ELIMINATION OF PROCESS CONSTRAINTS IN PLASTICS INJECTION MOLDING

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ABSTRACT

Innovation in injection molding is fundamentally constrained by the physics which determine the pressure, flow, and thermal dynamics. This paper provides a high level review and analysis of the governing principles to identify theoretical limits on process performance. While incremental improvements can be made through process optimization, this paper indicates that more substantial gains are possible through new process concepts. New process designs enable critical boundary conditions to be controlled, with performance and productivity improvements beyond the theoretical limits of conventional injection molding.

INTRODUCTION

Nearly all injection molding processes can be continuously improved with respect to performance and/or cost. Continuous improvement in molding technologies are providing molders with increases in productivity and reductions in materials and energy usage [1]. With competition, the processes are commoditized and differentiated along a performance: cost curve in which nearly all producers maintain similar profit margins determined by market forces plus or minus some variation associated with the efficiency of their internal processes. As time progresses, however, the magnitude of potential improvements are reduced as the process performance approaches unknown but real constraints.

The maturation of several molding technologies is evidenced by the S-shaped curves in Figure 1. Development and initial adoption is slow, followed by rapid growth in which major gains in product quality and cost are realized. For instance, the reciprocating screw was the dominant method for plastication in injection molding, and provided significant improvements in melt consistency, product quality, and cycle time reduction. PC-based control systems are similarly augmenting and/or replacing PLC-based control systems, thereby providing improvements in machine response and flexibility. Eventually, however, these technologies become standardized and commoditized with small or incremental gains in the benefit to cost ratio. This is a well established phenomenon in the management of technology [2].

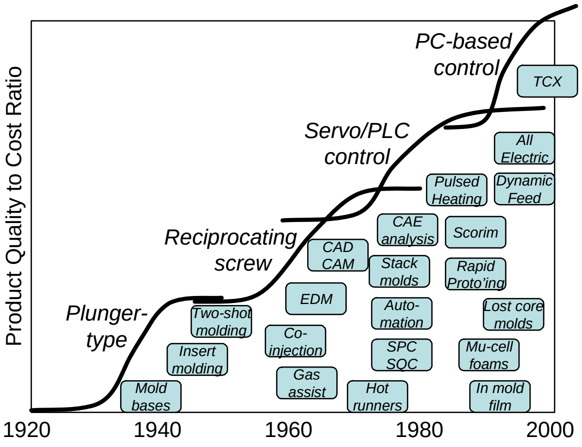

Figure 1: Evolution of some molding technologies

Breakthroughs in process, mold, material, and/or machine designs are required to relax the existing set of process constraints, and thereby enable higher levels of performance at lower costs. Also shown in Figure 1 are several specific molding technologies. The placement of these technologies in Figure 1 is only intended to show the approximate date of development and not a specific impact on the product quality to cost ratio. It is observed that a continual stream of innovation has sustained the plastics industry by providing new process capabilities to design and manufacture more complex products at reasonable costs.

In the evaluation of any molding system, it is important to consider the current state of performance compared to the theoretical feasibility. The "efficient frontier" is a term used to imply that one aspect of a design, process, or system can not be improved without adversely affecting other important aspects. It is rarely possible to continually increase performance and continually decrease costs. Any such gains made from "continuous improvement" are typically achieved by reducing the inefficiency currently in a system. Awareness of the concept of the efficient frontier can help the decision maker to improve their product by increasing performance or reducing costs. In practice, however, it is not possible to precisely know the boundaries of the efficient frontier and operate at a truly efficient point. This may seem surprising, but it is true for at least three reasons including indefiniteness of specifications, behavioral uncertainty, and relative valuation of multiple objectives. Further discussion of these concepts related to uncertainty is provided elsewhere [3].

This paper considers the fundamental process constraints associated with the flow, pressure, and temperature of the polymer melt that determine the moldability, quality, and cost of molded plastic products. Specifically, very simple analysis shows the feasibility, benefits, and costs of isothermal filling of injection molds with isobaric solidification of an 'optimal' plastic product. The discussion will focus on 'optimality' with respect to trade-offs between energy utilization of the process and the performance attributes of the molded plastic product.

ANALYSIS

The injection molding process fundamentally consists of stages corresponding to the plastication of the polymer melt, the filling of a mold cavity with the molten plastic, the packing and solidification of the plastic, and the ejection of the molded plastic product. The following analysis provides some fundamental observations of the injection molding process in general, and is not intended to represent any one specific molding process.

