

BEST PRACTICES IN INJECTION MOLDING

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This article describes the impact of best practices in part design, tooling, and standard operating procedures for tight tolerance molding. Fundamentally, precise dimensional consistency is difficult to achieve due to complex material properties coupled with the natural material and process variation of the injection molding process. As such, the goal of this work is to enable design and process engineers to understand and account for the effects of manufacturing and end-use variation. This knowledge could then be applied to evaluate best practices and technologies in design and manufacturing, thereby efficiently delivering robust engineered products to the marketplace.

The creation of new product concepts is the primary added value activity of design. However, it is the production and end-use of the design that ultimately creates wealth for society. While most molding applications are designed assuming known material and processing data, the environment surrounding the manufacture and end-use of the design is largely uncontrolled. As such, the robustness of the product design and manufacturing process largely determines the product's efficiency, reliability, and perceived quality (1).

Figure 1 illustrates a segment of a typical product development process. In this process, the design specification acts as a contract between the customer and the product development team. During the detailed product design and mold tooling, significant efforts are made to ensure that the resulting molded part will

meet the required design specifications. Multiple part and mold design iterations are commonly evaluated before a 'robust' solution is accepted.

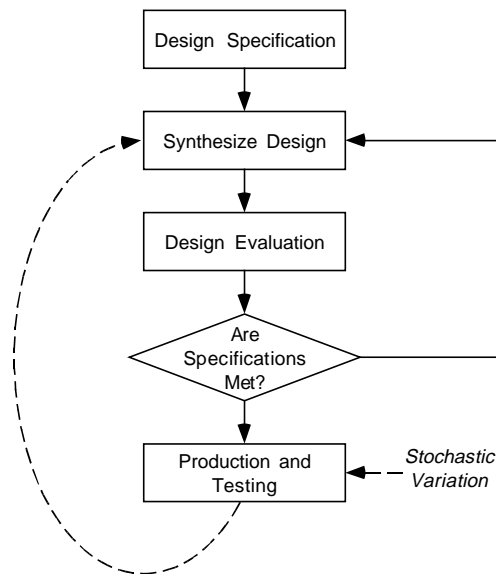


Figure 1: A Common Development Process

The injection molding process poses two significant challenges for the product development team. First, the final part properties and performance are determined by processing as well as geometric design and material properties. Second, the material properties and process dynamics are extraordinarily complex. These phenomena hinder the prediction of end-use properties and our understanding of the effect of manufacturing variation on product performance. For instance, small changes in the specification of a wall thickness for a molded part can result in large swings in the cavity pressure distribution which, in turn, may inadvertently affect the material shrinkage and part dimensions.

To overcome these difficulties, improved analysis techniques have been developed to better predict part performance for candidate designs. In theory, more accurate analysis techniques could eliminate the need for costly mold tooling and evaluation iterations. In reality, even the most advanced analyses are incapable of reliably providing accurate estimates of performance for candidate designs given the effects of uncertain material properties and process variation. As such, the product development process for the injection molding

process is often forced to utilize iterative evaluations in which steel must be cut with no guarantee that the mold alterations will deliver the desired product performance. One or more external design iterations may be necessary to bring the product to acceptable quality or performance levels as indicated by the dashed feedback loop in Figure 1. These late design iterations often require costly tooling changes and delay the product launch (2).

THEORY

The goal of the described theory is to assess the value of proposed 'best practices' and technologies for injection molding prior to investment and implementation. Unfortunately, the underlying theory is elaborate, requiring a moderate understanding of statistics, numerical simulation, injection molding, optimization techniques, and design methodology. As such, only a high level review of the underlying theory will be presented in this paper. More detailed descriptions and functional program shells are available for those interested (3).

This research extends the previous work in two fundamental ways. First, the research models the propagation of fundamental sources of variation through the molding process to derive a distribution of molded part properties. Second, the proposed methodology incorporates an estimate of the manufacturing response to improve the part properties during production when faced with instances of significant variation.

The methodology, presented in Figure 2, explicitly considers stochastic variation in both the design and manufacturing processes. The technique utilizes optimization of the manufacturing process conditions within a Monte Carlo simulation to evaluate the robustness of a candidate design for an instantiated set of material properties and process conditions (4). The intended output of the methodology is a robust product and process design which should not require additional design-build iterations during tool commissioning.

