Dynamic Temperature Control in Injection Molding with New Conformal Heating/Cooling System

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ABSTRACT

The cooling is an important process in injection molding. It can represent more than 60% of the total molding cycle time, affecting directly the shrinkage and warpage of the plastic part. Therefore, designing a good cooling system is very important as it greatly affects the cycle time, the quality and indirectly the price of the product. Conventional straight cooling channels are machined into mold components with gun drills. Alternative methods to create cooling channels that conforms or fits to the shape of the cavity and core of the mould providing better heat transfer have been proposed before.

This paper deals with a new cooling system that follows the shape of the part in core and cavity.

This alternative method uses a metallic mold with thin walls, to increase the heat absorption from the molten plastic and reduce thermal inertia, mounted in a chamber constructed from a thermo-insulating material. Between the active elements of the mold and the exterior chamber a heating/cooling fluid is circulating. This ensures quasi isothermal filling conditions and a uniform as well as a more efficient cooling process.

KEYWORDS: injection molding, cooling system, isothermal filling.

1. Introduction

The cost-effectiveness of the mold injection process is mainly dependent on the time spent on the cycle which includes injection, cooling, plate movement and ejection. Also, in order to avoid defects in the plastic parts, the temperature in the mould must be homogeneous. Thus, the design of a good cooling system is crucial, being able to reduce the cycle time drastically and improve the part quality and lower the price [1].

Generally, heat must be rapidly and uniformly extracted from the plastic material until the part reach a stable state, which permits de-molding without any risk to warp. Proper design is necessary for the optimum heat transfer process between the melted plastic material and the mould.

The traditional design process relies on experience and intuition, by creating several straight holes of different shapes inside the mould core and cavity and then forcing a cooling fluid to circulate and conduct the excess of the heat away. An alternative design of cooling system that conforms to the shape of the cavity and core of the mould can provide better heat transfer.

Most existing work on the cooling systems for injection molding research has been directed to improve the effectiveness and efficiency of cooling. Tang et al. [3] described a methodology for the optimal design of channel location and coolant flow rate, using finite element analysis. Li [4] described a procedure of decomposing a complex shape into shape elements and developed an algorithm for the recognition of features specific to the cooling system and generate cooling channels. K. M. Au [5] used a scaffolding architecture that conforms to the shape of the part for optimal cooling design. Sach et al. [6] described the production of injection molding tooling with conformal cooling channels using the Three Dimensional Printing (3DP) process.

This paper proposes a new cooling system that allows the dynamic control of the cooling phase of the injection process. The method is feasible based on a new design of core and cavity that allow low thermal inertia.

2. The heat transfer problem

Traditionally, in the cooling stage of injection molding, heat is conducted from the hot polymer to the comparatively cold mold and then conducted through the mold to the cooling line, where it is removed by the coolant. In condition of long filling times and low volumetric flow rates, when the hot polymer comes in contact with the cold mold wall, it develops a solid skin on the contact surface between the part and mold. These frozen layers propagate to the core of the part increasing the flow resistance and making the mold cavity difficult to fill [7].

Since injection and cooling processes are connected and developed continuously, they lock inside various levels of stress and orientation that reduce optical, structural, and other part properties [7-10]. These conditions are shown in fig. 1.

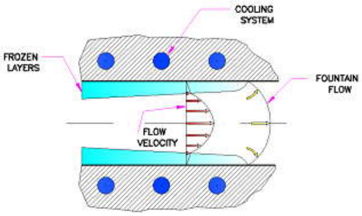

Fig. 1. *Development of frozen layers during mold filling*

To attenuate the negative effects of cold mold walls, manufacturers may raise mold temperatures, melt temperatures, injection pressures, or injection velocities [12, 13]. But high injection pressure drives to the need for a high clamp force during filling, and may also result in reduced part properties and high scrap rates. On the other hand, a lower viscosity polymer or higher part wall thickness may reduce the structural properties with cost and performance disadvantages.

