Proceedings of ICAD2000
First International Conference on Axiomatic Design
Cambridge, MA – June 21-23, 2000

AXIOMATIC DESIGN OF THE INJECTION MOLDING PROCESS

David O. Kazmer
kazmer@ecs.umass.edu
Department of Mechanical & Industrial Engineering
University of Massachusetts Amherst
Amherst, Massachusetts 01003

ABSTRACT

Injection molded components are consistently designed to minimize the design and manufacturing information content of the enterprise system. The resulting designs, however, are extremely complex and frequently exhibit coupling between multiple quality attributes. Axiomatic design principles were applied to the injection molding process to add control parameters that enable the spatial and dynamic decoupling of multiple quality attributes in the molded part. There are three major benefits of the process redesign effort. First, closed loop pressure control has enabled tight coupling between the mass and momentum equations. This tight coupling allows the direct input and controllability of the melt pressure. Second, the use of multiple melt actuators provides for the decoupling of melt pressures between different locations in the mold cavity. Such decoupling can then be used to maintain functional independence of multiple quality attributes. Third, the heat equation has been decoupled from the mass and momentum equations. This allows the mold to be filled under isothermal conditions. Once the cavity(ies) are completely full and attain the desired packing pressure, then the cooling is allowed to progress.

Keywords: injection molding process design, controllability, dynamic system decoupling

1 INTRODUCTION

Injection molding is capable of producing very complex components to tight specifications. The process consists of several stages: plastication, injection, packing, cooling, and ejection. In injection molding and its variants (coinjection, injection compression, gas assist molding, etc.), thermoplastic pellets are fed into a rotating screw and melted. With a homogeneous melt collected in front of the screw, the screw is moved forward axially at a controlled, time-varying velocity to drive the melt into an evacuated cavity. Once the melt is solidified and the molded component is sufficiently rigid to be removed, the mold is opened and the part is ejected while the next cycle's thermoplastic melt is plasticized by the screw. Cycle times range from less than four seconds for compact discs to more than three minutes for automotive components.

Injection molding appears to violate two fundamental principles of axiomatic design [1]. Recent research has indicated that the component's information content is a primary driver of tooling cost, and has a significant effect on processing cost and tooling time [2]. The large amount of information contained in a molded component's design suggests violation of the axiom to minimize information content. However, the application of this axiom must be considered at the system level. Figure 1 shows two designs for the internal chassis of an office automation product: design (a) represents a modular design consisting of six components that are later assembled; design (b) represents a fully integrated, single component design for this product. Which subassembly design minimizes information content?

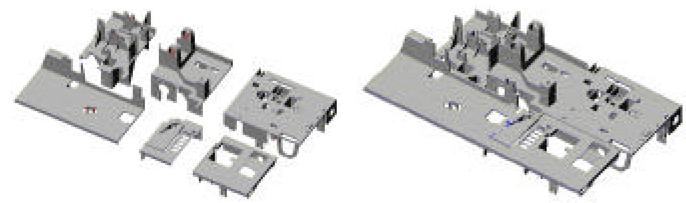


Figure 1: Internal chassis designs

The subassembly design with minimal information content is dependent upon other company information. For instance, design (a) would be minimize the enterprise-level information if multiple products across a product platform could utilize many of the same sub-components. However, design (b) minimizes the subassembly information by eliminating the system need for subcomponent development, coupling between subcomponent dimensions, assembly guidelines, and production quality and inventory control policies. As such, complex injection molded parts have been implicitly developed to minimize the enterprise-level information content.

Maintenance of functional independence within a molded part, however, has not been achieved due to the physics of the injection molding process. A typical molded part may consist of several hundred identifying dimensions, twenty toleranced dimensions, as well as additional aesthetic and structural requirements. The quality of the manufactured product is determined by the dynamics of the injection molding process. Unfortunately, the controllability of injection molding has been limited by the nonlinear behavior of the polymeric materials, dynamic and coupled process physics, and convoluted interactions between the mold geometry and final product quality attributes. A revised system's view of the modern conventional injection molding process [3] is presented in Fig. 2. The machine parameters are indicated on the left side of the figure, and some common quality attributes are listed on the right. In this figure, the process is decomposed into five distinct but coupled stages. The output of each stage not only directly determines the initial conditions of the next stage, but also influences some of the final qualities of the molded part.

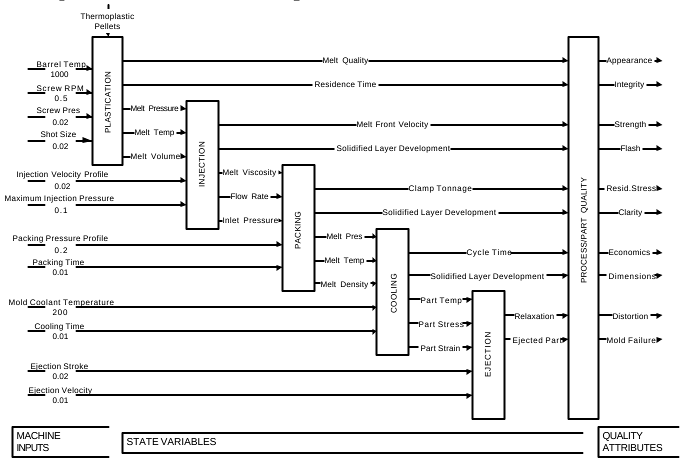


Figure 2: System's view of the injection molding process

Independence of the multiple quality attributes is not achievable with conventional injection molding. However, new molding processes can be developed that fundamentally alter the initial conditions and the boundary conditions to the process physics. These added control parameters then allow the spatial and/or dynamical decoupling of multiple quality attributes in the molded part.

