Incorporating Dimensional Requirements into Material Selection and Design of Injection Molded Parts

Kurt A. Beiter, Graduate Research Associate
The Ohio State University
Department of Mechanical Engineering
Columbus, OH 43210-1107

Kos Ishii, Associate Professor
Stanford University
Department of Mechanical Engineering
Stanford, CA 94305

Submitted to 1996 ASME Design Automation Conference
January 1996

ABSTRACT

This paper presents a methodology for incorporating part dimensional tolerancing into material selection for engineering thermoplastics. This work builds on the authors' previous efforts on integration of mechanical performance and manufacturing cost into candidate design selection. The benefit of this approach is the simultaneous consideration of the implications of material selection and part geometry on estimated manufacturing cost during candidate design selection. The research approach uses the Pressure-Volume-Temperature (PVT) method to estimate shrinkage in thermoplastic parts. The authors then present a method for calculating production costs for meeting part tolerance requirements. Example calculations and a computer program illustrate the proposed methodology.

1 INTRODUCTION

1.1 Background

In traditional thermoplastic material selection, designers consider part performance requirements in narrowing down, or *pruning*, a set of candidate materials. Typical issues include material cost, stiffness, creep, impact and fatigue resistance, dimensional stability, service temperature, chemical and UV resistance, hardness or abrasion resistance, regulation compatibility (e.g., flame retardancy or FDA approval), flow characteristics, and surface finish.

Quantitative pruning of candidate materials occurs on several levels. For instance, aesthetic, regulation, and service environment requirements can immediately eliminate certain materials. And, detailed structural and process analyses, mechanical, thermal, cost, and processing property requirements will narrow the search even further. For critical applications, or for part requirements for which no adequate predictive models may exist (e.g., long term creep, or abrasion resistance), engineers must often resort to prototype and testing to arrive at a final material choice.

The preceding scenario for plastic material selection assumes that time, knowledge, and capital resources are available at sufficient levels throughout the design process. In practice, however, compressed lead times, unavailable material property data, unfamiliarity with application-specific material behavior, and uncertainty regarding the interaction between geometry, material, and process often lead to non-optimal material selection.

1.2 Previous Work

Ever increasing numbers of plastic materials elevated the need for a systematic material selection methodology. Dixon’s work on GERES (Nielsen, 1986) applies a knowledge-based approach to GE’s engineering database. This pilot program uses IF-THEN rules to categorize the candidate set of materials to match the user’s needs. This feature accommodates qualitative rules related to the specific usage for which the materials are designed. GERES incorporates both quantitative and qualitative knowledge about plastic materials obtained from a group of plastics experts at GE plastics. Beiter, et al. (1991) describe a procedure for selecting a polymer based on a weighted sum of material property preferences. Ashby (1992) describes a procedure for material selection based on an objective function for design attributes such as weight, cost, strength and stiffness. The objective function characterizes the functional requirements, geometry, and material properties and, combined with a specified constraint precedence, leads to a material performance index, which he uses to select a material. Oehler, et al. (1994) discuss integrating basic requirements (UV resistance, flammability rating), loading, and manufacturing constraints into material selection.

The above approaches suffer from one or more of the following shortcomings:

1) They do not explicitly capture the fact that material properties and geometry can be combined in different manners to meet the same required system properties (e.g., stiffness as a *system* property, rather than a *material* property).
2) They do not explicitly consider the effect that processing may have on system properties (e.g., orthotropic effects, level of packing pressure and material shrinkage rates on part dimensional stability).
3) They do not map system (material, geometry, process) performance to a comparative scale.

Molding thermoplastic parts that meet dimensional tolerances in a cost-effective manner poses several challenges to the designer. The designer must understand the reasonable tolerance limits for candidate materials, molders, and particular molding process control. Typically, designer’s or molders will use material *mold shrinkage* data to estimate achievable part tolerances (Malloy, 1994). While mold shrinkage data does provide a qualitative comparison of material dimensional stability, it does not explicitly capture the effects of process variables (packing pressure, mold and melt temperature). At advanced stages of design, injection molding process simulation can estimate part shrinkage and out of plane distortion. However, results from this level of analysis usually come later in the design process, at which time it is more difficult to make the changes that simulation may suggest. This research employs a material shrinkage model that is explicitly based on process variables, and suitable for candidate design selection.

1.3 Research Approach

This paper builds upon the authors' ongoing research on material selection methodology that utilizes simplified mechanical, process, and geometry models in conjunction with material properties to map the cost of meeting system performance requirements to a single relative scale (Beiter, et al., 1995). The material selection methodology considers the following performance issues:

1) *Part stiffness:* allowable deflection of a flat plate or other simple geometries will determine a wall thickness. This model must also incorporate time and temperature effects, orthotropic effects (distinct flow and cross-flow moduli) in the case of fiber-filled materials, and the effect of ribbed patterns on system stiffness.
2) *Impact behavior:* minimum radius on ribbed plates to ensure ductile (more predictable/less catastrophic) failure.
3) *Fatigue:* cyclic loading conditions with a known stress magnitude yield a cycles-to-failure estimate.
4) *Shrinkage:* system shrinkage response (the combined effect of material PVT behavior and processing variable levels) places limits on achievable geometric tolerances.
5) *Cooling time:* the largest component of cycle time, is strongly dependent on wall thickness, and, to a lesser extent, on material properties.
6) *Flow length:* wall thickness is constrained by achievable flow length; high-strength materials may allow thinner wall sections, but can inhibit part fillability.

To perform material selection on a uniform scale, this research also considers system cost. Cost appears to be the most natural objective function scale on which to compare two or more materials. Expected contributions of this research include:

1) Systematic approach to selecting the optimum plastic material for a given set of prescribed mechanical requirements.
2) A computer decision support tool that incorporates the phenomenological models in conjunction with the material property database necessary to perform the above-mentioned analysis.
3) Insight into the role that the interaction between material properties and geometry has on the relative ranking of suitable materials.
4) A framework for using mechanical and manufacturing performance models to conduct material and process selection.

The next section of this paper reviews material shrinkage behavior and the PVT method. Section three details our proposed method of assigning tolerance to cost, with example calculations. Section four explains the computer implementation of our material selection methodology.

2 SHRINKAGE ANALYSIS

2.1 Overview

Polymers exhibit a density sensitivity to pressure and temperature that poses challenges to designers in applications requiring tight tolerances or in environments with widely varying service temperatures. Material data suppliers often supply material *mold shrinkage* values for purposes of material selection and dimensioning of the mold tool. However, mold shrinkage is a function of several process conditions, the part geometry, and the molder's sophistication. This section explains the use of polymer Pressure-Volume-Temperature (PVT) data to estimate part shrinkage, and results and limitations of the PVT model.

Figure 2.1 shows PVT relationships for an amorphous and a semi-crystalline polymer. Semi-crystalline polymer densities exhibit a greater sensitivity to temperature and pressure than do amorphous polymers, and in general are less desirable for tight-tolerance conditions. Also, the density of the molten polymer is generally more sensitive to variations in temperature and pressure than the polymer in its solid phase.