Plastication: A polymer melt suitable for injection into the mold must be produced from solid plastic pellets. The minimum amount of energy, Q_{melt}, required to plasticize the polymer melt is related to the change from the temperature of the pellets, T_p, to the melt temperature, T_m, the plastics' heat capacity, C_P, and its mass, m:

$$Q_{melt} = C_P \cdot m \cdot \left(T_m - T_p\right) \quad (1)$$

Filling: Once plasticized, the polymer melt is injected to fill the cavity. Regardless of shape of the cavity, the pressure in the cavity decreases monotonically from the maximum pressure at the point of injection to atmospheric pressure at the melt front. Assuming flow in a rectangular channel, the pressure, P, required to fill the cavity is related to the nominal thickness of the cavity through which the melt flows, h, the distance that the melt must flow, l, the apparent viscosity of the plastic, η, and the filling time, t.

$$P = \frac{12 \cdot \eta}{h^2} \cdot \frac{l}{t} \quad (2)$$

In molding practice, the effective thickness of the flow channel and the apparent viscosity of the polymer melt are strongly dependent on the filling time. Specifically, for long filling times and low volumetric flow rates, heat conduction from the hot polymer melt to the cold mold wall forces the development of a solidified layer, which significantly reduces the effective thickness through which the polymer may flow. Such a condition is shown in Figure 1.

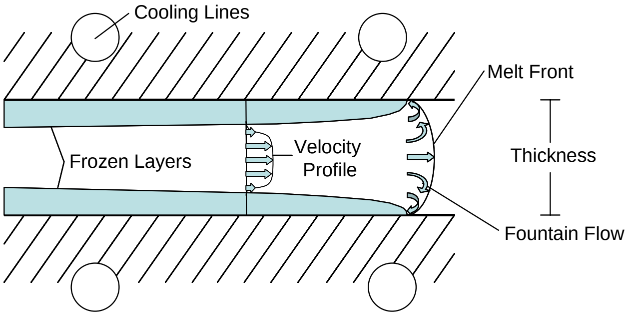

Figure 1: Development of a solidified layer during injection mold filling

For very short filling times, very high pressure is required to drive the melt into the mold cavity as is practiced for thin wall molding where melt pressures of 200MPa (30,000 psi) are commonly utilized. In this case, the polymer flow is dominated by high internal heat generation, significant heat convection with the moving polymer melt, and relatively low heat loss by conduction to the mold, as previously studied [4].

As shown in Figure 2, unacceptably high injection pressures result from very short and very long injection times. The feasible range of acceptable injection times is a measure of the moldability of the application, with an intermediate injection time frequently utilized to provide achievable lower injection pressures. In many molding applications, however, constraints on injection pressure and clamp tonnage necessitate the use of thicker walls, additional gates, lower viscosity materials, or higher mold and melt temperatures than would otherwise be desirable.

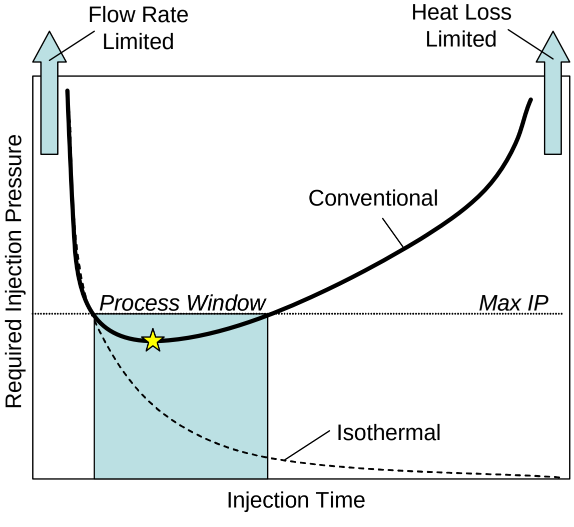

Figure 2: Allowable range of fill times due to flow rate and heat loss constraints

Packing: Once the polymer melt fills the mold cavity, a packing pressure is maintained to force more material into the cavity and compensate for the solidification and shrinkage of the polymer as it solidifies. The pressurization and depressurization of the polymer follows the pressure-volume-temperature (PVT) curve shown in Figure 3, with the volumetric shrinkage resulting from the cooling of the post-molded product.

