Design and Optimization of Conformal Mold Cooling Passages

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Abstract

A novel approach to optimize mold cooling using a seamless combination of simulation and optimization tools under a unified framework is presented. Heat transfer in the mold is modeled using a transient heat conduction equation with appropriate source/sink terms. Crystallization kinetics and the latent heat contribution of the polymer are also considered. Cooling passages are modeled exactly in three dimensions, and also using one-dimensional cooling circuits. The latter method is used to accurately specify the heat transfer boundary conditions in the passage by separately computing the coolant flow. The keys to this modeling approach are the data structure that represents the problem domain and the interface between the solver and optimization tool. The simulation is designed specifically with optimization in mind. A sample analysis and results highlighting the methodology is presented in this work.

1. Introduction

Over the last decade, demands on injection molding in terms of manufacturing thin-walled parts and meeting stringent tolerances have increased dramatically. It is not unconventional to have parts with thickness variations of over an order of magnitude, sections as thin as a few hundredths of an inch, and tolerances of less than a percent. Expectations of higher production rates and superior part quality have made the process design more critical than ever.

Typically, more than *two-thirds of the cycle time* is spent in the cooling phase. The importance of rapid and uniform cooling has a direct bearing on the part quality and production rate. In addition, demands on mold temperature control due to thin parts have led to the development of advanced techniques such as pulsed cooling/heating. Recent advances in metal freeform fabrication techniques (for one example, see [1]) have also paved the way to the manufacture of conformally cooled molds. In order to take advantage of these new capabilities, better simulation and optimization tools are necessary. The objective of this effort is to develop a set of such tools to optimize mold temperature control lines, and a methodology to use them.

Better tools will enable exploitation of the greater design freedom with the result of reduced cooling times and more uniform cooling in large plastic parts, increasing mold productivity and part quality. Reduced cycle time is achieved by minimizing the sections with low cooling efficiency and by detecting bypassed and high pressure-drop cooling channels. Minimizing the areas of the mold-melt interface with hot spots and ensuring that the temperature variation in the part is within an acceptable tolerance results in high part quality by reducing residual stresses and the resulting part warpage.

Even though optimization tools are being successfully used for mold and die design, they have been used only with limited success in the case of optimization of the mold cooling passages themselves. For instance, Park and Kwon [2] use BEM to perform the analysis under cycle averaged temperature conditions. The part is included using a 1-D approximation, and only heat transfer is considered in the part. Among various optimization parameters are the radius of the channels and their location. Works by Tang *et al* [3] consider optimization in single and multi-cavity molds using a finite element method. As with [2], only heat transfer in the plastic part is considered. The additional heat transfer effects due to the latent heat of crystallization are not. Interestingly, some works, such as Li [4], pay attention to arriving at a good initial design before embarking into analysis or optimization.

Additional references in these works can be consulted for a detailed literature review. The research effort presented here addresses some of the limitations seen in the available literature:

a) Cooling channels are meshed into the mold and can be arbitrary in shape.
b) Channels can be moved automatically (see [5] for a similar example).
c) Heat transfer coefficients and coolant pressure drops are computed using a flow network embedded in the 3D model.
d) Both transient and steady state (cycle averaged) temperature conditions are considered.
e) Both heat transfer and reaction/crystallization kinetics in the part are included.

In Section 2, a brief description of the mathematical model is presented. Details of the optimization algorithm and the procedure are discussed in Section 3. A brief discussion, conclusions, and suggestions for future work follow.

2. Mathematical Model

2.1 Heat Transfer Model

Heat transfer in the mold is modeled using a steady/transient anisotropic heat conduction equation with appropriate terms to account for heat sources such as the latent heat of crystallization. The steady model with cycle averaged temperature boundary conditions is provided for the purposes of faster optimization and design solution. The transient model includes part-kinetics, so both heat transfer and part-kinetics equations are solved in the part domain. This model can also be used along with the optimization engine. However, it is used mostly for obtaining a detailed understanding of the process.

2.2 Kinetics Model

The model assumes the part is completely filled. Crystallization (or curing) kinetics of the part are modeled using a combination of the nth order and autocatalytic models. The latent heat addition is computed based on the kinetics data.

2.3 Modeling Cooling Circuits

Cooling paths can be modeled either as one-dimensional cooling circuits or they can be meshed in three dimensions. In the latter case, the convection heat transfer coefficient and fluid temperature are specified as the boundary conditions. In order to simplify this specification, an underlying 1-D circuit made of beam elements is specified for computing these coefficients and the pressure drop in the circuit. Flow of coolant is not simulated, but computed using empirical relations using parameters such as the Reynolds number, Prandtl number, surface roughness, etc.