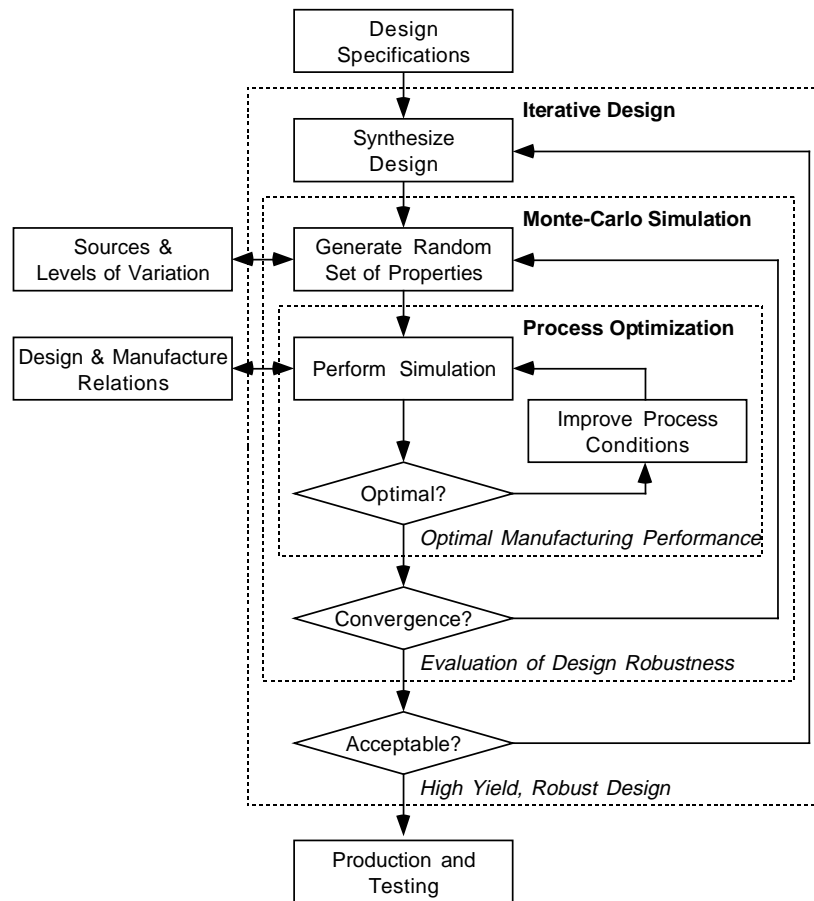


Figure 2: Robust Product & Process Design Methodology

The methodology begins with the product specifications and design synthesis, identical to the process shown in Figure 1. However, the design evaluation has now been replaced with a stochastic optimization which explicitly considers the probabilistic nature of the design and manufacturing processes. To enable evaluation of the design and manufacturing robustness, the following items are required:

- a set of product specifications, indicated by the vector τ ;
- a candidate product and process design represented by the design variables, \mathbf{x} , and the manufacturing process variables, \mathbf{y} ;
- an estimate of the sources and levels of variation within the design and manufacturing processes, $\delta\mathbf{x}$ and $\delta\mathbf{y}$; and,
- a set of design to manufacturing relationships, usually implemented as a numerical simulation, to predict the properties of manufactured parts from mold design, material properties, and process dynamics.

Once a candidate product and process design is synthesized, a random set of design and process conditions is instantiated as consistent with $\{\delta\mathbf{x}, \delta\mathbf{y}\}$. Given this instance of the design, an evaluation is performed to estimate a set of the manufactured product's end-use properties, represented by the vector μ . The expected value of each part property, μ_i , will be compared to its specification, τ_i . For a two-sided specification (1), the robustness can be calculated using equations [1] or [2].

$$\mathfrak{R} = \frac{-1}{3} \Phi^{-1} \left(\frac{1}{2} - \frac{1}{2} \prod_{i=1}^n \left(1 - 2\Phi \left(-3 \frac{(USL_i - LSL_i) - 2|\mu_i - \tau_i|}{6\sigma_i} \right) \right) \right), \text{where:} \quad (1)$$

- $n \equiv$ Number of product attributes
- $USL_i \equiv$ Upper specification limit of the i – th attribute from specification
- $LSL_i \equiv$ Lower specification limit of the i – th attribute from specification
- $\tau_i \equiv$ Target value of the i – th attribute from specification
- $\mu_i \equiv$ Estimate of the i – th attribute from simulation
- $\sigma_i \equiv$ Estimate of the standard deviation of i – th attribute from simulation
- $\mathfrak{R} \equiv$ Robustness of product and product and process design
- $\Phi \equiv$ Normal probability density function
- $\Phi^{-1} \equiv$ Inverse normal probability density function

$$\mathfrak{R} = \frac{-1}{3} \Phi^{-1} \left(\frac{1}{2} - \frac{1}{2} \prod_{i=1}^n (1 - 2\Phi(-3 \cdot Cp_i)) \right), \text{where:} \quad (2)$$