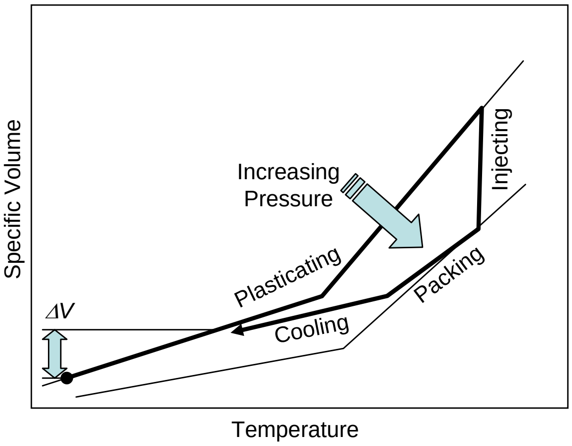

Figure 3: Densification of polymer during molding

Cooling: Once the plastic melt at the gate solidifies, no additional material can be forced into the cavity and the pressure decays. The amount of energy to be removed, Q_{cool}, required to cool the polymer melt is related to the change from the melt temperature, T_m, to the ejection temperature, T_e, the heat capacity of the plastic melt, C_P, and its mass, m:

$$Q_{cool} = C_P \cdot m \cdot (T_m - T_e)\,[J] \tag{3}$$

The energy per square meter of surface area, Q, can also be considered as a function of the wall thickness, h:

$$Q = C_P \cdot \rho \cdot h \cdot (T_m - T_e)\,[J/m^2] \tag{4}$$

The average cooling power per square meter, P_{cool}, is:

$$P_{cool} = \frac{C_P \cdot h \cdot \rho \cdot (T_m - T_e)}{t_{cooling}}\,[W/m^2] \tag{5}$$

The cooling time, $t_{cooling}$, can be estimated using one-dimensional heat transfer as [5]:

$$t_{cooling} = \frac{h^2}{2\pi\alpha} \ln\left[\frac{\pi}{4}\left(\frac{T_m - T_c}{T_e - T_c}\right)\right] \tag{6}$$

where α is the thermal diffusivity and T_c is the mold coolant temperature. It should be noted that for many materials and processing conditions, molders have found the following approximation of eq. (6) useful where h is measured in mm:

$$t_{cooling} \approx 4 \cdot h^2 \tag{7}$$

PROCESS DESIGN

The performance of conventional molding processes are governed by these physics, with significant trade-offs required in the design of the part geometry, molding process, and polymeric materials. For instance, a light product may require thin walls. However, the filling of such a thin-walled product may require very high injection pressures and a lower viscosity resin. High injection pressure drives the need for a high clamp tonnage, and may also result in reduced part properties and high scrap rates. Lower viscosity resins will also tend to reduce the structural properties of the thin walled, molded product.

For these reasons, it is desirable to consider the development of new molding processes that decouple filling, packing, and cooling. Specifically, it is desirable to maintain the temperature of the mold surface above the glass transition temperature of the polymer during the filling. Such isothermal mold filling would provide two benefits. First, isothermal filling would prevent the cooling of the polymer melt and development of the solidified layer, thereby enabling longer fill times to be used and decreasing the injection pressure required to fill the mold. Second, isothermal filling would allow for the equilibration of pressure throughout the cavity after mold filling. The packing stage could then proceed from a uniform state.[1]

Isothermal filling of mold cavities has been an active area of academic and industrial research for some time [6-12]. A resistance heater based on deposition of thin insulative and conductive layers has been recently developed [15-17]. The developed process design is shown below in Figure 4. A resistance heater deposited on the mold surface provides direct control of the temperature at the polymer interface. To reduce the power requirements and also provide excellent abrasion resistance, the heater is deposited between the two asymmetric ceramic layers. The design variables include the material properties and thickness of the insulative layers, the energy density of the deposited heater, and the energy density of the cooling system determined by design of the mold and selection of the mold coolant temperature. This paper will next address several fundamental issues regarding the process design.