2 AXIOMATIC MOLDING PROCESS DESIGN

While it is not possible to change physical laws, it is possible to significantly alter the initial and boundary conditions such that the process is dominated by different dynamics and exhibits very different behaviors. Consider, for example, some of the differences between the injection molding and extrusion processes. Both processes utilize a polymer melt in a similar temperature, pressure, and shear rate range. Both processes utilize a mold wall as an impermeable boundary condition to shape the polymer melt into a useful solid form. However, the extrusion process does not have an impermeable boundary at the end of the extrusion length. This simple difference allows the extrusion process to be continuous, with process models and dynamics to be approximated as steady state with no initial conditions. By comparison, the injection molding process must maintain many additional initial and boundary conditions to control the dynamic filling and cooling of the polymer melt.

The polymer state (pressure, temperature, and morphology) directly determines the molded part quality [4]. Thin cavity filling of polymer melt corresponds to creeping flow ($Re<<1$) which is coupled to a temperature field characterized by a thin cold layer ($Pe>>1$) surrounding a hot core region [5]. As an example, consider a reference velocity of 10 cm/sec, reference thickness of 3 mm, and a viscosity of 100 Pa Seconds. The Reynolds number based on this case is very small, (10-3), indicating the validity of the highly viscous creeping flow assumption. Furthermore, the flow regions are considered fully developed, and both the unsteady and the gravitational force effects can be ignored due to negligible local acceleration. On the other hand, the thermal diffusivity, $a = k/rCp$, of typical polymer melts is (10^{-3}) cm^3/sec, and the kinematic viscosity, $n = h/r = 10^3$ cm^2/sec; hence, the Prandtl number is about (10^6) and Peclet number, $Pe = Re*Pr$, is (10^3).

Using these assumptions, the molding process physics can be modeled as shown in Figure 3.

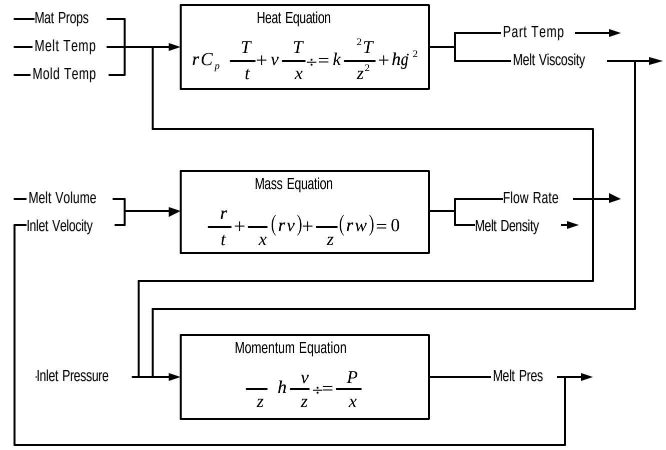


Figure 3: Coupled process physics

The solution of the pressure and flow fields in injection molding is obtained by solution of the coupled mass and momentum equations. Generally, the mass equation provides a convergence criterion for flow rate about which the momentum equation is iteratively solved to produce an accurate pressure field. For each instant of time, all the nodal pressures on the mesh are solved simultaneously. Iteration is required to update the shear rate, viscosity, and flow rate estimates until full convergence is achieved. For a compressible flow, the net mass flux must equal any mass gains or losses within the element [6]. The necessary system of equations can be developed, assembled, and solved using a conventional Galerkin formulation for a fixed mesh and transient melt front. Such research and commercial simulations have been developed, and can be utilized in designing improved molding processes that enable the functional decoupling of multiple quality attributes according to axiomatic design principles.

This paper discusses two significant applications of axiomatic design principles for injection molding process development. The first application utilizes multiple dynamic actuators to spatially decouple the flow and pressure of the melt at different locations in the mold cavity. The second application utilizes thermal transients to dynamically decouple the temperature field during the polymer injection from the cooling of the molded part. The resulting process physics are shown in Figure 4.

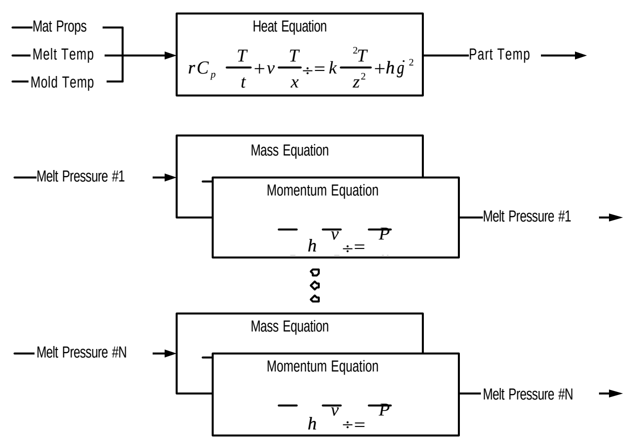


Figure 4: Modifieded process physics

There are three major benefits of the process redesign effort. First, closed loop pressure control has enabled tight coupling between the mass and momentum equations. This tight coupling allows the direct input and controllability of the melt pressure. Second, the use of multiple melt actuators provides for the decoupling of melt pressures between different locations in the mold cavity. Such decoupling can then be used to maintain functional independence of multiple quality attributes. Third, the heat equation has been decoupled from the mass and momentum equations. This allows the mold to be filled under isothermal conditions. Once the cavity(ies) are completely full and attain the desired packing pressure, then the cooling is allowed to progress.