- $Cp_i \equiv$ Process capability index of the i – th specification

This definition of design robustness, a multi-dimensional form of the process capability index, is representative of the capability of the design and process to produce acceptable molded parts. A robustness equal to one represents product performance at the target level with three standard deviations to the closest specification limit. For a Motorola “Six Sigma” capability (5), the design robustness is required to be 2 or greater. The calculated robustness is an aggregate performance measure which includes the consequences of product

and tolerance design, process capability, and stochastic variation. There are several beneficial properties of this definition for robustness:

- models the process' ability to deliver multiple product specifications;
- allows for direct inclusion of different kinds of specifications;
- consistent with Taguchi's concept of tolerance design since it promotes central tendencies with small deviations in part properties, rather than a goal post mentality (6);
- consistent with design axioms to minimize information content since the production yield will tend to decline geometrically as the number of requirements increase; and,
- convex behavior allows for global optimization (3).

Returning to the methodology of Figure 2, it is extremely unlikely that the initial process conditions will result in near-optimal product properties. As such, an optimization of the process variables, y , is performed to maximize the yield of acceptable parts. In industry practice, this process optimization is performed by a process engineer on the production floor through 'trial and error.' In this methodology, the process variables may be improved through Simplex and other optimization techniques.

Once the process conditions have been optimized to maximize the yield of good parts for a given set of design and process conditions, another set of stochastic conditions is randomly instantiated. The simulations and optimization are then again repeated to estimate the predicted yield for this set of conditions. With many iterations of the Monte Carlo simulation, a distribution of the end-use properties develops which leads to convergence of the design and manufacturing robustness, \mathfrak{R} . As previously defined, a robustness equal to one represents a candidate design which is tolerant of design and manufacturing variations and should produce the desired product performance at the target quality levels.

Low values of robustness indicate that the stochastic variations in design and processing will result in either undesirable and/or inconsistent product

performance. These candidate designs are incapable of satisfying the product specifications with acceptable levels of yield and quality. As in a conventional development process, the design and process engineers may synthesize a new set of product and process designs to re-evaluate. While the development of this methodology is non-trivial, it should be stressed that there is no additional burden on the design or process engineer in the product development process.

APPLICATION

Tight tolerance and technical molding applications are becoming increasingly common as the injection molding process continues to emerge as the premier vehicle for delivering high quality, value-added product to the marketplace. These applications can have increased standards for product capability and quality which challenges the ability of design and process engineers to deliver acceptable molded parts on time and under budget. In fact, several industry managers have testified that "we are starting to see the migration of customers to other manufacturing processes for time-critical applications."

Practitioners are utilizing increasingly sophisticated design analyses and molding processes in an effort to minimize the time and cost required for development of molding applications. In theory, these advanced technologies provide more robust product and tool designs while reducing the sources of manufacturing variation. In reality, the performance and added value of these methods is not always clear. Design and engineers need to know the comparative gains which can be made by adopting a process before physical implementation.

The described methodology was applied to evaluate the robustness of different product and process designs by comparing standard operating procedures to industry best practices. The results quantify the likely impact of development strategies from which developers can select the strategy with the appropriate cost:benefit characteristics. Altogether, three different 'best practices' are investigated for tight tolerance applications:

- a design engineer minimizing the number of critical design specifications on a molded part;
- a tool engineer utilizing constant material shrinkage versus differential shrinkage estimates in mold tooling; and,
- a process engineer re-optimizing the process with material and environment shifts.

With this information, the product and process development team can determine the correct implementation and quality strategy. While these applications of the methodology were developed to provide a valuable example for the plastics industry, it should be clear the described methodology is readily extensible to other types of product designs and process technologies.

Part Description

The molding application is an electronics housing, shown in Figure 3. The part is molded of CYCOLOY™C2950 resin, an ABS-PC blend from GE Plastics (Pittsfield, MA). The melt is conveyed into the cavity through a direct, center-sprue gate. The nominal processing conditions for the filling stage consisted of mold and melt temperatures of 70 C and 270 C, and an injection time of 1.5 seconds. A packing pressure of 50 MPa was then maintained for 5 seconds, followed by a twenty second cooling time.

