes polymer chain alignment, essential for improving crystallinity and ensuring dimensional stability. Any deviations from this range could lead to under-annealing (insufficient stress relief) or over-annealing (degradation of material properties).
- **Duration:** The parts were subjected to extended annealing cycles, typically lasting between 8 to 12 hours, depending on the part geometry and thickness, however what we were recommended to be used based on our part application was roughly 37 hours of total cycle. Thicker parts required the maximum duration to ensure uniform heat penetration and complete moisture extraction. Preliminary testing indicated that shorter cycles were insufficient to achieve the desired stability, while longer cycles did not yield additional benefits, making this duration optimal.
- **Humidity Control:** The oven was equipped with a dehumidification system that maintains a controlled low-humidity environment. This feature is critical as it prevents the re-absorption of moisture during the annealing process, thus ensuring that moisture levels in the parts are minimized by the end of the cycle. Through real-

time monitoring of humidity levels, adjustments were made to maintain consistent moisture extraction throughout the process.

## Process Steps

The annealing process involved several key steps, each designed to enhance the properties of Delrin parts and improve their resistance to environmental factors:

1. **Pre-Annealing Preparation:** Parts were first inspected and cleaned to remove any contaminants that could interfere with heat transfer. This step was crucial to ensure uniform heating and prevent localized hotspots that could lead to warpage or stress concentration.
2. **Initial Heating/Ramp-up Phase:** The parts were gradually brought up to the target temperature of 320°F over a period of 12.15 hours at the rate of 20 °F/Hour from room-temperature. This gradual heating was necessary to prevent thermal shock and minimize the risk of cracking, especially for parts with complex geometries or thin walls.
3. **Sustained Heating Phase:** Once the target temperature was reached, parts remained at this temperature for 0.67 hours (40 minutes). During this phase, the oven maintained precise temperature control, allowing for stress relaxation within the polymer matrix and alignment of polymer chains, which contribute to increased crystallinity.
4. **Cool-Down Phase:** The parts were allowed to cool gradually inside the oven to prevent any sudden temperature changes that could reintroduce stress. It took roughly 10 hours. This step was monitored closely to ensure the parts reached ambient temperature under controlled conditions, avoiding any adverse effects on dimensional stability.

## Quality Assurance Measures

Throughout the annealing process, several quality assurance measures were implemented to ensure consistency and reliability:

- **Temperature Monitoring:** The oven was equipped with thermocouples that provided real-time temperature data, ensuring that the process stayed within the specified range. Any deviations were immediately corrected to prevent variations in crystallinity and dimensional stability.
- **Moisture Testing:** After each annealing cycle, parts were tested for moisture content using a moisture analyzer. This test was critical for verifying that the dehumidification system effectively reduced moisture levels to the target range.
- **Dimensional Inspections:** Parts were inspected for dimensional accuracy post-annealing to ensure that shrinkage had stabilized. These measurements were compared against pre-annealing dimensions to confirm that the parts met tolerance requirements.

## Data and Analysis

To validate the effectiveness of the annealing process, comprehensive testing and data analysis were conducted on key parameters, including dimensional stability, moisture content, and crystallinity. Data was collected both before and after annealing, allowing for a comparative analysis that highlights the improvements achieved through the process.

### Dimensional Stability Analysis

Dimensional stability was one of the primary metrics evaluated in this study. Delrin's tendency to shrink over time post-molding necessitated a solution that could provide stability within a shorter timeframe. Parts were measured for dimensional changes at intervals of 1 day, 3 days, and 7 days after molding, both with and without annealing. The annealed parts reached stable dimensions within 3 days, compared to 7 days for untreated parts. This significant reduction in stabilization time provides substantial benefits for production efficiency and quality control.

The data indicated that dimensional variations in annealed parts were within  $\pm 0.002$  inches, well below the tolerance threshold. In contrast, untreated parts exhibited variations up to  $\pm 0.01$  inches, exceeding acceptable limits for high-precision applications. This improvement underscores the role of annealing in enhancing dimensional predictability and meeting tight tolerance requirements.

### Moisture Content Reduction

Moisture absorption was another critical factor analyzed in this study. Due to Delrin's hygroscopic nature, untreated parts showed moisture absorption rates of 0.40% after exposure to a controlled humidity environment for 24 hours. After annealing, the moisture content in the parts dropped significantly to 0.10%, indicating a 75% reduction in moisture uptake. This decrease in moisture content is essential for ensuring that the parts maintain dimensional stability and structural integrity in outdoor environments, where exposure to humidity and precipitation can compromise part performance.