2.1 DYNAMIC PRESSURE CONTROL

The complex nature of the injection molding process necessitated the development of sophisticated, numerical process simulations. These numerical simulations are utilized to estimate the progressing melt fronts, pressure distribution, and temperature dynamics of the process. Design decisions that are effected include number of gates, location of gates, pressure drop through gates, wall thickness, process input parameters, shrinkage compensation, and others. These process simulations have been widely adopted, and have enabled the development of extremely advanced molding applications. This infrastructure is necessary since the molding process is not capable of significantly altering the molded part quality attributes once a mold is manufactured. Thus, significant effort must be expended during product development to ensure the mold tooling delivers the desired product before the tooling enters production.

According to axiomatic design, the molded part's multiple quality attributes are coupled and cannot be independently maintained. To investigate the controllability of the injection molding process, a half-factorial design of experiments [7] was performed to determine the main effects between the critical process parameters and three part dimensions:

$$\begin{Bmatrix} L1 \\ L2 \\ L3 \end{Bmatrix} = \begin{bmatrix} 0.57 & 0.10 & 0.43 & 0.02 \\ 0.51 & 0.18 & 0.29 & 0.00 \\ 0.23 & 0.05 & 0.18 & 0.10 \end{bmatrix} \begin{Bmatrix} Pressure \\ Velocity \\ Temperature \\ ScrewSpeed \end{Bmatrix} \quad (1)$$

In this equation, the machine parameters have been scaled to the range of 0 to 1, indicative of the maximum feasible processing range for this application. The resulting coefficients of the linear model are actual change in part dimensions (measured in mm) for the printer output tray shown in Figure 5. It should be noted that once tooling is completed, the dimensional changes available through processing are quite limited though functionally significant.

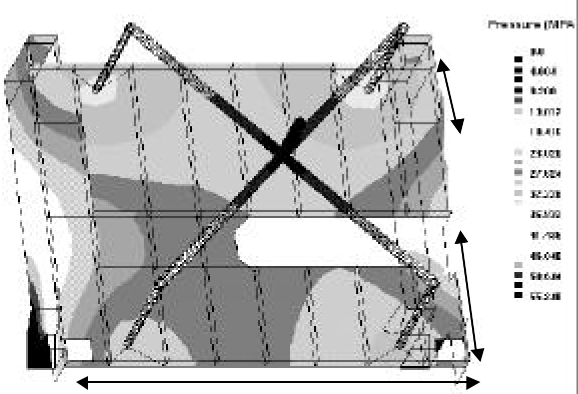


Figure 5: Geometry and packing pressure distribution

There are two significant conclusions that can be drawn from eq. (1). First, all three of the dimensions react similarly to changes in the process settings. Thus, the molding process behaves as a one degree of freedom process in which only one quality attribute is controllable. Second, the equation shows the relative effect that each of the processing variables can have on the product quality attributes. Pressure was the most significant process variable, followed by temperature, velocity, and others.

Next, the controllability of the process' pressures and temperatures were investigated. Melt temperature was quickly discarded due to slow thermal diffusion and poor spatial localization. Closed-loop control of cavity pressure had recently been implemented and shown to achieve a consistent process and uniform set of product attributes [8-10]. Adaptive control and learning methods had been developed to track cavity pressure profile, though at only one location in the mold [11-13].

Several placement locations and actuator designs were considered. Unfortunately, the first generation device did not consider the poles of the plant, and thus required a sophisticated adaptive feedback controller to iteratively converge on the desired cavity pressure dynamics. This first controller required a vast amount of information, both within and between process cycles, to drive the adaptation mechanisms in the controller. Due to the design and controller limitations, the process capability was no better than conventional molding, though significant process flexibility was enabled through the added control axes. Later design generations resolved these limitations through the use of improved geometric topologies and parametric design.

The current embodiment is shown in Figure 4, in which the valves meter the flow of melt from the runners into the mold cavity. The pressure drop and flow rate of the melt is dynamically varied by the axial movement of each valve stem which controls the gap between the valve stem and the mold wall. By de-coupling the control of the melt at different valve stem positions, melt control at each gate can override the effects of the molding machine and provide better time response and differential control of the melt. Each valve acts as an individual injection unit, lessening dependency on machine dynamics. For closed loop control, manifold pressure transducers were used in the runner drops instead of in the cavity. This implementation not only provides lower cost and greater reliability, but also renders a conventional appearance for the system.