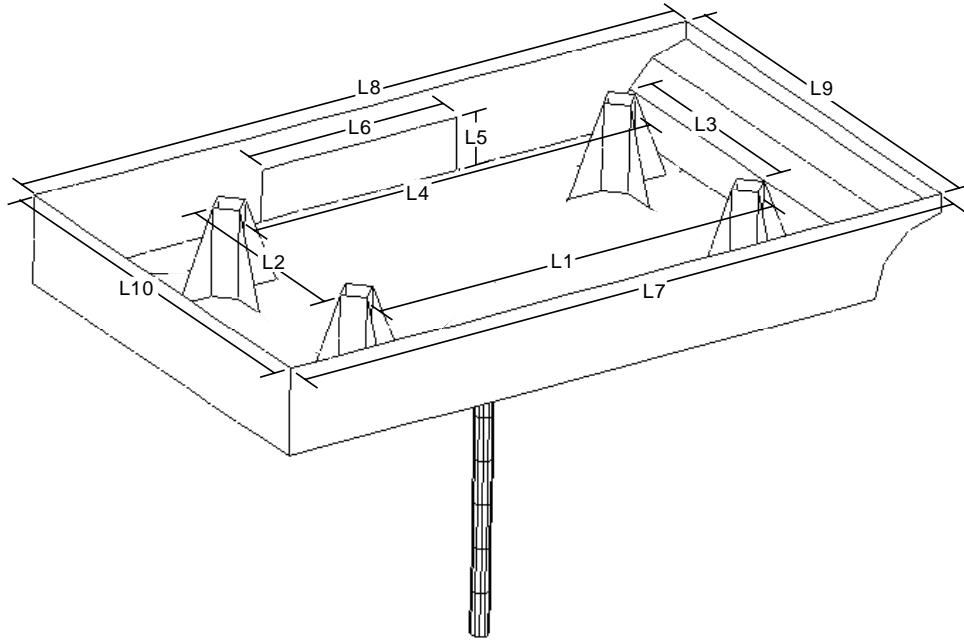


Figure 3: Typical Molded Part and Specified Dimensions

In this application, the design specification includes three critical dimensions for locating and attaching a mating part to the four gusseted bosses shown in Figure 3. Dimension L1 has been specified as 250 ± 0.2 mm while dimensions L2 and L3 have been specified as 100 ± 0.2 mm. The specified tolerances are not actually ‘tight’ but more typical of industry standards (7). Given this part description, the goal is to quantify the impact of the described best practices.

Minimize the Number of Critical Specifications

A common design axiom is KISS or “keep it simple, stupid.” Nam Suh (8) has contributed significantly to the area of axiomatic design, with two similar design axioms: 1) minimize information content, and 2) maintain functional independence of specifications. These statements are all synonymous to a best practice in plastic part design, indicating that the number of specified dimensions in a tight tolerance application should be kept to a critical few.

To quantify the impact of this best practice for part design, a series of stochastic simulations were coupled with mold filling simulations using the described methodology. For each instantiated set of material properties and

machine parameters, a process simulation was performed to estimate the yield when only L1 is specified, then L1 and L2 being specified, and so on until all ten dimensions were specified as critical. The resulting process yield (as calculated by equations 1 and 2) is shown in Figure 4.