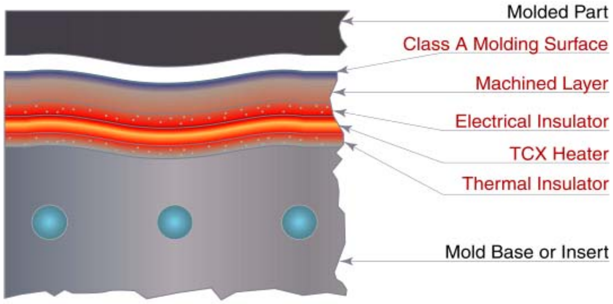

Figure 4: TCX^{TM} Mold Cavity Heating System

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[1] To avoid the development of non-uniform stress distribution in packing due to viscous melt flow from the gate to the freeze front, profiled thickness compression of the polymer in the mold cavity is suggested. This approach provides two substantial benefits. First, shrinkage compensation is accomplished through reduction in the mold thickness. As a result, a uniform pressure is maintained throughout the cavity. Second, the shrinkage compensation can be maintained longer than would normally be possible in conventional molding, which would result in lower shrinkage and improved aesthetic and structural part properties.

Required Heating Power

A first fundamental question regarding the feasibility of such an isothermal molding process design is the heating power required to maintain the surface at a uniform temperature given the heat transfer to the circulating mold coolant.[2] Substituting eq. (7) into eq. (5) provides the approximate power of the cooling system required to extract energy from the melt without delaying the molding cycle:

$$\overline{P}_{cool} = \frac{C_P \cdot \rho \cdot (T_m - T_e)}{4h} \, [W / m^2] \qquad (8)$$

It is noted that as the wall thickness decreases, the cooling system must extract more heat per unit time. The in-mold heaters must temporarily counteract the cooling system. For a typical resin, e.g. ABS, C_P, T_m, and T_e are 2000 J/KgC, 250C, and 110C respectively. Available resistance heating technology can provide approximately 100 W/in^2 (157,000 W/m^2). Substituting these values, into eq. (8) provides a lower limit for the wall thickness and cycle time:

$$\overline{P}_{heat} = \frac{70{,}000}{h} < 157{,}000 \rho \, [W / m^2] \Rightarrow h > 0.44\,\text{mm} \qquad (9)$$

This result implies that the process design is limited to applications with wall thickness above 0.44 mm and cycle time above 0.8 sec. While not a significant constraint for the process design, wall thicknesses below 0.44 mm are feasible, however, if the cycle time is extended and cooling and heating power are proportionally reduced.

Cycle Delays Due to Reduced Heat Transfer

A second fundamental question regarding the feasibility of such an isothermal molding process design is the possible extension of cycle times due to the addition of insulative layers between the plastic melt and the mold coolant. The heat transfer due to conduction in a conventional mold is:

$$P_{cond} = \frac{k \cdot (T_m - T_c)}{x} \, [W / m^2] \qquad (10)$$

where x is the distance from the plastic melt to the mold coolant.[3] For a typical application, e.g. ABS with a P20 mold, k, T_m, T_c and x are 41 W/mC, 250C, 60C, and 0.025m respectively. Substituting these values into eq. (10) provides a maximum heat transfer rate by conduction of 312,000 W/m^2. In reality, the heat transfer rate will be much lower due to thermal contact resistance at the polymer: mold and mold: coolant interfaces as well as the requirement for each cooling line to extract heat from a large breadth of the mold.

Referring to Figure 4, it observed that the heater will be encased between two ceramic layers to provide electrical isolation and abrasion resistance. Each of these layers has a thickness, $x_{ceramic}$, on the order of 0.015in (0.3mm) and a thermal conductivity, $k_{ceramic}$, of approximately 5W/mC. It is proposed that the mold coolant temperature is reduced to counteract the effect of the thin insulative layers. A system of two equations with two unknowns is solved:

$$\begin{gathered} P_{cond} = \frac{k_{mold} \cdot (T_{ceramic} - T_c)}{x_{mold}} \\ P_{cond} = \frac{k_{ceramic} \cdot (T_m - T_{ceramic})}{x_{ceramic}} \qquad (11) \\ \Downarrow \\ T_c = T_m - \frac{P_{cond} \cdot x_{mold}}{k_{mold}} - \frac{P_{cond} \cdot x_{ceramic}}{k_{ceramic}} \end{gathered}$$

which indicates that the mold coolant temperature, T_c, must be reduced by an amount equal to the temperature drop through the ceramic layers indicated by the last term in eq. (11). For the values provided above, this temperature drop is 37C which would require the mold coolant to be lowered to 23C in order to maintain the same maximum heat transfer rate of 312,000 W/m^2. This process change is certainly feasible.