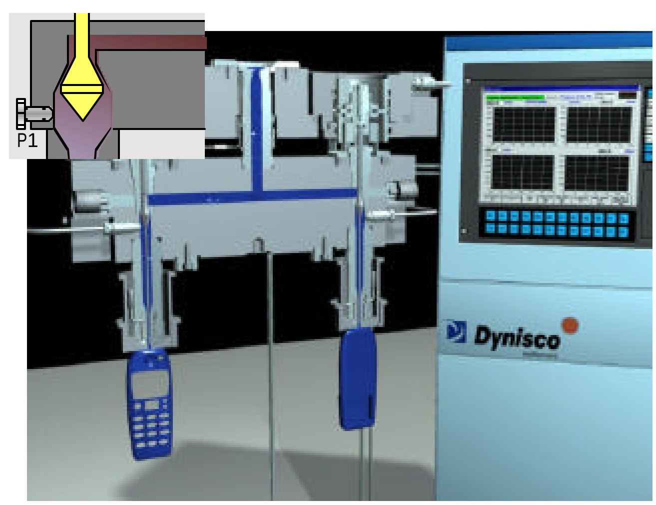


Figure 6: Dynisco's Dynamic Feed™ System

The resulting controllability of the injection molding process is demonstrated in Fig. 7 where multiple pressure profiles can be maintained in the mold cavity of a single part. In the same cycle, three different magnitudes of melt pressure were exerted at different gates for the part shown in Figure 5. The control pressures for the holding stage at Gate 1 and 2 are 41.4 MPa (6000 psi.) while Gate 3 is 20.7 MPa (3000 psi.) and Gate 4 is 62.1 MPa (9000 psi.). In conventional injection molding, the melt pressure would be the same at all gates. This level of process control has not previously been achieved by any molding technology thus far. Each gate can exert a unique holding pressure.

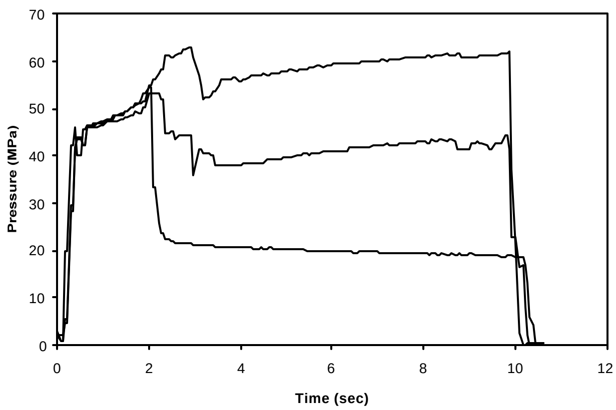


Figure 7: Dynamic Flow Regulation Design

The material shrinkage and dimensions change at differing locations in the part based on the pressure contours and histories around the gates. The ability to change individual dimensions or other quality attributes without re-tooling mold steel provides significant process flexibility. It is possible to augment eq. (2) with the additional degrees of freedom and re-examine the controllability of the three part dimensions:

$$\begin{Bmatrix} L1 \\ L2 \\ L3 \end{Bmatrix} = \begin{bmatrix} 0.02 & 0.05 & 0.08 & 0.01 \\ 0.03 & 0.09 & 0.05 & 0.00 \\ 0.01 & 0.02 & 0.03 & 0.01 \end{bmatrix} \begin{Bmatrix} Pressure \\ Velocity \\ Temperature \\ ScrewSpeed \end{Bmatrix} + \begin{bmatrix} 0.00 & 0.31 & 0.60 & 0.00 \\ 0.10 & 0.17 & 0.00 & 0.16 \\ 0.00 & 0.02 & 0.00 & 0.21 \end{bmatrix} \begin{Bmatrix} P1 \\ P2 \\ P3 \\ P4 \end{Bmatrix} \quad (2)$$

There are two significant implications of this result. First, the closed loop control of cavity pressures has significantly reduced the dependence of part dimensions on machine settings, as evidenced by the reduction in the magnitude of coefficients for the primary machine settings. This effect has also been evidenced by reductions in the standard deviations of multiple part dimensions by an average factor of five, resulting in an increase in the process capability index, *Cp*, from less than 1 to greater than 2.

The second matrix in eq. (2) is also evidence of the improved dimensional controllability provided by the dynamic regulation of the cavity pressure distribution. In general, changing the cavity pressure at the gate closest to a dimension provides the major effect on part dimensions. Additionally, independent control of the valve stems provides the capability to vary dimensions at one location without altering the dimensions at another location. This flexibility does not exist in conventional molding because hold pressure changes intended to influence one area of the part can be transmitted to other areas of the part through the static feed system. It should be noted, however, that the total magnitude of dimensional change available with dynamic pressure regulation is approximately the same as for conventional molding.

These results have a significant impact on the product and tooling development process. Currently, numerical mold filling simulations and expert judgments are combined to estimate the process behavior and make critical design decisions. If these decisions are incorrect, then tooling modifications may be required. Improved controllability of the injection molding process permits correction for many design inaccuracies during the mold commissioning stage without retooling. Such a change in the development process could substantially reduce the tool development costs and hasten time to market.