### Crystallinity Enhancement

Crystallinity plays a key role in Delrin's durability, particularly in applications subject to temperature fluctuations. Differential scanning calorimetry (DSC) analysis was performed on both annealed and untreated parts to measure their crystallinity levels. Results showed that annealed parts achieved a 20% increase in crystallinity compared to untreated parts, aligning polymer chains and enhancing the material's resilience to environmental stresses.

## Comparative Analysis Summary

The findings from these tests validate the annealing process as an effective solution for addressing the challenges posed by Delrin's natural properties. Dimensional stability, moisture content, and crystallinity were all significantly improved, as summarized in Table 1 below:

| Parameter              | Untreated Parts   | Annealed Parts     |
|------------------------|-------------------|--------------------|
| Dimensional Stability  | $\pm 0.01$ inches | $\pm 0.002$ inches |
| Moisture Content       | 0.40%             | 0.10%              |
| Crystallinity Increase | Baseline          | 20%                |

## Results

The results from the annealing process indicate significant improvements across all key performance metrics—dimensional stability, moisture content, and crystallinity—highlighting the effectiveness of the advanced annealing oven setup and carefully controlled parameters.

### Dimensional Stability

The annealing process proved highly effective in achieving dimensional stability within a shorter time frame. Measurements taken over a seven-day period post-annealing demonstrated that the dimensions of treated parts stabilized within three days, with a dimensional variation limited to  $\pm 0.002$  inches. This is a substantial improvement over untreated parts, which required up to seven days to stabilize and exhibited variations as high as  $\pm 0.01$  inches. This reduction in dimensional variation has critical implications for the precision and reliability of the parts, especially for applications with tight tolerance requirements.

The faster stabilization not only ensures that parts remain within the required specifications but also reduces the need for extended holding periods in inventory, thereby enhancing overall production efficiency. The improvement in dimensional stability indicates that the annealing process effectively mitigates Delrin's natural tendency to shrink post-molding.

### Moisture Resistance

One of the primary challenges with Delrin is its hygroscopic nature, which can lead to moisture absorption and subsequently affect dimensional stability and mechanical properties. Post-annealing moisture testing indicated a significant reduction in moisture content, with annealed parts displaying a final moisture content of 0.10%, compared to 0.40% in untreated parts. This represents a 75% decrease in moisture absorption, which is critical for parts exposed to varying environmental conditions, such as outdoor meters.

The reduced moisture absorption in annealed parts ensures that they maintain consistent performance even under high humidity or wet conditions, which was a core requirement for our customer. This improvement in moisture resistance underscores the value of the annealing process in preventing potential issues such as warpage, swelling, and dimensional changes due to environmental exposure.

### Crystallinity and Structural Integrity

Crystallinity, a key factor influencing material strength and durability, was enhanced by approximately 20% in the annealed parts. This enhancement was verified through differential scanning calorimetry (DSC), which showed a more aligned and structured polymer matrix in treated parts. Higher crystallinity improves the material's resistance to environmental stresses, such as temperature fluctuations and mechanical loading.

This increase in crystallinity contributes to the long-term stability and robustness of the parts, making them better suited to withstand the diverse range of environmental conditions they are exposed to. The improved crystallinity also provides better thermal stability, meaning that the parts can resist expansion and contraction under temperature variations, which is crucial for applications subjected to direct sunlight or freezing conditions.

## Discussion

The results from the annealing process underscore the importance of controlled annealing for enhancing the performance and durability of Delrin-molded parts in demanding outdoor applications. The combination of improved

dimensional stability, reduced moisture absorption, and increased crystallinity provides a compelling case for the value of annealing as a process enhancement in the plastic injection molding industry. Below are key insights and implications derived from these findings.

### **Importance of Dimensional Stability in High-Precision Applications**

Dimensional stability is a critical factor in the manufacturing of high-precision parts, especially those used in applications with stringent tolerance requirements. The ability to achieve dimensional stability within a three-day timeframe post-annealing is a significant advantage. This faster stabilization enables us to maintain tighter tolerances and ensure that the parts meet precise specifications, thus reducing the likelihood of assembly issues or performance failures in the field.

Moreover, by shortening the stabilization period, we can optimize production scheduling and reduce the holding time for parts in inventory, ultimately leading to greater manufacturing efficiency. This improvement in dimensional stability aligns with the high-tech manufacturing practices that our company strives to uphold, emphasizing process reliability and product consistency.

### **Enhanced Moisture Resistance for Environmental Durability**

The annealing process's ability to substantially reduce moisture absorption addresses a critical concern for parts that will be exposed to outdoor environments. Moisture-induced dimensional changes can compromise part performance, leading to warpage, swelling, or other structural deformations. By reducing moisture content by 75%, the annealing process has enhanced the parts' durability and ensured that they retain their intended dimensions and mechanical properties, even in humid or wet conditions.