Cycle Delays Due to Slow Initial Response

A third fundamental question regarding the feasibility of such an isothermal molding process design is the possible extension of cycle times due to the initial heating of the mold surface required prior to the injection of the melt. Similar to eq. (5), the initial heating time, $t_{heating}$, is governed by the available heater wattage and design (h, C_P) of the ceramic layers:

$$t_{heating} = \frac{C_P \cdot \rho \cdot h \cdot (T_m - T_c)}{P_{heating}} \, [\text{sec}] \qquad (12)$$

Assuming consistent values of C_P, h, T_m, T_c of 800J/kgC, 0.3mm, 250C, and 23C, respectively, and a very conservative estimate of 5W/in^2 (7,900W/m^2) for the heating power, an initial heating time of 0.010 seconds is obtained. The initial heating of the mold surface could be readily conducted during the mold closing portion of the cycle.

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[2] Some process designs call for stoppage of the coolant circulation during the filling of the mold. Such a process design increases the complexity of the design without significantly reducing the power requirements given the temperature transients occurring throughout the mold steel.

[3] The authors note that this analysis assumes static melt and mold coolant temperatures and perfect thermal contact conditions. Relaxation of these assumptions is beyond the scope of this paper, though the interested reader is referred to 13. Yu, C.J. and J.E. Sunderland, *Determination of ejection temperature and cooling time in injection molding.* Polymer engineering and science, 1992. **32**(3): p. 191, 14. Xu, H. and D.O. Kazmer, *A Stiffness Criterion for Cooling Time Estimation.* International Polymer Processing, 1999. **13**(3): p. 249-255.

DEMONSTRATION

To demonstrate the capability of the developed isothermal molding technology, a spiral mold was designed as shown in Figure 5. In the mold, two symmetric spiral cavities are provided. One cavity has a conventional design with a wall thickness of 1 mm and a flow length of 1000 mm…a flow length to wall thickness which is beyond conventional injection molding. The other cavity is geometrically identical but has a spiral heater deposited below the mold walls. This mold design allows direct comparison between conventional molding and isothermal molding at the same process conditions.

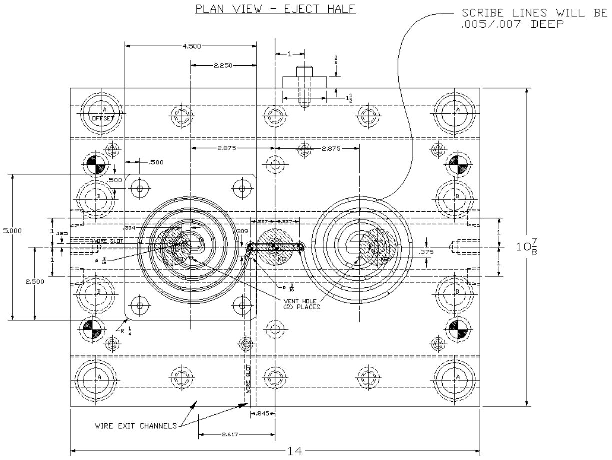

Figure 5: Spiral mold design

Molding trials were conducted on a 1988 HPM molding machine with an 80 ton hydraulic clamp. A polypropylene resin with a melt flow of 20 was utilized with a melt temperature and mold temperature of 450F and 120F, respectively. A maximum hydraulic pressure of 30% (600 psi) was specified with a 20 second injection forward time. This set of conditions was chosen to guarantee a pressure limited flow situation with sufficient time for melt flow. Figure 6 provides a photograph of the two molded spirals without heat being provided. This figure demonstrates that the spiral cavities are mostly balanced in a cold condition. The ceramic layers on the isothermal side do slightly reduce the heat transfer rate as previously predicted, and slightly increase (14%) the flow to the isothermal side of the mold when they are not activated as compared to the conventional molding.

Figure 6: Photograph of conventional vs. isothermal molded spirals without heat

When heat is applied to provide isothermal filling at the same machine conditions, however, the plastic melt flows substantially farther as shown in Figure 7. In this molding, 220V was provided to the deposited heaters, providing approximately 600W along the length of the spiral. As this heating level, the isothermal mold cavity was maintained at 512F, above the melt temperature! The flow length was no longer dominated by the development of a solidified layer in the mold cavity and, in theory; any flow length could be achieved by extending the filling time. In this experiment, however, the lack of heat provided to the sprue bushing and gate allowed the development of a solidified layer in the feed system, which reduced the rate of flow to the isothermal cavity.