The described process is also significant in that it moves polymer control from the molding machine to the mold itself. This reduces the molding machine to a ‘polymeric pump.’ Variations in injection pressure, flow rates, pack pressures, or pack times are all compensated through dynamic pressure and temperature control. The market repercussions could be significant, as 1) an old machine without closed loop control can provide consistency equal to modern machines, and 2) a mold commissioned on a molding machine in the United States is ensured to produce consistent parts on a molding machine overseas. The mold becomes its own self-contained quality control mechanism, resulting in substantial productivity and quality gains.

2.2 DYNAMIC TEMPERATURE CONTROL

In the cooling stage of injection molding, heat is typically conducted from the hot polymer to the comparatively cold mold, then conducted through the mold to the cooling line, where it is convected away by the coolant. Recent research has attempted to dynamically control the thermal and fluid properties of the melt within the molding cycle. While dynamic pressure control has been proven feasible [14] and has been commercialized, the relatively slow thermal transients have prevented similar gains in temperature control.

The cooling stage of injection molding cycle is not ideal for a variety of reasons, impacting both the product quality and production economics. The process physics dictate that the mold temperature must be less than the polymer heat deflection temperature such that a rigid part is ejected. However, the cold mold temperature conducts heat from the hot polymer melt to the cold mold during injection, causing the development of a skin on the exterior of the part and propagation of frozen layers towards the core of the part. These frozen layers increase the flow resistance, making the mold cavity difficult to fill. Since frozen layers are developed continuously during injection and cooling, they ‘lock in’ varying levels of stress and orientation. This variation in polymer morphology as a function of thickness reduces optical, structural, and other part properties [15-18].

To compensate for the negative effects of cold mold walls, manufacturers may run the mold at higher mold temperatures, higher melt temperatures, higher injection pressures, and higher injection velocities [19, 20]. Alternatively, a lower viscosity polymer or higher part wall thickness may be required with cost and/or performance disadvantages. All of these options negatively impact the economics of production.

In fact, the economic drivers dictate higher mold temperatures during injection (to allow thin part wall thicknesses and low injection pressures) but lower mold temperatures during cooling (to allow rapid solidification). This optimal mold temperature control strategy is infeasible given current control strategies and material technologies. The size of the mold, together with its high heat capacity and thermal inertia, prevents dynamic closed loop control of the mold surface. This statement is based on objective analysis as well as observation of prior academic and industrial research [21-28]. For instance, Jansen [29], Chen [30], and other researchers have utilized a thermoelectric device within the mold wall to dynamically heat and cool a portion of the mold. However, the time response of these active control elements is relatively slow, on the order of seconds. Also, there is limited ability to induce a large thermal differential due to the mass and properties of the mold.

Alternative researchers [23-26] utilized thin insulative coatings on the surface of the mold to delay the onset of freezing until after polymer injection. Such coatings did not provide adequate durability, but a similar technique is being successfully utilized behind metallic stampers in production of optical media to reduce the cycle time by 0.2 seconds. On a broader scope, mold inserts with high thermal conductivity [31-33] are being more frequently utilized to increase the rate of heat transfer in thick and/or hot sections of the part.

As previously stated, no thermoelectric or other thermal actuator exists which will provide the desired transient mold wall temperature control. Moreover, other passive elements (such as insulators or conductors) can only delay or augment the flow of heat from the polymer melt to the cooling line. It is evidenced from these previous attempts that dynamic closed loop control strategies have been unable to either increase the performance of the molded part or reduce the manufacturing cost. Coatings and inserts – approaches which do not use active control elements – have proven somewhat effective and are gaining acceptance and penetration in the molding industry. For the plastics industry, any successful technology must require little additional complexity and cost while being sufficient robust for high volume production.

The objective of current research is to develop a novel and more capable method for dynamic control of mold wall temperature throughout the injection molding process. The resulting technology should enable high mold wall temperatures during the injection and packing stages to facilitate polymer flow and uniform part properties, but then induce low mold wall temperatures to facilitate solidification of the molded part. Ideally, the mold wall temperature should equal the melt temperature during filling, but equal the room temperature during cooling. Such decoupling of mold temperatures during the molding cycle has not yet been achieved. Dynamic temperature control would enable three primary benefits:

1. Higher quality parts. By increasing the mold temperature during polymer injection, the development of an outer skin and frozen layers will be completely avoided. Pressure and thermal gradients across the part will be minimized, leading to reduced birefringence, low residual stress, etc.
2. Reduced wall thickness. By maintaining a high mold temperature during polymer injection, the flow conductance will be greatly increased. This will allow for drastic wall thickness reductions or fewer gates.
3. Reduced cycle times. By reducing the mold wall temperature during the cooling stage, the part will more quickly solidify, resulting in significant productivity increases. Moreover, lower ejection temperatures will result in significantly less post-molding shrinkage thereby reducing the need for dimension changes.

The current approach consists of three simple concepts as shown in Fig. 8. First, the mold coolant is maintained at lower temperatures than would normally be feasible with conventional injection molding. Next, a significant temperature transient is profiled in the mold steel prior to the start of injection by convecting a heated gas across the surface of the mold according to a known time/temperature/flow rate profile. Finally, the molding cycle is begun with the heat transfer dynamics proceeding 'open loop' to obtain the desired dynamic mold wall temperature behavior as a function of time during the molding cycle.