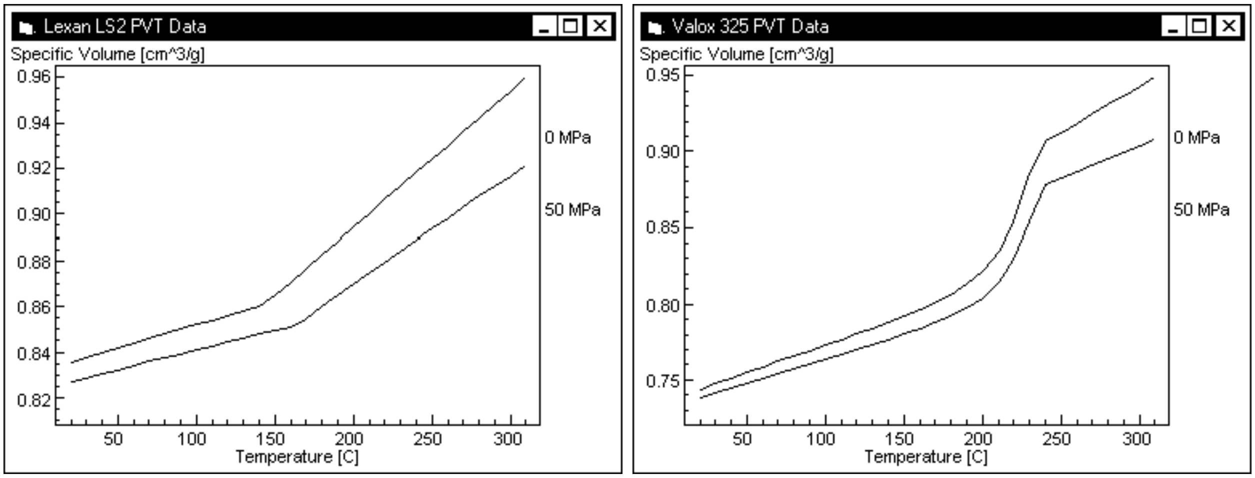


Figure 2.1: PVT diagrams for an amorphous (left) and semi-crystalline (right) polymer

For purposes of numerical analysis, the PVT relationship for a polymer is often expressed as a two-dimensional curve fit in pressure and temperature. Several functional forms of PVT behavior for a polymer exist, and a more common one used by many injection molding process simulation codes is the Double-domain Modified Tait equation (Zoller, 1989), given below:

$$\upsilon(T,p) = \upsilon_0(T)\left\{1 - C\ln\left(1 + \frac{p}{B(T)}\right)\right\} + \upsilon_t(T,p) \tag{2.1}$$

where

$$\left.\begin{aligned} \upsilon_0(T) &= b_{1m} + b_{2m}\bar{T} \\ B(T) &= b_{3m}e^{-b_{4m}\bar{T}} \\ \upsilon_t(T,p) &= 0 \end{aligned}\right\} \text{for } T > T_t, \tag{2.2}$$

$$\left.\begin{aligned} \upsilon_0(T) &= b_{1s} + b_{2s}\bar{T} \\ B(T) &= b_{3s}e^{-b_{4s}\bar{T}} \\ \upsilon_t(T,p) &= b_7 e^{(b_8\bar{T} - b_9 p)} \end{aligned}\right\} \text{for } T < T_t \tag{2.3}$$

and

$p =$ pressure
$T =$ temperature
$T_t = b_5 + b_6 p =$ transition temperature
$\bar{T} = T - b_5$
$C = 0.0894$ (universal constant)

In Equations 2.1 to 2.3, b_1 through b_9 are curve-fit constants determined from PVT data for a specific material. The PVT data or the fitted constants are available from material suppliers and are often supplied with simulation codes.

2.2 The PVT Method

The PVT method for estimating shrinkage of an injection molded part uses the PVT relationship exhibited by the polymer and the approximate molding process conditions to estimate volumetric shrinkage, S_V, and linear shrinkage, S_L (Bhusko, et al., 1995). Figure 2.2 shows a PVT diagram with two constant pressure curves (P_0 and P_{pack}), and an idealized process trace. The polymer enters the mold at point A in the molten state, and fills the mold at constant temperature under increasing injection pressure from P_0 to P_{pack}. At B, the polymer begins to cool at constant packing pressure P_{pack}. At C, the gate freezes off and the packing pressure can no longer be maintained. The polymer continues to cool, only now at constant specific volume v_D as the cavity pressure slowly decays. At D, the polymer has reached atmospheric pressure, and continues to cool to point E, but now at constant atmospheric pressure P_0.

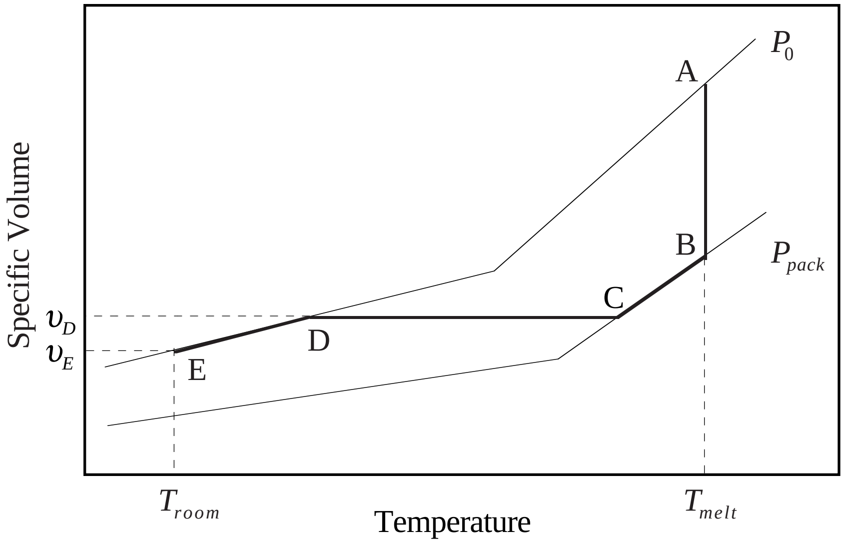


Figure 2.2: PVT diagram with molding process trace

The shrinkage is calculated using the specific volumes at the time at which the gate freezes (at point C, when no more polymer can enter the mold cavity) and the final part temperature (T_{room}) at point E. Volumetric shrinkage is then defined as

$$S_V = \frac{\upsilon_D - \upsilon_E}{\upsilon_D} \tag{2.4}$$

In the uniform and isotropic shrinkage model the linear shrinkage is 1/3 of the volumetric shrinkage:

$$S_L = \frac{S_V}{3} \tag{2.5}$$

2.3 Process and Geometry Effects on Shrinkage

The effects of packing pressure, melt and mold temperature, and gate thickness are all captured by the PVT method. Packing pressure has the greatest effect on shrinkage, and shrinkage decreases with increasing packing pressure (Figure 2.3). Higher packing pressures force more material into the cavity, resulting in greater expansion of the material as it depressurizes relative to the contraction of the material as it cools. Molders will often increase packing pressure to rectify undesirable material shrinkage, although excessive packing pressure can cause greater residual stresses, part warpage, and parts that may actually stick in the mold during ejection.