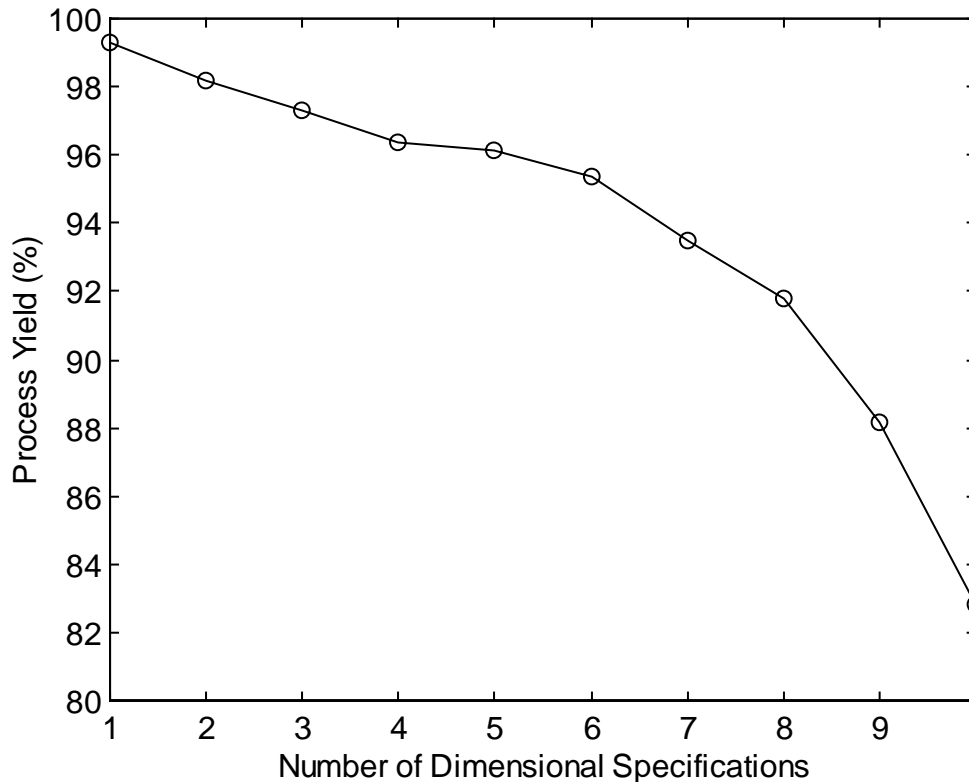


Figure 4: The Impact of Number of Specified Dimensions on Process Capability

Figure 4 shows that the process capability will be less than one regardless of how many dimensions are specified as critical. For instance, the process capability is 0.83 which corresponds to a 99.3% yield when only L1 is specified as critical. This indicates that the standard molding practice of utilizing uniform shrinkage estimates and standard operating procedure is not capable of delivering high yields of tight tolerance molded parts. Some process improvements in mold design or molding practice will be necessary.

As additional dimensions are specified as critical, the process capability quickly degrades. Interestingly, the shape of the curve indicates which dimensions are easier to achieve and maintain. For instance, dimensions L4

and L5 result in fairly low reductions in the process capability. This is due to the fact that the dimensions are close to the gate, and that the tolerances are fairly large compared to the measured lengths. In contrast, dimension L10 results in a significant drop in the process capability since it is at the end of fill and has a relatively tight tolerance of 200 ± 0.2 mm.

The results of the methodology indicate the validity of best practices for tolerance design. First, the number of critical specifications on a molded part should be minimized. Second, the tolerances on critical specifications should be kept as loose as possible. Third, critical specifications are easier to maintain closer to the gate. These best practices will greatly improve the robustness of the molded parts, but place additional burden on the plastic part designer. Perhaps other best practices can improve the process capability while reducing this burden on the designer.

Tool Mold with Differential Shrinkage Estimates

Given a set of specified part dimensions and tolerances, tight tolerance mold design guidelines are used to attain and maintain the desired part attributes (9). These tooling guidelines commonly include: 1) utilize a uniform wall thickness across the part to reduce differential shrinkage, 2) build adequate stiffness into the mold base to reduce mold deflection, and 3) use multiple mold interlocks to reduce dimensional play in the parting plane.

The fundamental issue of tight tolerance plastic part design is the control of non-uniform shrinkage caused by temperature, pressure, and orientation distributions across the part. Figure 5 plots the pressure contours in the electronics housing at the end of the filling stage. Even though the sprue gate has been placed in the center of the cavity, the slightly asymmetric part topology causes significant variation in the cavity pressure distribution. These pressure differentials will continue during the packing stage, resulting in varying volumetric shrinkage during the melt solidification.