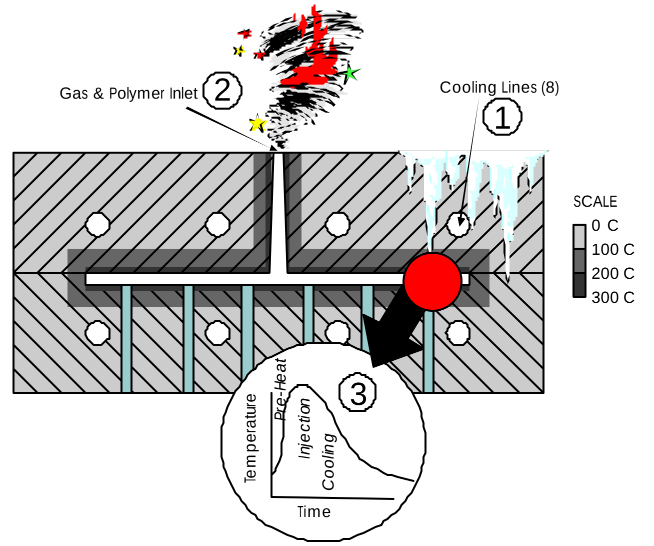
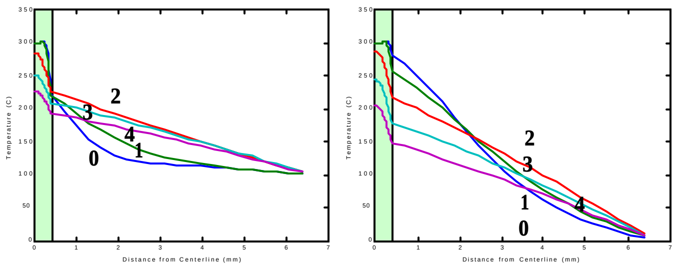


Figure 8: Dynamic Cooling Control

This process concept leverages existing practices in the plastics industry to facilitate implementation. For instance, convection of the heated gas facilitates rapid heating of the mold surface but requires gas channels for the heated gas to exit. These gas channels already exist in the vents of all existing injection molds. As another example, consider the energy required removing heat from the mold – the existing infrastructure of coolant lines and mold water chillers are sufficient. As such, only a high temperature, high pressure gas supply is needed and even this type of auxiliary equipment is being utilized for gas assisted injection molding.

Since experimental work is not complete, a numerical solution of the heat, mass, and momentum equations has been utilized for performance analysis. The viscous flow and heat transfer analyses are coupled to provide a non-isothermal, non-Newtonian, compressible simulation of all stages of the injection molding process. This transient process simulation was utilized to analyze the conventional molding of a 1.2mm thick compact disc molded of neat polycarbonate at a melt temperature of 300C and a mold coolant temperature of 100C. The proposed process utilizes an initial heated mold surface temperature of 260C and a mold coolant temperature of 0C. Other important process parameters such as pack pressure, injection velocity, and mold open time have been held constant to mirror the observed production of optical media. To provide an accurate representation of the process, twenty molding cycles were simulated where the thermal result of the previous cycle is the initial condition to the next cycle. This permits an estimation of the temperature profile throughout the mold at the start of the cycle, as if the mold had been running in steady state production.

The resulting temperature distribution through a cross section of the polymer and mold are plotted as significant time events in Fig. 9. Trace #0 indicates the initial temperature profile of the mold when the polymer is injected. In the conventional process, the mold is at low temperatures during injection, causing a 100C differential between the polymer skin and core. In the proposed process, a thermal transient is initiated to provide a high mold surface temperature. Altering the gas temperature and time exposure can modify the initial temperature distribution in the mold.



Conventional *Dynamic Cooling*

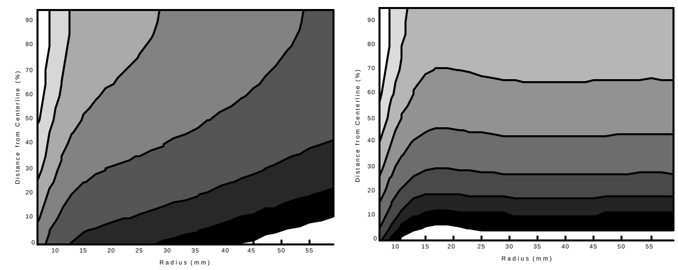
Figure 9: Temperature through Cross-Section of Part & Mold

The subsequent curves represent the temperature distribution at one-second intervals. It is evidenced by these graphs that conventional molding has exactly the reverse temperature behavior from what is desired. The cold mold wall during injection will cause increased flow resistance and reduction in part properties while the hot mold coolant reduces the heat transfer during part cooling. Reducing the mold coolant temperature significantly increases the heat transfer during cooling but further reduces the mold wall temperature during injection…this is necessary for cycle time reduction. The proposed process provides for minimal thermal transients during injection yet still permits rapid subsequent part cooling.

The thermal gradients of Fig. 9 are critical to predicting and controlling other process dynamics and subsequent part properties. During injection, for instance, increased flow conductance is desired to reduce the required injection pressure. This will not only allow the manufacture of larger parts given a specified machine capacity, but also increase the uniformity of the part properties. Given the rheological and thermal properties of polycarbonate, the resulting pressure contours from the center to the edge of the compact disc can be predicted: conventional molding requires approximately 19Mpa pressure to fill the mold while the near-isothermal filling provides a reduction in the injection pressure to 10 Mpa. This reduction in injection pressure does significantly expand the moldability of the product, requires less energy for manufacture, enables molding of larger parts, and increases the uniformity of the part quality.