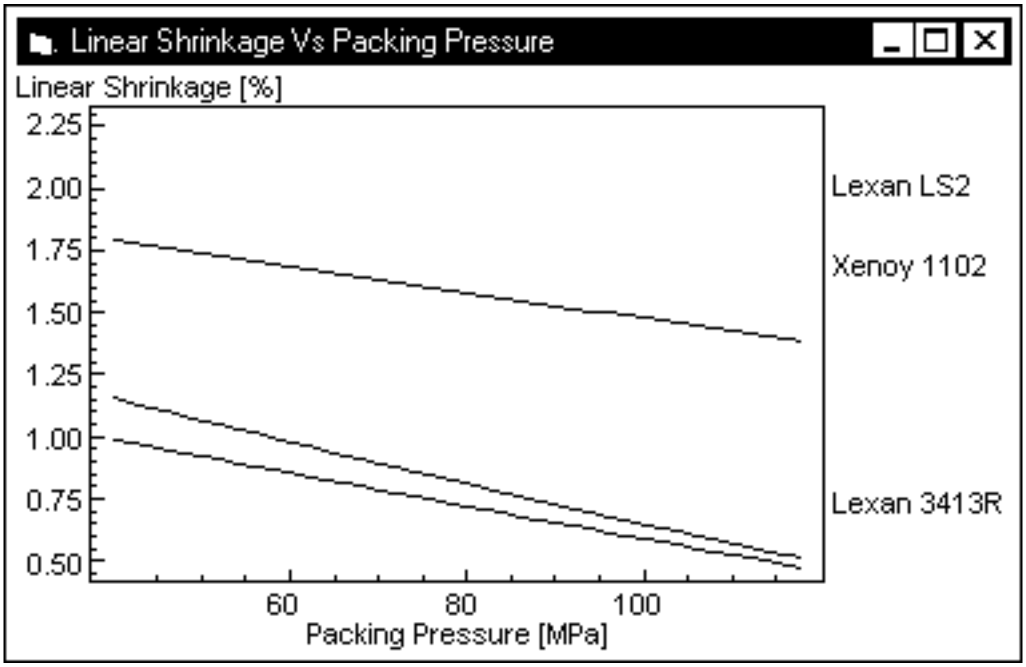


Figure 2.3: Linear shrinkage as a function of packing pressure

Figure 2.4 shows melt temperature effects on shrinkage. Shrinkage increases with higher melt temperatures. This occurs since the cooling time of the part relative to the cooling time of the gate increases, resulting in gate freeze-off earlier in the molding cycle.

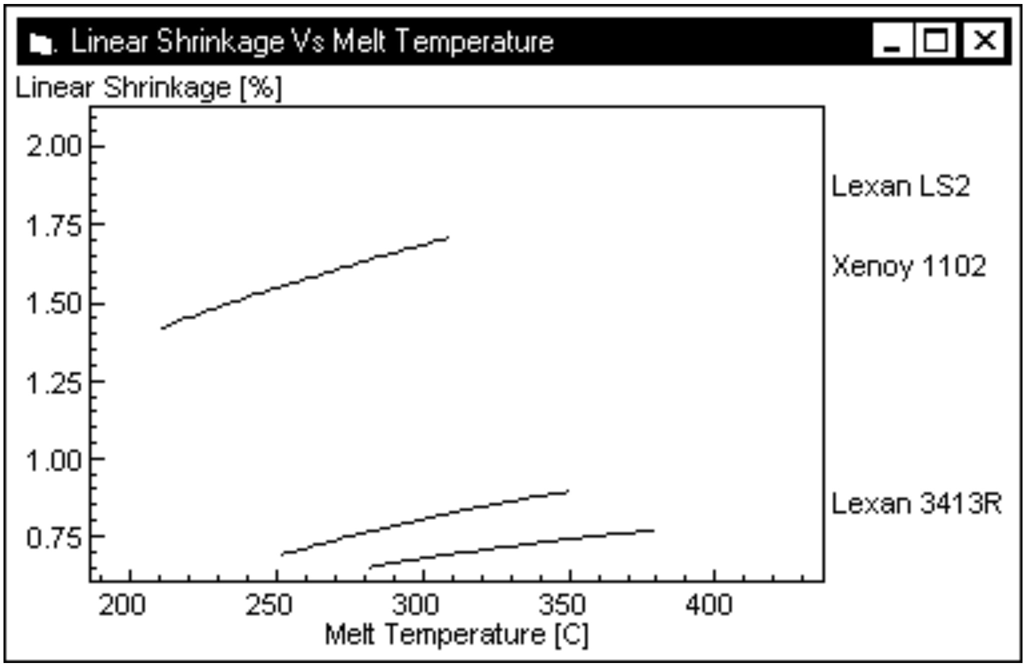


Figure 2.4: Linear shrinkage as a function of melt temperature

Figure 2.5 shows mold temperature effects on shrinkage. Shrinkage decreases with increasing mold temperature since the cooling time of the part relative to the cooling time of the gate *decreases*, resulting in gate freeze-off *later* in the molding cycle. In general the effects of melt and mold temperatures on material shrinkage are much less pronounced then the effect of packing pressure.

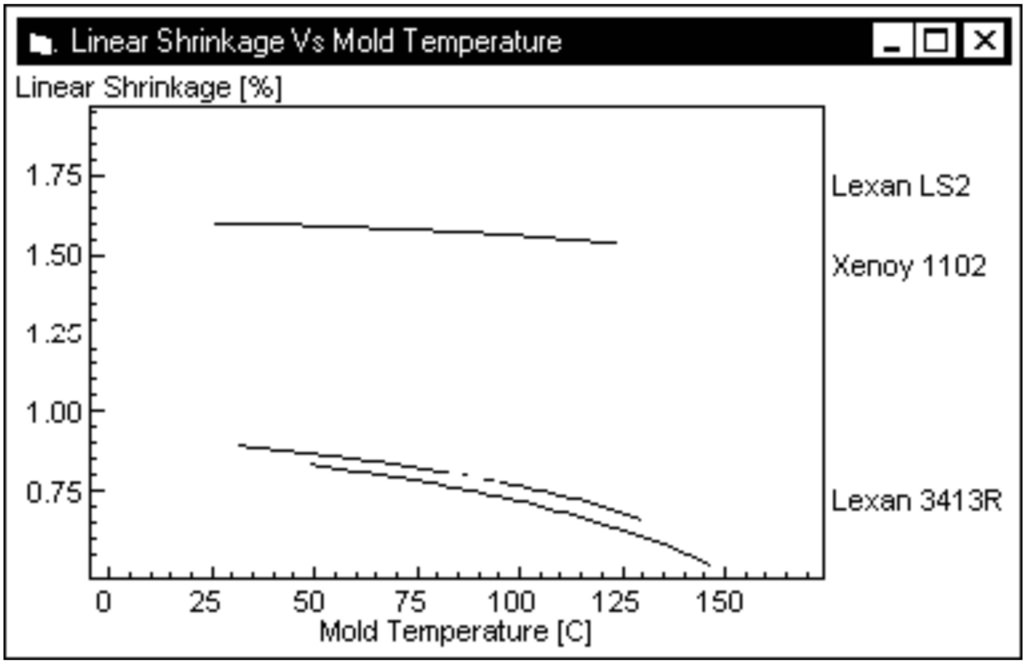


Figure 2.5: Linear shrinkage as a function of mold temperature

As the gate size increases, shrinkage decreases (Figure 2.6). As gate size increases relative to the nominal wall thickness, the point in time at which the gate freezes off occurs later in the process, allowing more packing flow through the gate to offset material shrinkage in the cavity. Larger gate sizes can alleviate excessive shrinkage in a part; however this can lead to parts that are more difficult to de-gate. In general, gates are sized to about 80% of the nominal wall thickness.