In fact, the optimal injection conditions require higher mold temperatures during injection (the temperature of the mold surface above the glass transition temperature of the polymer) and lower mold temperatures during cooling (to allow rapid solidification). Such isothermal mold filling would provide two benefits. First, isothermal filling would prevent the development of the solidified layer, enabling longer fill times to be used and decreasing dramatically the injection pressure required to fill the mold. Second, isothermal filling would allow the equilibration of pressure throughout the cavity after mold filling (isobar filling). The packing stage could then proceed from a uniform state.

3. Related Work

Mold injection in isothermal conditions has been an active research subject in industrial design [11-18]. Researchers have utilized thermoelectric devices or resistance heaters based on deposition of thin isolative and conductive layers within the mold wall to dynamically heat and cool a portion of the mold. Alternative methods utilized thin insulating coatings on the surface of the mold to delay the development of freezing layers during the polymer injection.

Other techniques use inserts with high thermal conductivity [14] to increase the rate of heat transfer in thick and/or hot sections of the part.

Unfortunately, the response time of these active control elements is relatively slow, on the order of seconds [11]. Normal molding conditions due to the mass of the mold defined by high heat conductivity and thermal inertia prevents precise dynamic control of the mold surface temperature. Also coatings can only delay the flow of heat from the polymer melt to the cooling line. Moreover passive elements as inserts will not be able to provide the desired dynamic mold wall temperature control.

New methods that use contour-like channels of different cross-section, constructed as close as possible to the surface of the mould to increase the heat absorption, are difficult to use due to the technological issues.

There are also developed vario-thermal processes, such as rapid heat cycle molding (RHCM) process [17], pulsed cooling process [18] and coolant temperature switch.

4. Design of Mold and Heating/Cooling System

Dynamic temperature control should enable high mold wall temperatures during the injection and packing stages to facilitate polymer flow and uniform part properties, and low mold wall temperatures to facilitate solidification of the molded part during cooling. Ideally, the mold wall temperature should be equal to the melt temperature during filling, and equal with the room temperature on the cooling stage.

Rising the mold temperature in the filling stage of injection molding has a lot of benefits:

1. Enhance the fluidity will improve the product quality [1, 2]. 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 residual stress;

2. By maintaining a high mold temperature during polymer injection, the flow conductance will be greatly increased. This will allow significantly wall thickness reductions or fewer gates;

3. By reducing the mold wall temperature during the cooling stage, the part will more quickly solidify and significantly increase the productivity with less post-molding shrinkage reducing the need for dimensional changes.

In these conditions, it is desirable to consider the development of new molding processes that allow the dynamic temperature control of the molding cavity.

The part chosen for this study is a simple concave injection molded plastic part as shown in Figure 1. Since the experimental work is not complete, simulations using Moldflow have been utilized to perform the analysis.

This process simulation program was utilized to analyze the conventional molding of a 1 mm thick concave part molded of ABS in normal conditions at a melt temperature of 252ºC and a mold temperature of 71ºC and compare the results and the new model.

The proposed new process utilizes an initial heated mold surface temperature of 252ºC. In the cooling stage the mold coolant temperature is 25ºC.

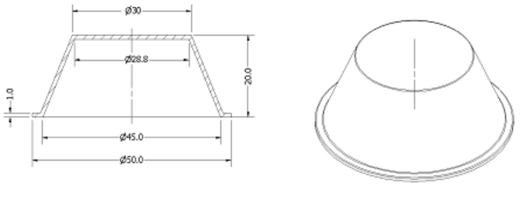

Fig. 2. *Molded Part*

Figure 2 shows the complete assembly model of core, cavity and heating/cooling system.