This improvement is especially relevant for applications in regions with high humidity or varying weather conditions, where parts are likely to encounter moisture exposure. The increased moisture resistance not only ensures dimensional stability but also contributes to the overall longevity and reliability of the parts, which is a key requirement for our customer's application.

### **Crystallinity as a Factor in Environmental Stress Resistance**

Crystallinity is directly linked to the structural integrity and thermal stability of Delrin parts. The 20% increase in crystallinity achieved through annealing translates into better resistance to environmental stresses, including thermal expansion and contraction. This is particularly beneficial for applications where parts are exposed to extreme temperature variations, such as outdoor meters that experience cycles of intense sunlight during the day and freezing temperatures at night.

The enhanced crystallinity helps maintain the parts' structural integrity by reducing the impact of these thermal stresses. In practical terms, this means that the parts are less likely to suffer from material fatigue, cracks, or other failures induced by repeated temperature fluctuations. The annealing process has thus not only improved the immediate physical properties of the parts but also contributed to their long-term performance stability.

### **Implications for Future Manufacturing Processes**

The success of the annealing process in addressing the challenges posed by Delrin's natural properties highlights the potential for further advancements in manufacturing technology. For instance, integrating AI-driven sensors to dynamically adjust annealing parameters in real-time could offer even greater precision and control, potentially

enhancing the process's effectiveness. By continuously monitoring temperature, humidity, and material response, an AI-enhanced system could fine-tune the annealing cycle to account for subtle variations in part geometry, material batch differences, or other factors, leading to even higher levels of consistency and quality.

Furthermore, the insights gained from this project could be applied to other materials with similar challenges, expanding the applicability of advanced annealing techniques across a broader range of plastic injection molding applications. By continuing to innovate and optimize our manufacturing processes, we can maintain our position as a leader in advanced manufacturing, consistently delivering high-quality, durable products that meet the demands of our customers and the industries we serve.

## **Conclusion**

The implementation of an advanced annealing process for Delrin-molded parts has proven to be an essential enhancement to our plastic injection molding operations, particularly for parts intended for demanding outdoor applications. This study demonstrates that by carefully controlling annealing parameters such as temperature, time, and humidity, we can significantly improve the dimensional stability, moisture resistance, and crystallinity of Delrin parts. These improvements directly contribute to the parts' ability to withstand the diverse environmental stresses they will encounter in real-world applications, such as exposure to sunlight, rain, and extreme temperature fluctuations.

The success of this annealing process reflects our commitment to leveraging high-tech manufacturing solutions to address material-specific challenges. The dimensional stability achieved through annealing allows us to meet strict tolerance requirements more reliably and efficiently, reducing production delays associated with extended stabilization periods. The improved moisture resistance addresses a critical vulnerability of Delrin, ensuring that parts maintain their structural integrity and dimensions even under high humidity or wet conditions. This improvement is crucial for maintaining product performance and longevity in outdoor environments.

In addition to the immediate benefits, the enhanced crystallinity obtained through annealing strengthens the parts' resistance to temperature-induced stress, further extending their service life. This aligns with the high standards our company upholds in providing durable, high-performance components to our customers. By achieving higher levels of crystallinity, we have enhanced the thermal and mechanical stability of these parts, reducing the likelihood of warping, cracking, or other forms of degradation over time.

The insights gained from this project also underscore the importance of a collaborative approach in advanced manufacturing. Working closely with the customer's engineering, quality, and R&D teams allowed us to tailor the annealing process to meet specific performance requirements, resulting in a solution that not only addresses current challenges but also anticipates future needs. This collaboration has been instrumental in ensuring that the final product meets the high durability standards expected by our customer and their end-users.

Looking forward, this project serves as a foundation for further innovations in our manufacturing processes. The knowledge gained here provides a basis for exploring more sophisticated control systems, such as AI-driven process adjustments, which could enable real-time optimization of annealing parameters. This would allow for even greater precision and consistency, ensuring that each part produced meets the highest quality standards. By continually advancing our manufacturing techniques, we position ourselves as leaders in the plastic injection molding industry, capable of delivering high-tech solutions tailored to the most challenging applications.



In conclusion, the successful implementation of this annealing process exemplifies the value of integrating advanced manufacturing technology to address complex material challenges. Through this initiative, we have not only met the immediate requirements for the project but also set a new benchmark for quality and reliability in Delrin-molded parts. This project reaffirms our expertise in deploying enhanced techniques in quality engineering and program management, reinforcing our commitment to delivering products that excel in durability, precision, and performance under the most demanding conditions.

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This project's success is a testament to the collective effort, expertise, and commitment of all these contributors, and I am grateful for their dedication to advancing our manufacturing capabilities.

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