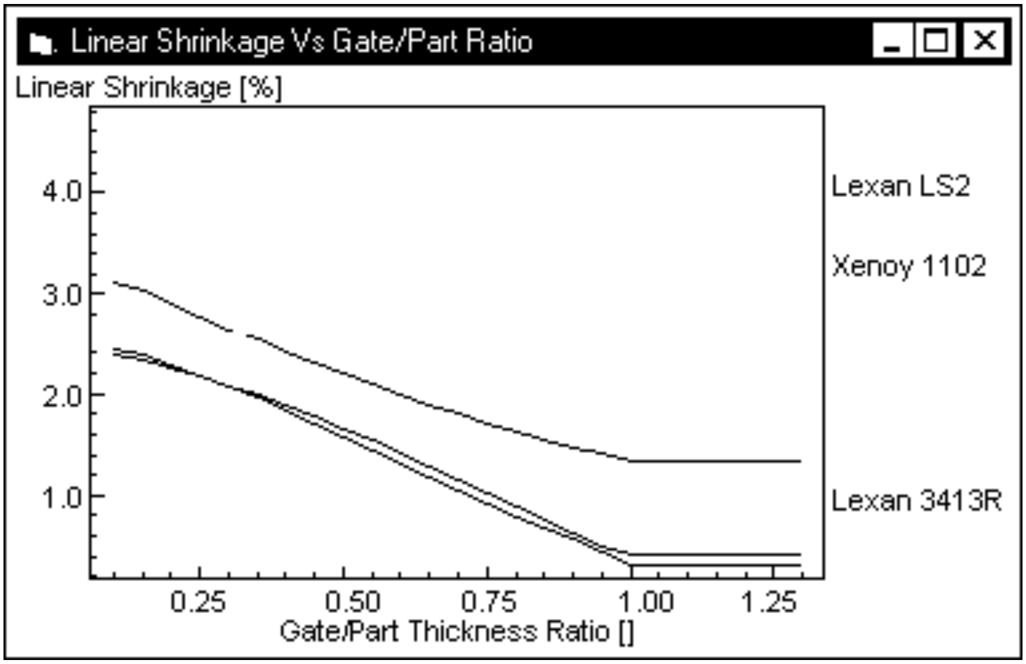


Figure 2.6: Linear shrinkage as a function of gate size

2.4 Limitations of the Model

The PVT method for estimating shrinkage is a uniform (equivalent shrinkage everywhere throughout the part), isotropic (equivalent shrinkage in the inflow, cross-flow, and through-thickness directions) model. In practice, materials exhibit non-uniform, orthotropic shrinkage behavior caused by temperature and pressure gradients across a part during processing and cooling. The PVT method assumes that temperature and pressure are the same everywhere throughout the part, and that the gate area experiences the same cooling boundary conditions as the part. In general material shrinkage is greater at locations furthest from the gate, where lower effective pressures inhibit material compensation.

Anisotropic material behavior due to flow orientation and fiber distribution will cause anisotropic material shrinkage. Amorphous unfilled materials exhibit more shrinkage along the flow direction than in the cross-flow direction; in filled materials, material shrinkage is more restrained along the direction of fiber orientation. Mold constraints will also contribute to anisotropic shrinkage, since material prevented from shrinking in one direction will induce greater shrinkage in another direction. The PVT method assumes that the material is free to shrink in all directions, although planned enhancements to the PVT method include orthotropic material modeling that will capture the effects of flow induced orientation.

3 ASSIGNING COST TO DESIRED PART TOLERANCE

3.1 Background

A number of factors influence the ability to manufacture injection molded parts that meet dimensional specifications, including error in estimating nominal material shrinkage process variation, mold tool manufacturing tolerances, and even material property variation. In most cases, designers or molders can estimate the nominal material shrinkage and account for it by cutting larger dimensions in the mold steel. Tool dimensional tolerances are usually less than 50% of part tolerances (Malloy, 1994), and high tolerance machining is widely available in the mold tooling industry. Molding quality parts with tight tolerance requirements is more sensitive to the molding process conditions and their repeatability than to any other factor. Therefore, the key to meeting dimensional tolerances and achieving high part yields is minimizing part to part variation, or using materials that are less dimensionally sensitive to process variations.

For the material selection problem, this paper proposes to link tolerance requirements directly to cost. In theory, there are a number of ways to accomplish this; two of them are:

1) *Machine–labor rate model:* Tighter tolerances require greater machine control and molder sophistication, and hence higher machine–labor rates.
2) *Yield-rate model:* Tighter part tolerances result in lower yields. Molders generally figure a yield rate into their cost structure, and adjust this yield rate downward to cover themselves on jobs requiring fine tolerances (often based on their practical experience with a particular material).

Due to space limitation, we focus on the machine–labor rate model in this paper.

3.2 Machine–labor Rate Cost Model

For applications requiring tight dimensional control, molders may elect to utilize a more sophisticated injection molding machine (with a commensurably higher labor rate). The machine–labor-rate model captures the effect of higher equipment and labor costs for tight tolerance applications.

This model requires an estimate of process deviations (mold and melt temperatures, packing pressure) for standard and fine tolerance molding processes (Table 3.2), and standard and fine tolerance machine–labor rates, R^{std} and R^{fine} respectively (Table 3.3).

Table 3.2: Process deviations for standard and fine tolerance molding processes[£]

Standard Process	Fine Process
Melt Temperature, T_{melt}: $\delta_{melt}^{std} = \pm 7$ (°C)	Melt Temperature, T_{melt}: $\delta_{melt}^{fine} = \pm 3$ (°C)
Mold Temperature, T_{mold}: $\delta_{mold}^{std} = \pm 7$ (°C)	Mold Temperature, T_{mold}: $\delta_{mold}^{fine} = \pm 3$ (°C)
Packing Pressure, P_{pack}: $\delta_{pack}^{std} = \pm 20$ (MPa)	Packing Pressure, P_{pack}: $\delta_{pack}^{fine} = \pm 10$ (MPa)

[£] Estimate by authors.

Table 3.3: Standard and fine tolerance machine–labor rates ($/hr)

Machine Tonnage	**<50**	**50-99**	**100-299**	**300-499**	**500-749**	**750-999**	**1000-1499**	**1500-2000**	**2000+**
R^{std} [§]	29.46	29.95	34.92	42.55	52.73	77.08	85.00	137.29	180.25
R^{fine} [£]	38.30	38.94	45.40	55.32	71.13	100.20	110.50	151.69	205.76

[§] Custom injection molders' machine–hour rates with operator, profit margin included (Plastics Technology, May 1993). [£] Estimate by authors.

Each injection molded part will have a set of *n target dimensions*, x_j, each with a corresponding *tolerance* t_j (where tolerance is prescribed as say $t_j = \pm 0.010$). Now consider Figure 3.2. Knowing R^{std} and R^{fine} will fix two points on the machine–labor rate—required tolerance curve shown in Figure 3.2, namely, the cost of achieving a fine tolerance Tol_j^{fine}, and the cost for achieving a standard tolerance Tol_j^{std}. Tol_j^{fine} and Tol_j^{fine} are not *prescribed* tolerances, but rather *achievable* tolerances for a specific process (standard or fine) and for a specific dimension j.