TEST.FNR
MULTI-LAMINATE ALGORITHM

PRESSURE [MPa]
0.0 to 50.120

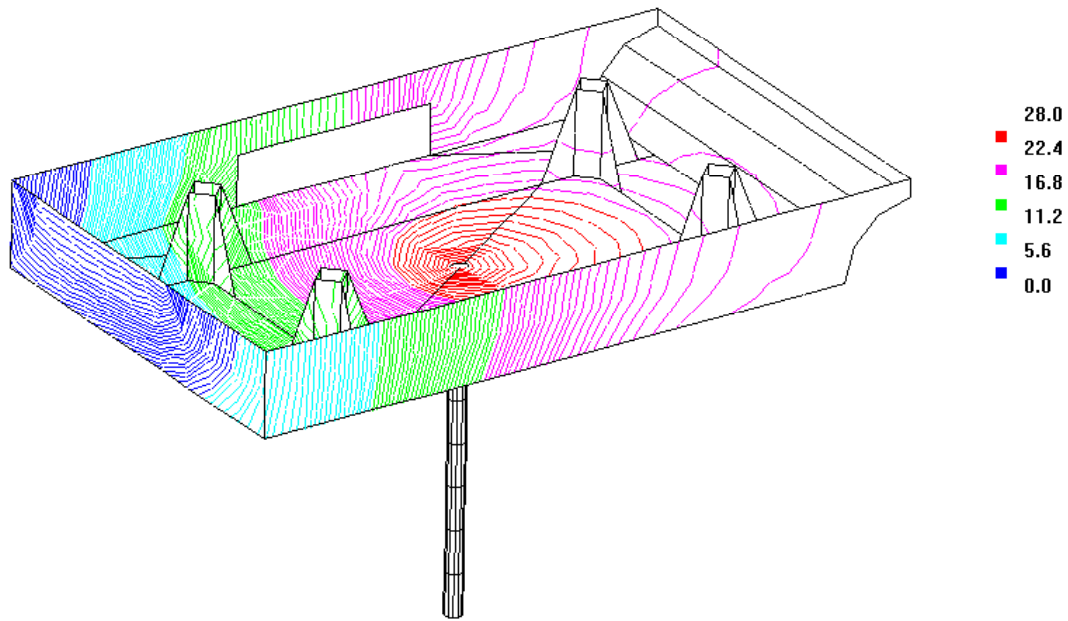


Figure 5: Cavity Pressure Distribution

Standard tool design practice is to utilize a nominal estimate for material shrinkage. This estimate is often provided by the material supplier with instructions for the tool designer to cut 'steel-safe,' such that more metal can be removed should mold changes be necessary to obtain acceptable dimensions. Using the described methodology, the fundamental sources of variation in the material properties and machine parameters were modeled using Monte Carlo techniques and computer simulation to estimate the resulting distribution of part dimensions. The results of five hundred iterations are shown in Figure 6 for standard tool design practices.

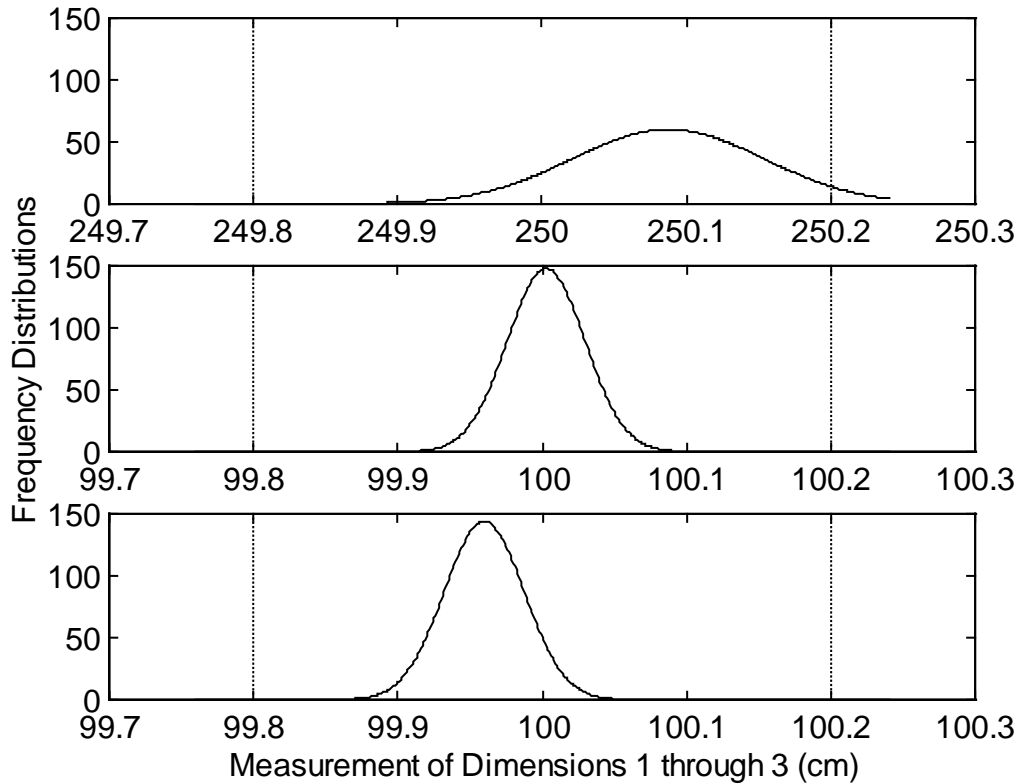


Figure 6: Distribution of Part Dimensions with Standard Tool Design

In this application, the tool designer utilized a correct estimate of 0.55% for the material shrinkage. As Figure 6 shows, however, the non-uniform cavity pressure distributions generated differential material shrinkage and part dimensions. As such, 96% of the molded parts will be acceptable, corresponding to a process capability of 0.62. It should be noted that changing the process conditions will not improve the part properties. Moreover, any error in the uniform shrinkage estimate would only reduce the process capability. For instance, a reduction in pack pressure or the shrinkage estimate might improve dimension one but would worsen dimension three. To improve the yield, additional tool iterations would be necessary to individually tune in the mold steel dimensions.