3. Optimization

3.1 Tools used for Optimization

Figure 1 shows the different tools and layers of interaction between the tools in the optimization process. The role of the process manager is to handle the data transfer between different subsystems and make automation of the design process possible. For successful optimization that involves modification to the mesh, a tight integration between the meshing/data generation tool and the solver is required. In this particular case, this interface is achieved via a TCL API layer both in the mesher (Altair HyperMesh®) and in the analysis tool. Altair Process Manager®, which can communicate either using TCL or Java Beans®, is used to integrate the applications. After the optimization analysis, the final geometry is transferred back to CAD software (such as UniGraphics®) for further verification and CAM.

3.2 Model Design for Optimization

The analysis tool used is designed specifically keeping optimization in mind, with a flexible data input method that can be manipulated by the process manager. Two or more files control the data supplied to the tool. One set, denoted as the GRF file(s), contains the mesh, process conditions, and other parameters. Another, the TCL control file, is used to load the GRF file(s) and select specific parts of the loaded data. The mesh supplied is made up of multiple domains. A solution can be obtained using a specific union of selected domains, with the ability to assign to specific material data to each domain at the time of solution. This approach enables meshing and selective use/comparison of multiple cooling paths in the data. The same degree of flexibility is provided in specifying the material data, boundary conditions, and process parameters. The optimization engine can modify most of this data using the API layer.

3.3 Optimization Algorithm

The cooling performance of an injection molding process can be optimized through a combination of activities such as:

a) Controlling the process parameters that govern the flow.
b) Moving the location of the cooling circuit.
c) Augmenting the heat transfer in the circuit through ribs or vanes.
d) Using special provisions such as thermal pins.

Irrespective of how the exact combination, the quality of the final design depends on the cooling time and uniformity of part cooling. Hence, these two measurable quantities are used to define the response and the constraint for the optimization engine. The pressure drop in the cooling channels and the pumping limitations are also included as constraints. Based on these objectives and constraints, line location and other process parameters are optimized.

Even though the cooling circuit is meshed in the domain as a flow path, an underlying one-dimensional cooling circuit is also defined. This one-dimensional circuit is made of beam elements and serves two purposes: to perform the flow and heat transfer computations necessary for specification of the boundary conditions, and to support post-solution heat transfer diagnostics. The heat transfer diagnostics are computed for each element in the circuit and consist of:

a) Pressure drop,
b) Percentage pressure drop with respect to the whole circuit,
c) Heat transferred,
d) Percentage heat transferred with respect to the whole circuit,
e) Average wall temperature, and
f) Wall temperature variation.

This diagnostic information is used to modify the cooling circuit. **Figure 2** shows the overall algorithm used for this process. The key to the solution process is the tool that modifies the input data based on the optimization.

4. Discussion

The location of the cooling channels is controlled by two different procedures. In the first, simpler, approach, multiple possible cooling channels are included in the mesh. Depending on the control parameters selective paths are chosen and the rest are treated as mold material. **Figure 3** illustrates the first approach. Both the cooling paths C1 and C2 are meshed as if they are part of the mold. The rest of the mold is denoted by domain M. Solutions can be obtained in any union of the domains. For instance, the solution for the problem can be obtained by considering union of domains $M \cup C2$ as mold, while a convection boundary condition is specified on the surface of B. This particular configuration is shown in **Figure 3b**. **Figure 4** shows the sample temperature contour plot for the model shown in **Figure 3b**. The model developed is fully three-dimensional and uses linear tetrahedron elements.

The second approach uses Altair HyperMorph® and actually moves the cooling channel arbitrarily in the domain based on defined shape variables. This is illustrated in **Figure 5**. The mesh movement shown in the figure is based on a single shape variable and the optimization engine controls the actual degree of movement based on the solution response.

The same basic integration approach can be used to incorporate input from tools such as Altair OptiStruct® to ensure that changes to line location do not violate structural constraints.

5. Conclusions

The research presented is an ongoing effort with the final goal of an automated tool for design and optimization of mold cooling passages. This effort will also include building an expert system to guide the optimization based on a heuristic database and manufacturing guidelines. Even though the individual aspect of each step is simple by itself, the integration of all of them into robust and usable software is a daunting task. In this scheme of design, it is vital to include a topology optimization tool to ensure structural integrity and also control the movement of cooling paths by the optimization engine within those limits.