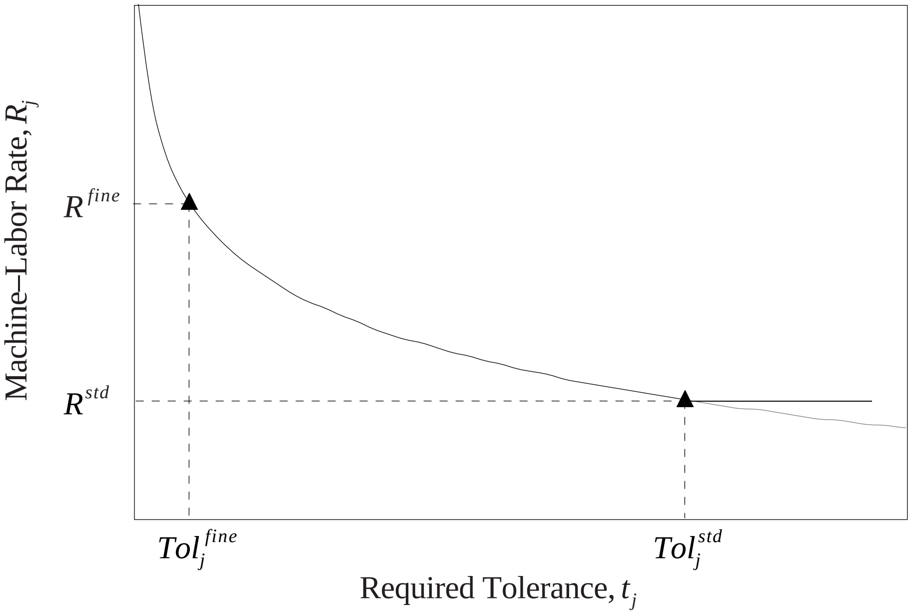


Figure 3.2: Machine–Labor rate as a function of desired tolerance

For material selection purposes, we would like to know the cost of achieving *any* tolerance. The authors employ a Log fit using the known machine–labor rates at Tol_j^{fine} and Tol_j^{std}:

$$R_j = \begin{cases} A_j \log(t_j) + B_j & \text{for } t_j < Tol_j^{std} \\ R^{std} & \text{for } t_j > Tol_j^{std} \end{cases} \tag{3.2}$$

where

R_j = machine – labor rate
t_j = required part tolerance for a dimension j
Tol_j^{std} = achievable tolerance at the standard process for a dimension j
R^{std} = machine – labor rate for the standard process
A_j, B_j = curve - fit constants derived below in Equation 3.6

Qualitatively, equation 3.2 captures the notion that tolerances below Tol_j^{fine} (tighter tolerances) are prohibitively expensive. For required tolerances above Tol_j^{std}, (looser tolerances), we set $R_j = R^{std}$.

Examination of the material shrinkage sensitivity to process variation will determine Tol_j^{std} and Tol_j^{fine}, which are unique to each material and each dimension of a part. The procedure is as follows. First, calculate the maximum and minimum linear shrinkage over the process variation using the PVT method. For the fine tolerance process,

$$\begin{aligned} S_{max}^{fine} &= \mathbf{max}\left\{ S_L\left(P_{pack} \pm \delta_{pack}^{fine}, T_{melt} \pm \delta_{melt}^{fine}, T_{mold} \pm \delta_{mold}^{fine} \right) \right\} \\ S_{min}^{fine} &= \mathbf{min}\left\{ S_L\left(P_{pack} \pm \delta_{pack}^{fine}, T_{melt} \pm \delta_{melt}^{fine}, T_{mold} \pm \delta_{mold}^{fine} \right) \right\} \end{aligned} \tag{3.3}$$

A similar calculation determines the maximum and minimum linear shrinkage for the standard tolerance process. Now, calculate the shrinkage deviation ΔS^{fine} and ΔS^{std}:

$$\begin{aligned} \Delta S^{fine} &= \frac{S_{max}^{fine} - S_{min}^{fine}}{2} \\ \Delta S^{std} &= \frac{S_{max}^{std} - S_{min}^{std}}{2} \end{aligned} \tag{3.4}$$

The achievable process tolerances for a given dimension j are:

$$\begin{aligned} Tol_j^{fine} &= x_j \Delta S^{fine} \\ Tol_j^{std} &= x_j \Delta S^{std} \end{aligned} \tag{3.5}$$

The constants A_j and B_j in equation 3.2 are:

$$\begin{aligned} A_j &= \frac{R^{fine} + R^{std}\left(1 - 2\log\left(T_j^{fine} - T_j^{std}\right)\right)}{\log\left(T_j^{std}\right) - \log\left(T_j^{fine}\right)} \\ B_j &= \frac{R^{fine} - \log\left(T_j^{fine} - T_j^{std}\right) R^{std}}{1 - \log\left(T_j^{fine} - T_j^{std}\right)} \end{aligned} \tag{3.6}$$

Finally, for material selection purposes, select the largest machine–labor rate required to manufacture a part within specifications; i.e.,

$$\begin{aligned} R_{prod} &= \mathop{\mathbf{max}}_{j}\left(R_j\right) \\ &= \text{maximum machine – labor rate over the } j \text{ dimensions} \end{aligned} \tag{3.7}$$

Our complete cost model includes R_{prod}, an estimated cycle time (from part cooling time calculations), and per–part material cost (Beiter, et al., 1995):

$$C_T = \underbrace{\frac{\left(R_{prod}\right)}{3600} t_c}_{\text{Processing Cost}} + \underbrace{V \cdot \rho \cdot C_{mat}}_{\text{Part Cost}} \tag{3.8}$$

where

C_T = total cost of the part ($/part)
t_c = cycle time for each part (s/part)
R_{prod} = injection molding machine – labor rate ($/hr)
V = volume of the part (m^3/part)
ρ = density of the material ($\mathrm{kg/m}^3$)
C_{mat} = cost of the material ($/kg)

This cost model is an approximation of variable cost per part, and does not include mold construction costs, mold complexity (e.g., sliders), number of mold cavities, total production run, components of part cycle time due to injection and mold open and closing time, retooling and setup time, colorant, and scrap.

Figure 3.3 shows graphically the cost of tighter tolerances on part manufacturing cost using the results of Section 3.2. This example shows that, for finer tolerances, less dimensionally stable materials (semi-crystalline materials) become more expensive to manufacture relative to dimensionally stable materials (amorphous or filled materials).