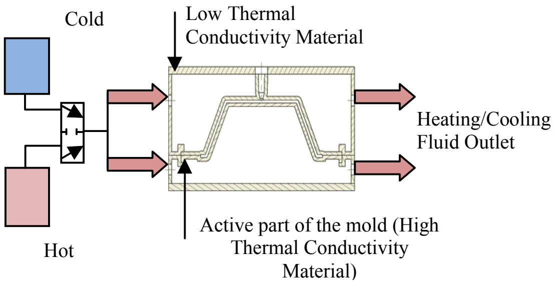

Fig. 3. *Mold*

The same type of fluid is used for heating and cooling. The current approach consists of three simple steps:

1. First, the mold heating fluid is injected at low pressure and a temperature equal to the melted polymer between the active parts of the mold and the exterior chamber. That would normally increase rapidly the temperature of the active part of the mold;

2. When the temperature inside the mold reaches the glass value, the injection process of the polymer starts at a low injection pressure.

Based on the rheological and thermal properties of ABS, the resulting injection pressure can be predicted: conventional molding requires approximately 32 MPa pressure to fill the mold while the near-isothermal filling provides a reduction in the injection pressure to 13 MPa for 0.34 s injection time and only 5 MPa for 3 s filling time (Tab. 1).

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 and the part quality since no solidified layers were developed until the end of the packing stage and the cavity pressure is uniform throughout the cavity.

A simple estimation using Moldflow [20] shows a reduction of (58÷100)% of the injection pressure at the end of the process, and of (57÷120)% of the clamp force (Tab. 1).

Table 1. *Injection Parameters in Isothermal Conditions*

	Filling Time [s]	Injection Pressure [MPa]	Clamp Force [tone]	Part Quality
Normal Cond.	0.36	32.255	2.213	Good
	0.34	13.588	0.795	V. Good
	1.02	8.866	0.474	V. Good
	1.33	7.867	0.27	V. Good
	2.05	6.469	0.341	V. Good
	2.35	6.043	0.251	V. Good
Isothermal Cond.	3.06	5.292	0.223	V. Good
	3.57	4.894	0.279	V. Good
	4.06	4.557	0.152	V. Good
	5.08	4.024	0.142	V. Good
	6.1	3.632	0.135	V. Good
	7.12	3.321	0.177	V. Good

3. Once the mold cavity is filled with molten polymer, additional melt is forced into the mold cavity to compensate for volumetric shrinkage. At the same time low temperature cooling fluid is pumped around the active part of the mold that determined rapid cooling of the part.

5. The heat transfer model

To design and calculate the heat exchange flux of a mold, the total amount of heat carried into the mold has to be first determined. The outside boundary of the cooling area is assumed to be adiabatic. In the filling stage due to the temperature of the coolant equal to the melt temperature, no heat will be transferred from the melted polymer thru the active part of the mold. In the cooling stage, heat flux from the melt has to be removed by the coolant now at room temperature.

The cooling process can be described by the following Fourier equation

$$\frac{\partial T}{\partial t} = a \frac{\partial^2 T}{\partial x^2} \qquad (1)$$

where a is thermal diffusivity defined by

$$a = \frac{\lambda}{\rho C_p} \qquad (2)$$

and:

λ - thermal conductivity;

ρ - density;

C_p - Specific heat capacity.

The following equation describes the heat flux loss [5, 18]

$$Q_c = C_p m (T_M - T_E) \qquad (3)$$

where:

Q_c - the amount of energy to be removed;

m - mass;

T_m - melt temperature;

T_E - ejection temperature.

It is important to consider

$$Q_c = Q_p + Q_a \qquad (4)$$

where:

Q_p - The amount of energy removed for cooling the plastic part;

Q_a - The amount of energy removed for cooling the active part of the mold.