Computer simulations have become fairly accurate in predicting material shrinkage and the resulting part dimensions. As such, a best practice for tight

tolerance molding has been recently proposed: utilize differential shrinkage estimates for calculation of mold steel dimensions. With this methodology, steel dimensions in areas of high pressure near the gate would be cut for less shrinkage than those areas at the end of fill. Knowing the deterministic pressure distribution across the cavity, this example utilized differential shrinkage estimates of 0.55% for L_1 , 0.5% for L_2 , and 0.60% for L_3 . Additional analysis were then performed resulting in the property distributions shown in Figure 7.

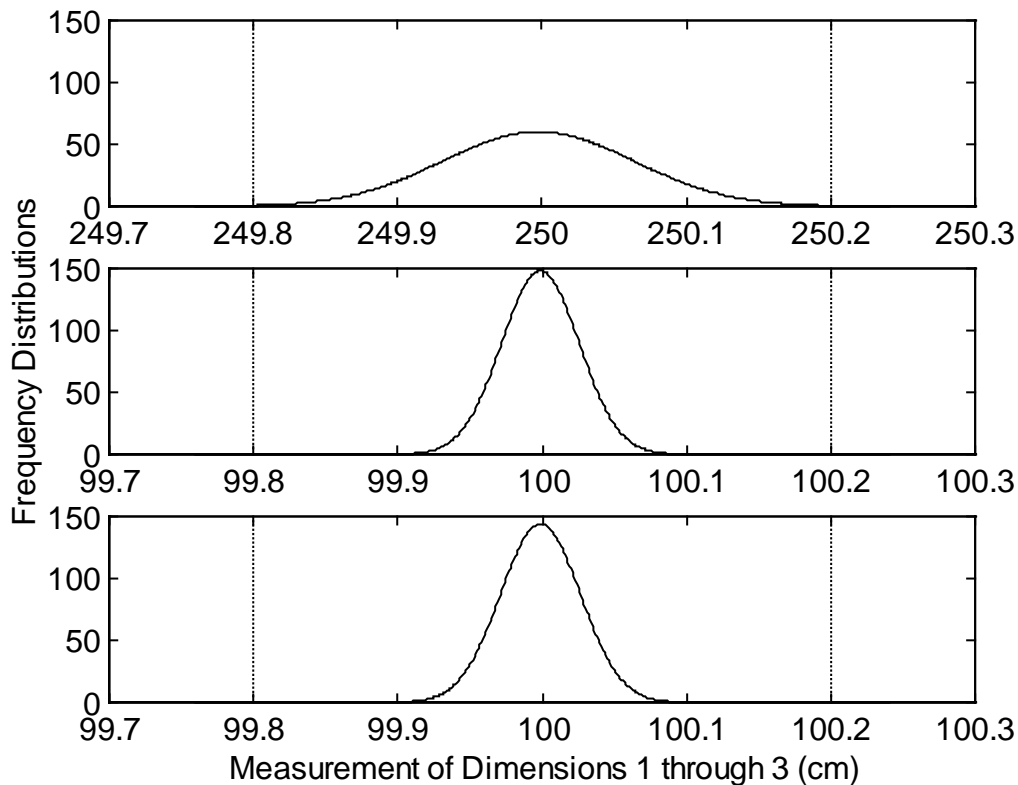


Figure 7: Distribution of Part Dimensions with Best Practice Tool Design

While dimensional variation has not been reduced, the resulting part dimensions are centered between the specification limits. The yield has increased to 99.86%, corresponding to a process capability of approximately 1.0. It should also be noted that slight errors in the shrinkage estimates would continue to provide better part properties than the standard practice of using uniform shrinkage estimates. Thus, tooling best practice would be to use

conservative differential shrinkage estimates which at least qualitatively reflect the expected behavior of the material shrinkage. However, if the material and shrinkage behavior is not well understood, the tool designer should resort to standard industry practice and utilize uniform and conservative shrinkage estimates.

Quality Monitoring and Control

The previous design utilized constant process conditions across all the runs. A best practice approach, becoming more common in industry, is to qualify the process for a given mold geometry on a specific machine with a specific lot of material – to continually optimize the process to achieve higher manufacturing yields. While there is stochastic variation between molding machines and material lots, the variation within a batch of parts is greatly reduced.

Using the described methodology, the process conditions were re-optimized to maximize the total yield for each instantiated set of material behavior and machine parameters. Figure 8 plots the distribution of part dimensions for a tool designed using uniform shrinkage estimates.