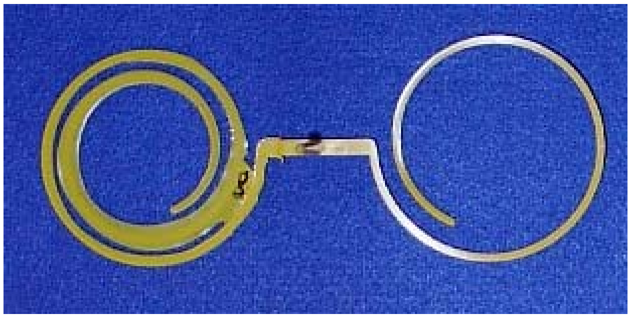

Figure 7: Photograph of conventional vs. isothermal molded spirals with heat

To investigate the relationship between heating power and flow length in the conventional and isothermal molding processes, a series of experiments were conducted at increasing supply voltages. While a thermocouple was placed in the mold between the support plate and B plate, a mold surface pyrometer was also used prior to the start of the molding cycle to estimate the temperature of the mold: polymer interface. Figure 8 provides the estimated mold surface temperature for the isothermal and conventional mold cavity while the coolant was being convected at a constant 120F. It is observed that the mold wall temperature is concave up, which could be expected since the heater power varies with the square of the supplied voltage.

For each molding cycle, the same injection pressure and flow rate were utilized. As can be observed from Figure 9, the increasing heater power and mold wall temperature enable greatly improved flow conditions – a 63% increase in flow compared to conventional injection molding. With isothermal molding, the advancing plastic melt will never solidify in the cavity, and the flow length should continue to increase with increasing injection forward times. As previously noted, the results would have been further improved if larger and/or heated sprue bushings and gates were also utilized.

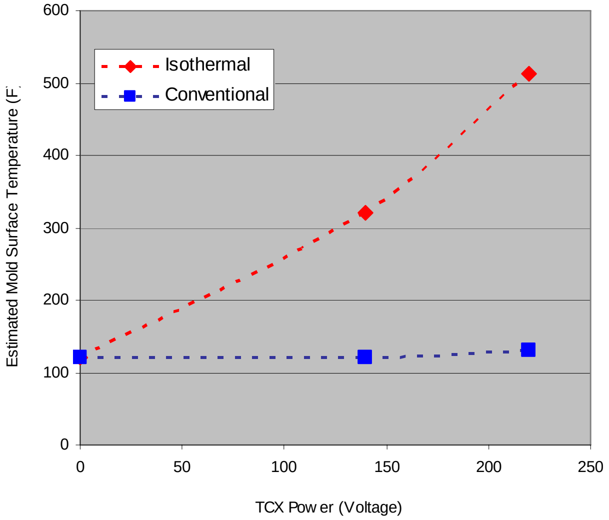

Figure 8: Effect of Fill Time on Flow Length

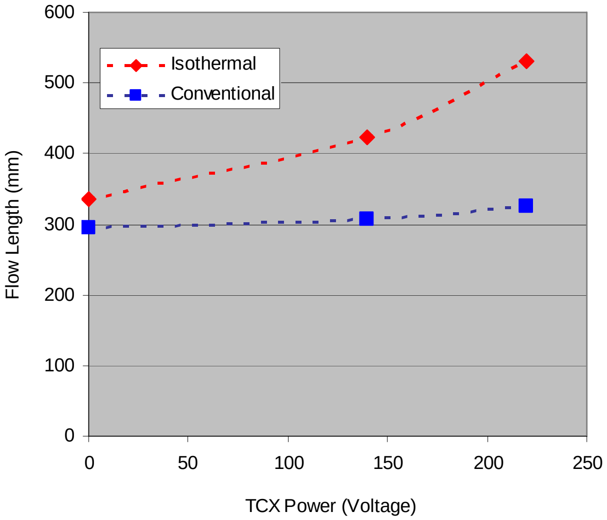

Figure 9: Effect of Fill Time on Flow Length

DISCUSSION

Given this analytical and experimental proof of feasibility of isothermal molding, the paper will now discuss the net impact on cost in a typical molding application. While it is conceivable that the isothermal molding process will allow increased piece part price due to improved aesthetic and structural properties, these benefits are difficult to quantify. As such, the following discussion will be constrained to potential cost savings. In particular, there are three primary areas of cost savings: reduction in wall thickness, reduction in cycle time, and reduction in clamp tonnage and associated hourly rates.