The time required for cooling can be estimated:

$$t_k = \frac{S^2}{\pi^2 a_{ef}} \ln\left(\frac{4}{\pi} \frac{T_M - T_W}{T_E - T_W}\right); \qquad (5)$$

- for plate geometry

$$t_k = \frac{D^2}{23.14 a_{ef}} \ln\left(1.602 \frac{T_M - T_W}{T_E - T_W}\right); \qquad (6)$$

- for cylinder (L>D)

$$t_k = \frac{D^2}{\left(\frac{23.14}{D^2} + \frac{\pi^2}{L^2}\right) a_{ef}} \ln\left(2.04 \frac{T_M - T_W}{T_E - T_W}\right), \qquad (7)$$

- for short cylinder

where:

t_K - Cooling time;

T_W - The average wall temperature that can be calculated with the formula

$$T_W = \frac{1}{2}(T_W \max + T_W \min) \qquad (8)$$

where

$$T_W \max = \frac{b_W T_W \min + b_M T_M}{b_W + b_M}, \qquad (9)$$

and:

T_{Wmin} - coolant temperature;

b - Heat penetrability that is given by

$$b = \sqrt{\rho \lambda C_p}, \qquad (10)$$

and is a measure of the material ability to conduct heat under transient conditions.

6. Discussion

Most of the problems arising in optimization of engineering systems are essentially multi-criteria problems. In case of contradicting objectives, there is no single global solution and it is often useful to determine a set of solutions that fits a predetermined definition for an optimum.

In the evaluation of any molding system, the problem is the selection of values for a number of coupled variables, focusing attention on a single objective, designed to quantify the performance and measure the quality of decision. This objective is maximized (or minimized), subject to constraints that may limit the decision. It is already known that criteria of a design or process cannot be improved without affecting the others. It is a real challenge to increase performance and at the same time to keep on decreasing costs. The gains made in improving a process are normally achieved by reducing the inefficiency that is already in a system.

A very simple analysis shows the benefits of isothermal filling of injection molds in isobaric conditions as an optimal plastic injection process.

As there are no doubts about the gains in quality, an important question regarding the feasibility of an isothermal molding process design is the possible extension of cycle times due to the thermal inertia of the heating/cooling system and due to the initial heating of the mold surface required prior to the injection of the melt.

For the typical application considered in this study (ABS), substituting the values into Eq. (4-10) and assuming perfect thermal contact conditions, provides a cooling time of 1.41s. That is visible less than 2.61s in conventional molding of the same part.

Assuming the active part of the mold is made by steel of a thickness of 5mm and C_p=460 J/KgK an initial heating time of 0.33 seconds is obtained.

With an injection time of 0.34s at 13.6 MPa, the cycle time is still reduced, at least theoretically by 30%. This significant percentage is able to cover the switching inertia from heat to cold fluid tank. Also specific techniques as initial heating of the mold surface to be conducted during the mold closing portion of the cycle could be used.

7. Conclusion

Dynamic temperature control enables substantial productivity, aesthetic and structural propertiy gains for the mold injection process. In particular, there are three primary areas of cost savings: reduction in wall thickness, reduction in cycle time, and reduction in clamp tonnage. However, the method requires additional costs of adding and removing heat at each cycle.

One drawback of rapidly cooling the mold surface is the large thermal stresses induced in the surrounding material. For this reason future work might include FEA transient thermal structural analysis to determine the effects of rapidly cooling of the active part of the mold.

Acknowledgements

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Controlul dinamic al temperaturii la injectarea în matrițe folosind un sistem de încălzire/răcire care urmăreşte profilul piesei

Rezumat

Răcirea este un element cheie al procesului de injectare a maselor plastice. Aceasta poate reprezenta mai mult de 60% din timpul total al ciclului, afectând în mod direct deformarea după injectare a reperelor din materiale polimerice. Prin urmare, proiectarea adecvată a sistemului de răcire este foarte importantă, deoarece afectează direct timpul unui ciclu, calitatea şi, indirect, prețul produsului. Metoda tradițională de realizare a canalelor de răcire o constituie prelucrarea acestora prin burghiere. Sunt studii care au propus şi alte metode pentru a crea astfel de canale care urmăresc profilul de bază al cavității, permițând un transfer mai bun de căldură.