6. Acknowledgements

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7. References

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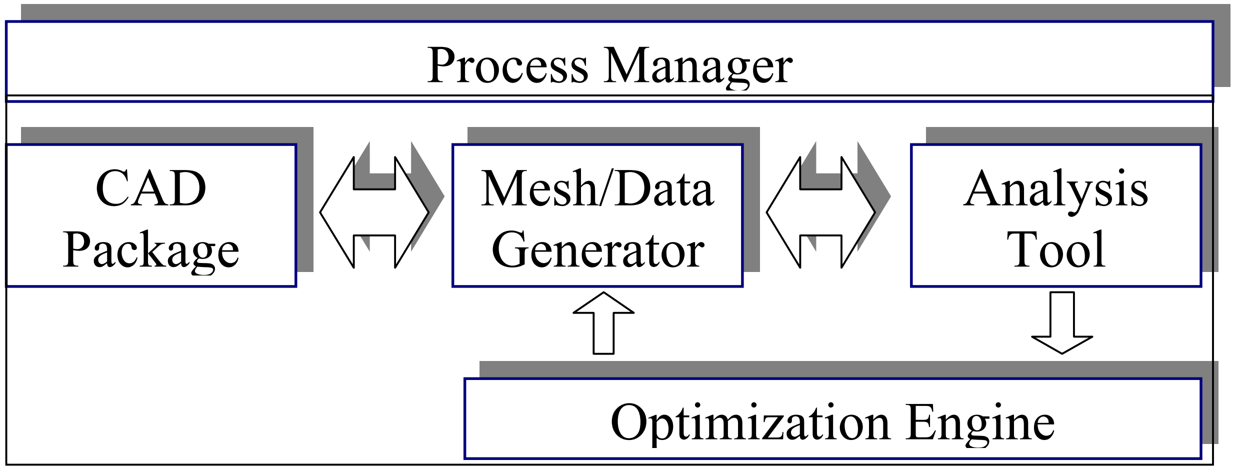


Figure 1: Interaction between different tools that are used for simulation. Communication is handled using the Tcl API interface.