For discussion purposes, consider the top cover of a laptop or rear housing of an LCD display shown in Figure 10. This part is approximately 300 mm by 200 mm, center gated with a wall thickness of 1.8 mm, which corresponds to a flow length: wall thickness ratio of 100:1. Molded of a high flow ABS/PC blend with an apparent viscosity of 300 PaSec, and a 1 sec injection time, this part requires an injection pressure of 166 MPa (24,200 psi) and clamp tonnage of 560 mTons. The melt and mold coolant temperature are 280C and 90C, respectively with a cycle time of 13.96 seconds.

Figure 10: Example Application

The marginal cost of the molded product is driven by material and processing costs. Given a material cost of $2/kg, the material costs would be approximately $0.216 per part. Given an hourly rate of $95/hour for a 560 mTon machine, the processing cost per part is approximately $0.369.

Consider a reduction in wall thickness from 1.8 to 1.4 mm, which would result in a 22% material savings. Such a reduction would normally be impossible per conventional injection molding without adding gates or other major process changes. With isothermal molding, an injection time of 4 seconds is chosen, which allows a significant decrease in the injection pressure from 167 MPa to 69 MPa (ref. eq. (2) and the isothermal curve of Figure 2). There is a net reduction in required clamp tonnage from 560 to 232 mTons. Even with the extended injection time, the net cycle time is reduced due to the significantly reduced cooling time associated with the reduction in wall thickness. As such, the processing cost is reduced by 52% due to the use of a less expensive molding machine with increased production rates.

Isothermal molding does, however, require the additional costs of adding and removing heat each cycle. For this application, a 4.65kW heater is utilized, being pulsed for 4 seconds each cycle. Given an energy cost of $0.12/KwHr and cooling system efficiency of 25%, the additional costs associated with adding and removing heat corresponds to $0.003 per part.

The cost analysis is provided in Table 1. It is impressive to note the potential cost savings (40%) that are possible by eliminating the process constraints in plastics injection molding. Again, this discussion has not considered the additional benefits that may be associated with enabling higher levels of performance or quality in the molded products

Table 1: Cost Impact

Geometry	*Conventional*	*Isothermal*
Width (mm)	300	300
Length (mm)	200	200
Thickness (mm)	1.8	1.4
Processing		
Viscosity (Pa Sec)	300	300
Melt Temperature (C)	280	280
Mold Temperature (C)	90	53
Injection Time (sec)	1	4
Injection Pressure (Mpa)	167	69
Clamp Tonnage (mTons)	562	232
Cooling Time (sec)	12.96	7.84
Cycle Time (sec)	13.96	11.84
Heater Power (kW)	N/A	4.65
Costs		
Energy Cost ($/KwHr)	N/A	$0.12
Material Cost ($/kg)	$2.00	$2.00
Machine Rate ($/Hour)	$95.23	$54.03
Heater Energy Cost ($)	$0.000	$0.003
Material Cost ($)	$0.216	$0.168
Processing Cost ($)	$0.369	$0.178
Comparison		
Total Marginal Cost ($)	$0.585	$0.349
Net Difference ($)		($0.237)
Net Difference (%)		(40.41)

CONCLUSIONS

Plastics injection molding is perceived by many as a mature technology. However, many performance constraints in plastics injection molding still exist that prevent the development and manufacture of higher performance products at lower cost. A primary issue is not whether these performance constraints can be overcome, but rather which performance constraints should be overcome. With respect to control of the melt temperature in plastics injection molding, this paper has provided analytical, experimental, and economic proof of feasibility. This analysis provides convincing argument that control of melt temperature should be overcome and beneficially utilized in many commercial applications.

As of the time of this conference, the TCX$^{\text{TM}}$ heater deposition technology is being developed for many industrial applications outside the plastics industry. The initial proof of principle molding experiments, while limited in scope, and the analysis above, demonstrate significant promise for isothermal molding using TCX$^{\text{TM}}$'s heating technology. Further long term cycle testing, evaluation with differing polymers and mold and part geometries as well as strategic partnerships are required to move the technology into molding practice.

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