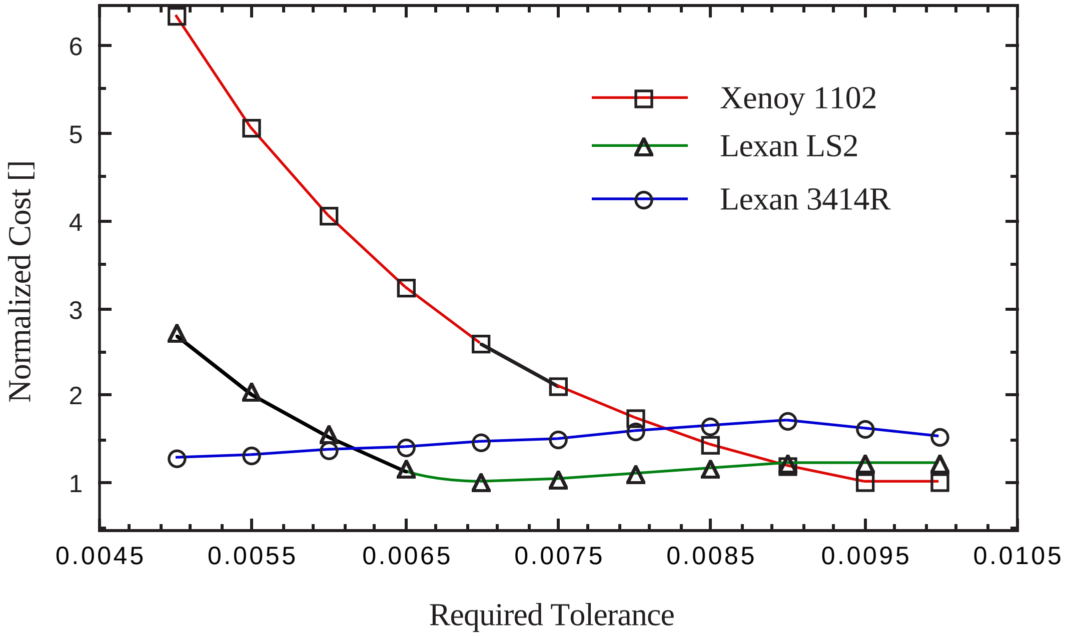


Figure 3.3: Normalized part cost as a function of desired tolerance

Figure 3.4 shows graphically the cost of achieving an allowable plate deflection versus application temperature (fixed edges, point load) for three different polymers. The analysis uses the cost equation (Equation 3.8) and Classical Plate Theory with time and temperature flexural modulus dependence. This example illustrates precisely that plate stiffness is a system property; i.e., a function of application requirements, material properties, geometry, and process conditions.

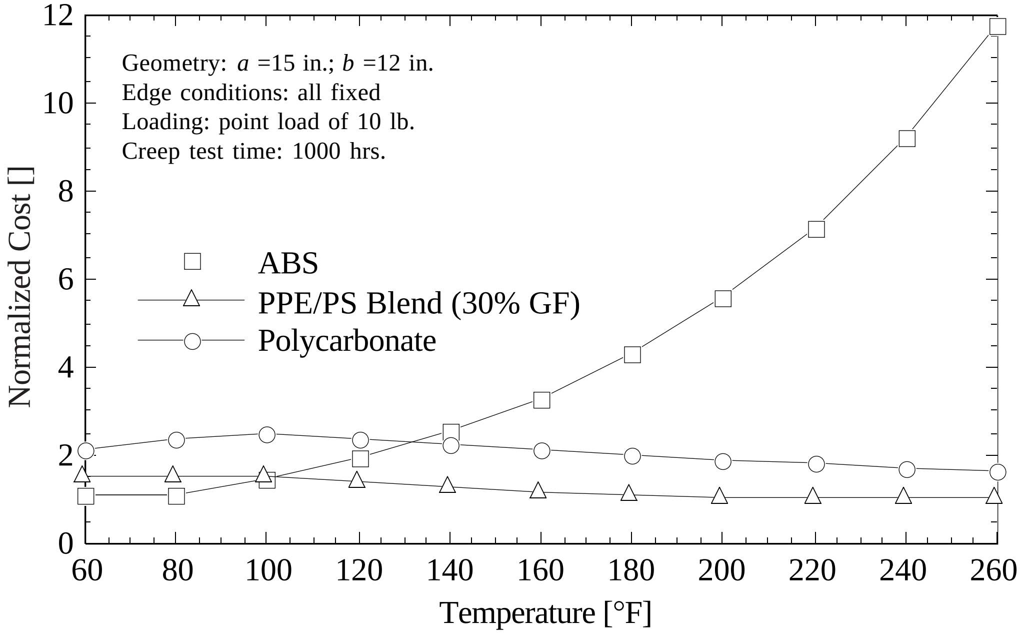
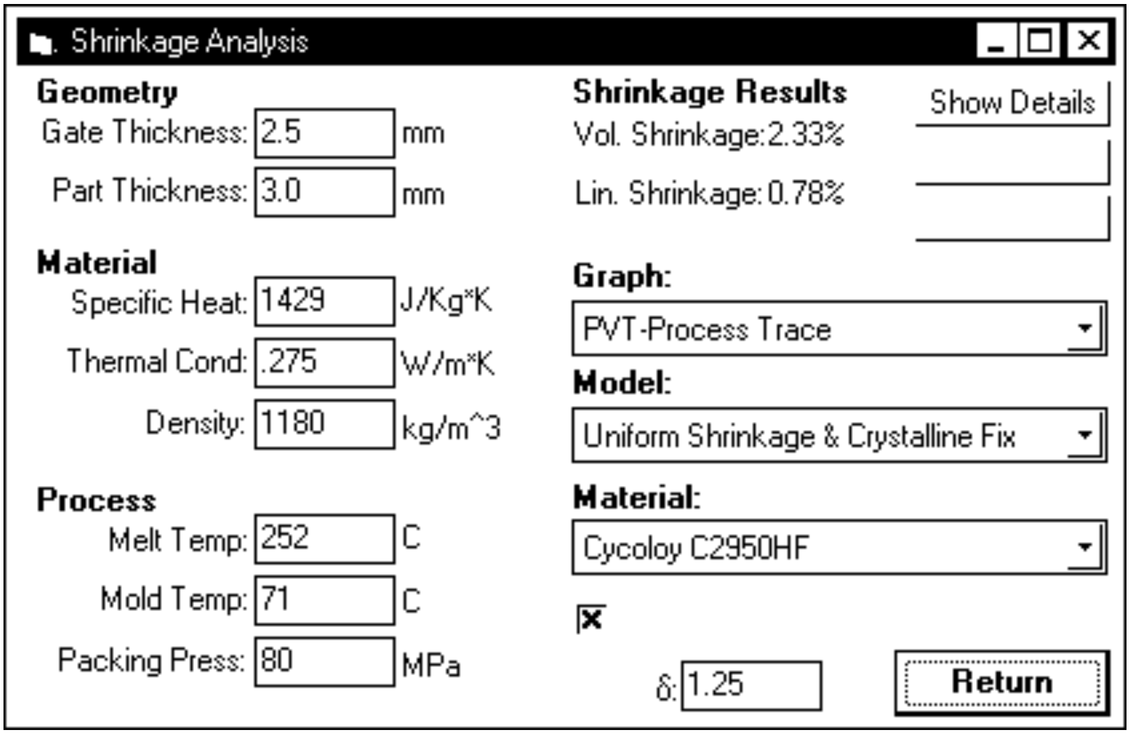


Figure 3.4: Normalized part cost as a function of application temperature

4. COMPUTERIZED TOOL

The authors have developed a computer tool that implements the material selection methodology outlined in this paper. The program runs on Macintosh (HyperCard) and Windows (Visual Basic) platforms. A material database contains material property, processing, and cost data. Figure 4.1 shows the input screen for material shrinkage analysis. All relevant input parameters have recommended values, although users may change input values to examine their effects. Figure 4.2 shows an example output of the PVT process analysis described in this paper. The interface also facilitates user training; users can quickly examine the effect of processing parameters on system shrinkage, and interactively view processing rules-of-thumb: e.g., greater packing pressures will decrease part shrinkage, higher melt temperatures will increase part shrinkage, and increased gate sizes will decrease part shrinkage.