Once the mold cavity is filled with molten polymer, additional melt is forced into the mold cavity at high pressure to compensate for volumetric shrinkage as the frozen layers propagate towards the core of the part. In the manufacture of optical media and lenses, accurate surface replication and low birefringence are desired. The former attribute requires high cavity pressure while the latter attribute requires uniform polymer morphology across and through the part.

The significance of the thermal and pressure histories can also be understood by examining the output part properties. As an example, we will consider birefringence, which is caused by a variation in optical properties that force light to travel at two or more distinct speeds while propagating through the compact disk. With a given grade of polycarbonate, the index of refraction is directly related to the specific volume of the molded part [34, 35]. Fig. 10 displays a cross section of specific volume across and through the optical disc at ejection. The ordinate axis represents the radial direction while the abscissa represents the thickness direction from the mid-plane of the optical disc. The graphs have been set to the same scale and may be compared directly. In conventional molding, a significant solidified layer develops near the gate (center of part) which has frozen during the high injection and packing pressures. The cavity pressure at the outer radius of the part is significantly lower during the end of the packing stage and throughout the cooling stage in both cases.



Conventional Dynamic Cooling

Figure 10: Specific Volume of Cross-Section of Compact Disc

Fig. 10 also shows the potential quality improvement should controllability of the thermal transients be achieved. Since the mold is filled at isothermal conditions, no solidified layers develop until the end of the packing stage and the cavity pressure is uniform throughout the cavity. Such uniformity will enable previously unattained surface replication, low birefringence, and dimensional properties. The specific volume is nearly constant across the radius of the compact disc through the first 30% of the thickness, which is the critical area that is later metallicized and scanned.

3 CONCLUSIONS

This paper has discussed the application of axiomatic design principles to gain controllability of the injection molding process. The resulting processes are powerful enablers for the molding industry. Multi-cavity pressure control enables spatial decoupling to increase the number of degrees of freedom governing quality attributes. Dynamic temperature control enables temporal decoupling of the injection and solidification stages to increase the process performance. As such, the potential productivity and quality gains from these processes are substantial.

These examples of successful manufacturing process design suggest application to similar approaches outside of polymer processing. A rigorous design methodology is attainable based on existing research foundations. Such manufacturing process design can provide breakthroughs for competitive advantage. Recent research in manufacturing and design has overly focused on robustness and consistency. As industry continues to lower its research priorities, it is academe's responsibility and opportunity to take greater risks and deliver fundamentally new process technologies.

4 ACKNOWLEDGMENTS

This work was funded through the period of 1992 to 2002 through (sequentially) General Electric Plastics, Dynisco Instruments, Stanford University Integrated Manufacturing Association, Kona Corporation, U.S. Department of Energy Innovative Process Program, National Science Foundation Division of Design, Manufacture, and Industrial Innovation, Hewlett-Packard Corporation, and the U.S. Office of Naval Research. The author would especially like to thank Brendan Cahill, Mark Doyle, Dave Hatch, Deepak Kapoor, Mark Moss, and Matt Niemeyer.

5 REFERENCES

[1] N. P. Suh, *The Principles of Design*, 1 ed: Oxford University Press, Inc., 1990.