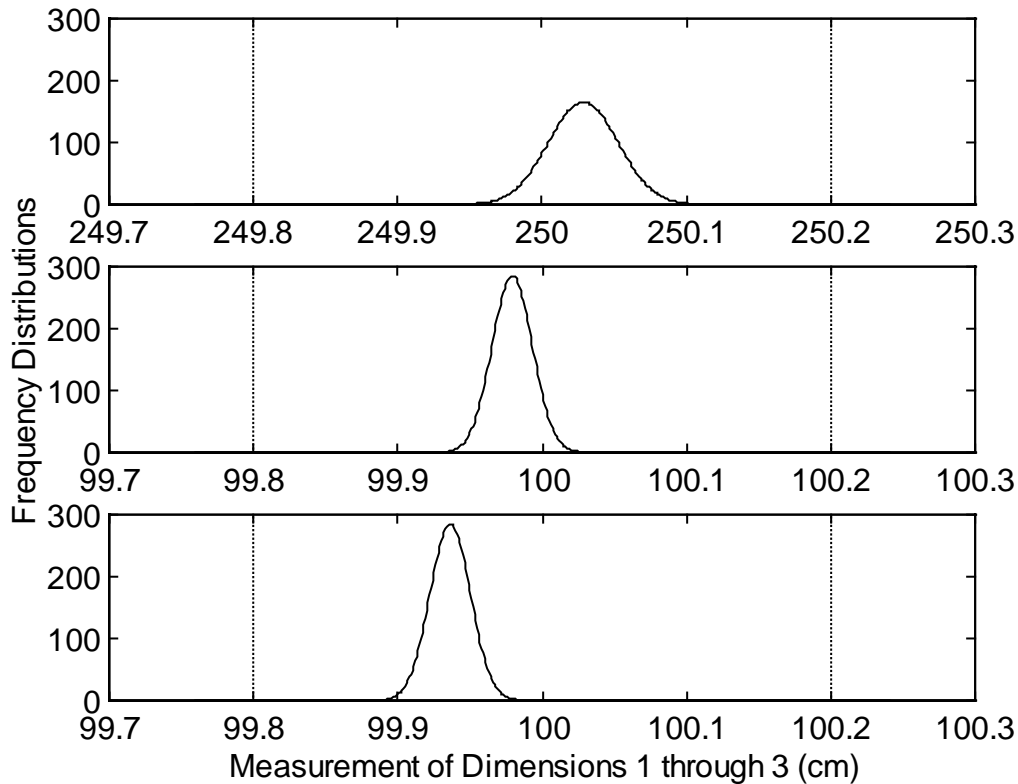


Figure 8: Distribution of Part Dimensions with Best Practice Molding

While the dimensions are not precisely centered with respect to the tolerance limits, the standard deviation of the dimensions has been reduced along with the range of dimensions. As such, all three dimensions are have several standard deviation to the closest quality boundary. The robustness of the molding process has been increased to 1.9, corresponding to a yield of approximately 100%. This is a considerable improvement in design robustness, especially considering that no additional investment in technology or process capability is required, just a change in the operation of the molding machine.

CONCLUSIONS

A methodology has been presented for examining the role of best practices within tight tolerance, plastic part design. This methodology is unique in that it is able to model both the fundamental sources of variation in the manufacturing

process as well as the likely response of the manufacturing engineer to that variation. As such, the methodology provides a platform from which various design and manufacturing technologies and practices can be evaluated. Moreover, the described methodology is extensible to other manufacturing processes and design systems.

With respect to tight tolerance molding, the methodology has quantified the impact of best practices to provide some valuable results for the plastics industry. The results are summarized in Table 1.

Table 1: Summary of Best Practices

Tooling Practice	Standard	Best	Standard	Best
Molding Practice	Standard	Standard	Best	Best
Percent Yield	96.5286	99.8564	~100	~100
Process Capability, \bar{X}	0.62	0.99	1.93	2.47
Defects per Million	34,700	1,400	20	<1

While all best practices will produce improvements in the part properties, each practice will have varying cost:benefit ratios. The product development team should consider the implementation cost and potential benefits of these practices. For this application, the results indicate that quality gains can be made more readily by reducing variation in the molding process than optimizing the part and mold design.

The results will vary for every molding application with its unique set of product specifications, mold geometry, and material properties. Qualitatively, the impact of best practices on the resulting product robustness will be quite similar. One thing is clear, moreover. Motorola '6 Sigma' quality levels, corresponding to a process capability of 2, are unlikely to be achieved without a combination of best practices throughout all stage of part design, tool design, and manufacturing.

ACKNOWLEDGMENTS

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