Geometry
Gate Thickness: 2.5 mm
Part Thickness: 3.0 mm

Material
Specific Heat: 1429 J/Kg*K
Thermal Cond: .275 W/m*K
Density: 1180 kg/m^3

Process
Melt Temp: 252 C
Mold Temp: 71 C
Packing Press: 80 MPa

Shrinkage Results
Vol. Shrinkage: 2.33%
Lin. Shrinkage: 0.78%

Graph: PVT-Process Trace
Model: Uniform Shrinkage & Crystalline Fix
Material: Cycoloy C2950HF
☒
δ: 1.25

Figure 4.3: Shrinkage analysis input screen

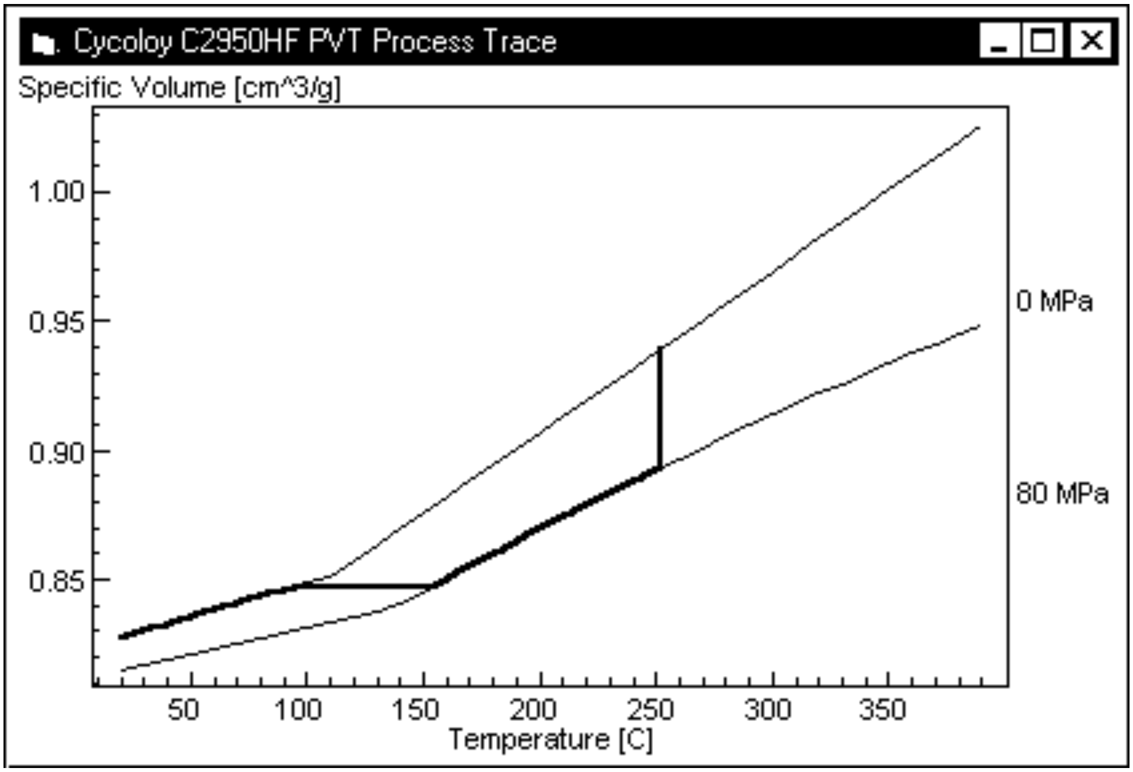
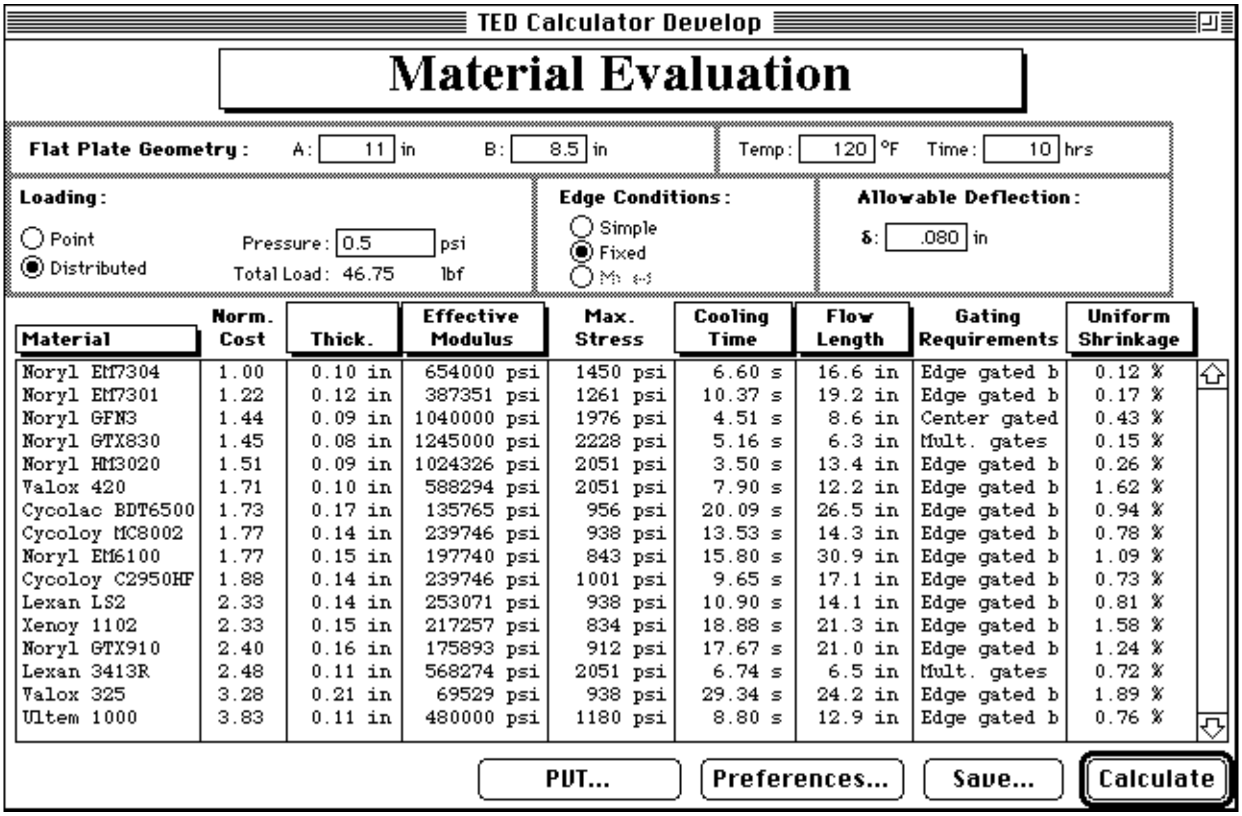


Figure 4.2: Material shrinkage analysis using the PVT method

The material selection summary screen is shown in Figure 4.3. The computer program produces a list of candidate materials ranked by normalized cost (relative to the lowest cost candidate) based on a desired maximum plate deflection δ. The resulting plate thickness permits calculation of a cooling time and achievable flow length. The current tool does not include fillability requirements in the final cost score. However, the program does note the gating requirements for each material (edge-gated, center-gated, or multiple drops required).