[2] A. K. Fagade and D. O. Kazmer, "Optimal Component Consolidation in Molded Product Design," presented at ASME 4th Design for Manufacturing Conference, Las Vegas, NV, 1999.
[3] C. Y. W. Ma, "A Design Approach to a Computer-Controlled Injection-Molding Machine," *Polymer Engineering and Science*, vol. 11, pp. 768-772, 1974.
[4] P. D. Coates and R. G. Speight, "Towards intelligent process control of injection moulding of polymers," *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, vol. 209, pp. 357-367, 1995.
[5] H. S. Lee, "Thin Cavity Filling Analysis Using the Finite Element Method with Control Volume Technique," in *Mechanical Engineering*. Troy, NY: Rensselaer Polytechnic Institute, 1989.
[6] Hwai Hai Chiang, "Simulation and Verification of Filling and Post-Filling Stages of the Injection Molding Process," in *Mechanical Engineering*. Ithaca, NY: Cornell University, 1989.
[7] J. T. Luftig and V. S. Jordan, *Design of experiments in quality engineering*. New York: McGraw-Hill, 1998.
[8] U. Langkamp, "Pressure and temperature sensors," *Kunststoffe Plast Europe*, vol. 86, pp. 1804-1812 German, 1996.
[9] J. W. Mann, "Process Parameter Control: the Key to Optimization," *Plastics Engineering*, vol. 30, pp. 25-27, 1974.
[10] M. R. Kamal, W. I. Patterson, N. Conley, D. Abu Fara, and G. Lohfink, "Dynamics and Control of Pressure in the Injection Molding of Thermoplastics," *Polymer Engineering and Science*, vol. 27, pp. 1403-1410, 1987.
[11] F. Gao, I. A. N. Patterson, and M. R. Kamal, "Self-tuning cavity pressure control of injection molding filling," *Advances in Polymer Technology*, vol. 13, pp. 111-120, 1994.
[12] C.-P. Chiu, M.-C. Shih, and J.-H. Wei, "Dynamic Modeling of the Mold Filling Process in an Injection Molding Machine," *Polymer Engineering and Science*, vol. 31, pp. 1417-1424, 1991.
[13] R. E. Nunn and C. P. Grolman, "Closed Loop Cavity Pressure Control in Injection Molding," *J. Reinforced Plastics and Composites*, vol. 9, pp. 2121, 1991.
[14] D. O. Kazmer and P. Barkan, "Multi-Cavity Pressure Control in the Filling and Packing Stages of the Injection Molding Process," *Polymer Engineering and Science*, vol. 37, pp. 1865-1879, 1997.
[15] W. C. Bushko and V. K. Stokes, "Solidification of thermoviscoelastic melts. Part II: Effects of processing conditions on shrinkage and residual stresses," *Polymer Engineering and Science*, vol. 35, pp. 365-383, 1995.
[16] S.-J. Liu, "Modeling and simulation of thermally induced stress and warpage in injection molded thermoplastics," *Polymer Engineering and Science*, vol. 36, pp. 807-818, 1996.
[17] Y. Ulcer and M. Cakmak, "Overview of structure-property relationships in injection molded poly(ethylene 2,6 naphthalene dicarboxylate) parts," presented at Polymer Preprints, Division of Polymer Chemistry, American Chemical Society, New Orleans, La, Usa, 1996.
[18] B. Xie and D. I. Bigio, "Case studies of morphology development for iPP during the injection molding cooling process," presented at Annual Technical Conference, 1996.
[19] P. Tantakom and N. R. Schott, "Processing strategies for thin wall injection molding," presented at Annual Technical Conference - ANTEC, Conference Proceedings, Atlanta, Ga, Usa, 1998.
[20] S. Cha and F. S. Lai, "Analytical study of thin-wall injection molding: Filling and cooling analysis," presented at Annual Technical Conference - ANTEC, Conference Proceedings, Indianapolis, In, Usa, 1996.
[21] Y. Lu, D. Li, and J. Xiao, "Simulation of cooling process of injection molding," *Progress in Natural Science*, vol. 6, pp. 227, 1996.
[22] G.-Y. Lai and J. X. Rietveld, "Role of polymer transparency and temperature gradients in the quantitative measurement of process stream temperatures during injection molding via IR pyrometry," *Polymer Engineering and Science*, vol. 36, pp. 1755-1768, 1996.
[23] S. J. Park and T. H. Kwon, "Thermal and design sensitivity analyses for cooling system of injection mold, Part 1: thermal analysis," *Journal of Manufacturing Science and Engineering, Transactions of the ASME*, vol. 120, pp. 287-295, 1998.
[24] R. Rossbach, "Laying-out heating/cooling channels in injection moulds," *Kunststoffe Plast Europe*, vol. 84, 1994.
[25] Y. Kurosaki, I. Satoh, and H. Kim, "Effects of thermal molding conditions on the residual stress and residual birefringence in an injection-molded polymer strip," *Nippon Kikai Gakkai Ronbunshu, B Hen/Transactions of the Japan Society of Mechanical Engineers, Part B*, vol. 59, pp. 3236-3242, 1993.
[26] R. Wimberger-Friedl, "Molecular orientation induced by cooling stresses. Birefringence in polycarbonate: III. Constrained quench and injection molding," *Journal of Polymer Science, Part B: Polymer Physics*, vol. 32, pp. 595-605, 1994.
[27] G. R. Smoluk, "Electronic communication; key goal in chillers, mold-temperature controllers," *Modern Plastics*, vol. 67, pp. 52-54, 1990.
[28] M. Nikitovic, "Optimal regulation of mould temperature in plastomer injection moulding," *Polimeri (Zagreb)*, vol. 12, pp. 109-114, 1991.
[29] K. M. B. Jansen, "Heat transfer in injection moulding systems with insulation layers and heating elements," *International Journal of Heat and Mass Transfer*, vol. 38, pp. 309-316, 1995.
[30] S. C. Chen and Y. C. Chung, "Numerical simulations of the cydic, transient mold heat transfer in injection model cooling process," *International Communications in Heat and Mass Transfer*, vol. 21, pp. 323-332, 1994.
[31] K. C. Apacki, "Copper-alloy molds provide thermal advantages and shorter cycle time for injection molding," presented at Annual Technical Conference - ANTEC, Conference Proceedings, Boston, Ma, Usa, 1995.
[32] Anon, "Basics of achieving accurate mould temperature," *British Plastics and Rubber*, pp. 20-21, 1996.
[33] D. J. Seres, "Precise mold temperature control," *Industrial Heating*, vol. 62, pp. 31, 1995.
[34] H. T. Pham, C. P. Bosnyak, and K. Sehanobish, "Residual stresses in injection molded polycarbonate rectangular bars," *Polymer Engineering and Science*, vol. 33, pp. 1634-1643, 1993.
[35] J. W. Shin, D. C. Rhee, and S. J. Park, "Experimental study of optical disc birefringence," presented at Annual Technical Conference - ANTEC, Conference Proceedings, Atlanta, Ga, Usa, 1998.