Lucrarea de față propune un sistem de răcire nou, care urmăreşte forma piesei. Metoda foloseşte o matriță metalică cu pereți subțiri, montată într-o incintă construită dintr-un material termoizolant atât pentru a creşte absorbția căldurii din materialul topit cât şi pentru a-i reduce inerția termică. Între elementele active ale matriței şi incinta exterioară este circulat un lichid de încălzire/răcire. Acest lucru asigură condiții quasi-izotermice, uniforme, de umplere, precum şi un proces mai eficient de răcire.

Il controllo dinamico della temperatura dentro gli stampi ad iniezione utilizzando un impianto di riscaldamento/raffreddamento che segue il profilo previsto

Riassunto

Il raffreddamento è un processo fondamentale per lo stampaggio a iniezione plastica. Questo può rappresentare più del 60% del ciclo totale, avendo un influenza direttamente sulla deformazione dopo l’iniezione delle parti in plastica. Pertanto, il disegno corretto del sistema di raffreddamento è molto importante perché influisce direttamente il tempo dello ciclo, la qualità e, indirettamente, il prezzo del prodotto. Il metodo tradizionale di realizzare i canali di raffreddamento lo constituisce l’utilizzo dei trapani lunghi. Altri metodi di creare questi canali che seguono il profilo di base della cavità, consentendo cosi una migliore trasmissione del calore sono stati gia proposti in precedenza.

Questo documento vi propone un nuovo sistema di raffreddamento, che segue il formato del pezzo. Il metodo usa una matrice di metallo con i pareti sottili per aumentare l'assorbimento di calore dalla plastica fusa e per ridurre la sua inerzia termica. La matrice e montata in una camera costruita con materiale termoisolante. Tra gli elementi attivi dello stampo e la camera esterna è circolato un liquido per riscaldamento/raffreddamento. Questo garantisce condizioni quasi-isotermiche, uniforme, di riempimento ed e anche un processo piu efficiente di raffreddamento.

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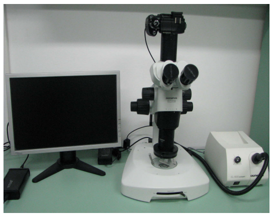
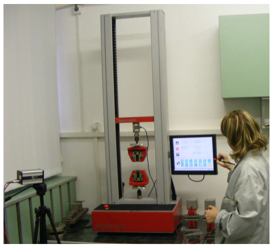
The research laboratory intends to be a research driven experiment of plastics and composites at national and international level. The scientific group consists of: 1 (one) full professor, 1 (one) associate professor and 3 (three) PhD students.
The research activities spam from basic research on mechanical characterization to product and manufacturing technology issues within polymeric materials and composites.





The research activities include:

- Injection molding: mold and equipment design; operation modeling; instrumentation and monitoring; morphology and microstructure development; mechanical behavior of moldings;
- Machining of plastics and composites: experimental determination of cutting forces, and surface roughness;
- Numerical modeling of polymeric materials and composite processing. Modeling and optimization of injection molding process parameters; prediction of the influence of the injection molding system on the quality of the injected parts and on the productivity of the injection molding process;
- Modeling of the cutting process (turning, drilling, milling etc); prediction of the cutting forces, optimization of machining parameters;
- Modeling and simulation of fracture phenomena in polymeric and composite materials using J integral, dynamic stress intensity factor, energy release rate, cohesive models;
- Mechanical characterization of the polymeric materials;
- Determination of the fracture toughness, energy release rate and crack opening displacements.

Research facilities:

- Injection molding machinery ARBURG ALLROUNDER 320 C 500 – 170 GOLDEN EDITION, maximum clamping force 500kN, controller SELOGICA, draying system, THERMOLIFT 100;
- Universal testing machine TESTOMETRIC M 350 5AT, 5kN;
- Video-extensometer TESTOMETRIC, software winTest;
- High-speed camera AOS 800x600 pixeli, 1000fps;
- Stereo-microscope Olympus SZX10 with photo camera;
- Elcometer 3120 Shore Durometer according to ASTM D 2240
- Analytical balance;
- Simulator for wear testing of acetabular cups.

The research is carried out in close collaboration with national and international industries and universities.