Flat Plate Geometry : A: 11 in B: 8.5 in

Temp: 120 °F Time: 10 hrs

Loading :

○ Point
● Distributed

Pressure: 0.5 psi
Total Load: 46.75 lbf

Edge Conditions :

○ Simple
● Fixed
○ [illegible]

Allowable Deflection :

δ: .080 in

Material	Norm. Cost	Thick.	Effective Modulus	Max. Stress	Cooling Time	Flow Length	Gating Requirements	Uniform Shrinkage
Noryl EM7304	1.00	0.10 in	654000 psi	1450 psi	6.60 s	16.6 in	Edge gated b	0.12 %
Noryl EM7301	1.22	0.12 in	387351 psi	1261 psi	10.37 s	19.2 in	Edge gated b	0.17 %
Noryl GFN3	1.44	0.09 in	1040000 psi	1976 psi	4.51 s	8.6 in	Center gated	0.43 %
Noryl GTX830	1.45	0.08 in	1245000 psi	2228 psi	5.16 s	6.3 in	Mult. gates	0.15 %
Noryl HM3020	1.51	0.09 in	1024326 psi	2051 psi	3.50 s	13.4 in	Edge gated b	0.26 %
Valox 420	1.71	0.10 in	588294 psi	2051 psi	7.90 s	12.2 in	Edge gated b	1.62 %
Cycolac BDT6500	1.73	0.17 in	135765 psi	956 psi	20.09 s	26.5 in	Edge gated b	0.94 %
Cycoloy MC8002	1.77	0.14 in	239746 psi	938 psi	13.53 s	14.3 in	Edge gated b	0.78 %
Noryl EM6100	1.77	0.15 in	197740 psi	843 psi	15.80 s	30.9 in	Edge gated b	1.09 %
Cycoloy C2950HF	1.88	0.14 in	239746 psi	1001 psi	9.65 s	17.1 in	Edge gated b	0.73 %
Lexan LS2	2.33	0.14 in	253071 psi	938 psi	10.90 s	14.1 in	Edge gated b	0.81 %
Xenoy 1102	2.33	0.15 in	217257 psi	834 psi	18.88 s	21.3 in	Edge gated b	1.58 %
Noryl GTX910	2.40	0.16 in	175893 psi	912 psi	17.67 s	21.0 in	Edge gated b	1.24 %
Lexan 3413R	2.48	0.11 in	568274 psi	2051 psi	6.74 s	6.5 in	Mult. gates	0.72 %
Valox 325	3.28	0.21 in	69529 psi	938 psi	29.34 s	24.2 in	Edge gated b	1.89 %
Ultem 1000	3.83	0.11 in	480000 psi	1180 psi	8.80 s	12.9 in	Edge gated b	0.76 %

Figure 4.3: Material selection summary screen

5 CONCLUSIONS AND FUTURE WORK

In this paper the author’s describe a procedure for incorporating part tolerance requirements into thermoplastic engineering material selection at the candidate design phase. The benefit of this approach is the simultaneous consideration of the implications of material selection and part geometry on estimated manufacturing cost.

This research relies on further developing several concepts, meeting certain technical and implementational challenges, and refining some existing methodologies further, such as:

1) *Material candidate pruning.* The essence of this proposed approach is that some selection criteria are *system* properties, i.e., functions of the geometry and material properties. However, many selection criteria are not; e.g., chemical and UV resistance, hardness or abrasion resistance, flame retardancy or FDA approval. The selection methodology must account for this distinction.
2) *Cost model development.* Meaningful performance models must be represented (via design variables) in the objective function. In addition to the current cost model, these also include the costs of using larger machines to achieve certain flow lengths, more

complex tooling to meet flow requirements, and quantifying the penalties of requiring tighter process windows.

3) *Performance model evaluation.* Fatigue, impact, and ultimate strength evaluation require calculating maximum stress states. This is usually a strong function of geometric features, which are not generally considered in the simpler, closed form equations. FEM analysis can yield detailed results, but usually requires more time and personnel resources. The performance model evaluation techniques must strike a balance between accuracy of results and ease of implementation.
4) *Selecting a global optimum.* We have proposed a system that considers only injection molded thermoplastic materials. Thermoplastic manufacturing processes alone are numerous, and in fact developed because they can provide a lower overall cost for component manufacturing for certain applications. A system that considers many process and material combinations would be a step in the right direction. Such a system would need a method of screening potential candidates to yield a manageable set (e.g., the methods of Ashby, 1992, and Ishii, et al., 1991). The integration and application of suitable performance models is an implementation challenge
5) *Methodology validation.* To verify the success of this approach, we could benchmark this system with several case studies, and compare the time and effort required to perform material selection in a more traditional fashion (assuming this can be measured or has been measured). Another approach is to examine existing production parts, with known functional requirements, and compare the results of using this approach with actual material design specifications. If this approach is general enough, it should capture the essential properties of the system and select a suitable material (in the very least). Other judgments could also come from putting this tool in the hands of designers (which we have done to some extent with a prototype version) and observing if this approach offers an advantage over typical procedures.

ACKNOWLEDGMENTS

This work is supported by the NIST Advanced Technology Program on Thermoplastic Engineering Design. The authors wish to thank Gerry Trantina, Pete Oehler, Wit Bhusko, and Andy Poslinski of General Electric Corporation, and Mike Wyzgoski and Howard Cox of General Motors Corporation for their comments on and support of this work.

REFERENCES

Ashby, M. F., *Materials Selection in Mechanical Design*, Pergamon Press, Oxford, England (1992)

Beiter, K., Krizan, S., Ishii, K., and Hornberger, L., “HyperQ/Plastics: An Intelligent Design Aid for Plastic Material Selection,” *International Journal of Advances in Software Engineering*, 1993, Vol.16, pp. 53-60

Beiter, K., Cardinal, J., and Ishii, K., "Design For Injection Molding: Balancing Mechanical Requirements, Manufacturing Costs, and Material Selection," To appear in the Proc. of the ASME Computer Integrated Concurrent Design Conference, Sept., 1995, Boston, MA.

Bhusko, W, and Oehler, P., Dimensional Stability Design Guide, General Electric Corporate Research and Development, Schenectady, NY, February, 1995.

Busick, D. R., Beiter, K. A., and Ishii, K. (1994) “Design for Injection Molding: Using Process Simulation to Assess Tolerance Feasibility,” To appear in the Proceedings of the 1994 ASME Computers In Engineering Conference, Minneapolis, MN, September, 1994.

Malloy, R. A., *Plastic Part Design for Injection Molding*, Hanser Publishers, New York, NY (1994)

Nielsen, E.H., Dixon, J. R., and Simmons, M.K. (1986) GERES: A knowledge-based material selection program for injection molded resins. ASME Computers in Engineering 1986, Chicago, IL, July, 1986. pp. 255-263.

Oehler, P. R., Graichen, C. M., and Trantina, G. G., “Design-based Material Selection” SPE ANTEC Proceedings (1994), pp. 3092-3096

Trantina, G. G., and Nimmer, R., *Structural Analysis of Thermoplastic Components*, McGraw Hill, New York, NY (1994)

Zoller, P., "PVT Relationships and Equations of State of Polymers," Polymer Handbook, 3rd Edition, pg. 475 (1989)