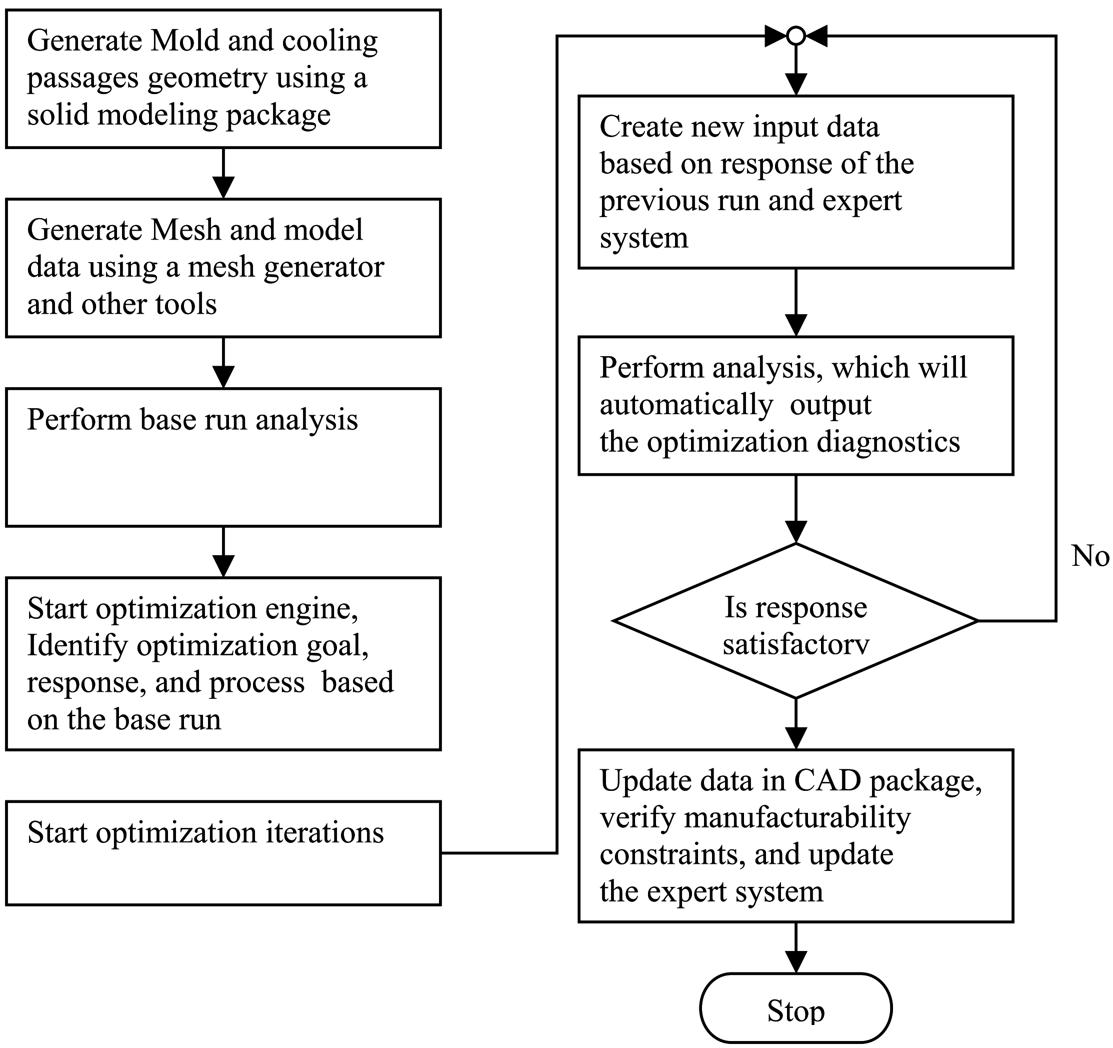


Figure 2: Optimization algorithm used to obtain solution

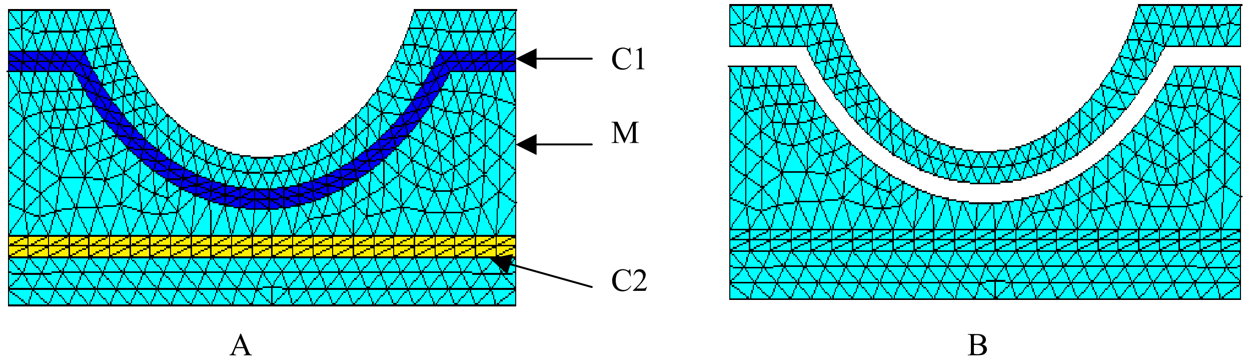


Figure 3: Part of the mold with multiple domains. A) The mesh input to the analysis tool is made of domains M, C1, and C2. Any or all can be used for obtaining a solution. B) The mesh obtained out of the union of M and C2 is used for the analysis. This domain is assigned steel as the material type. A convection boundary condition is specified on the exterior of C1 and the mesh in C1 is not included for obtaining a solution.

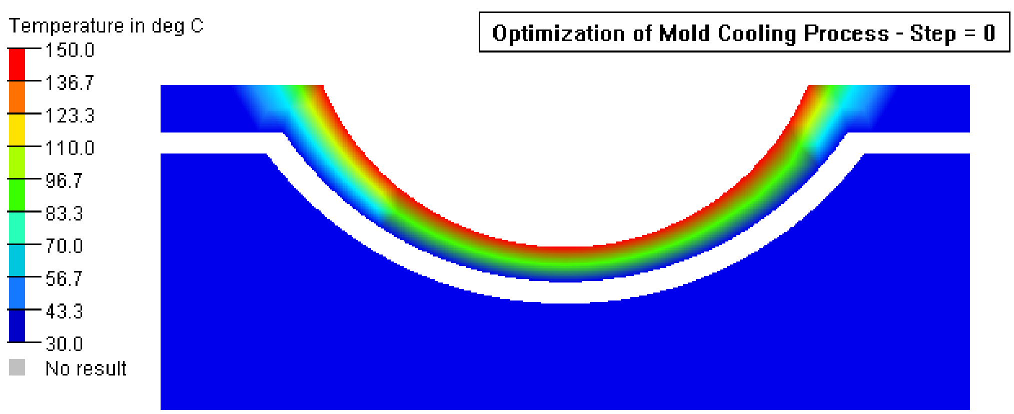
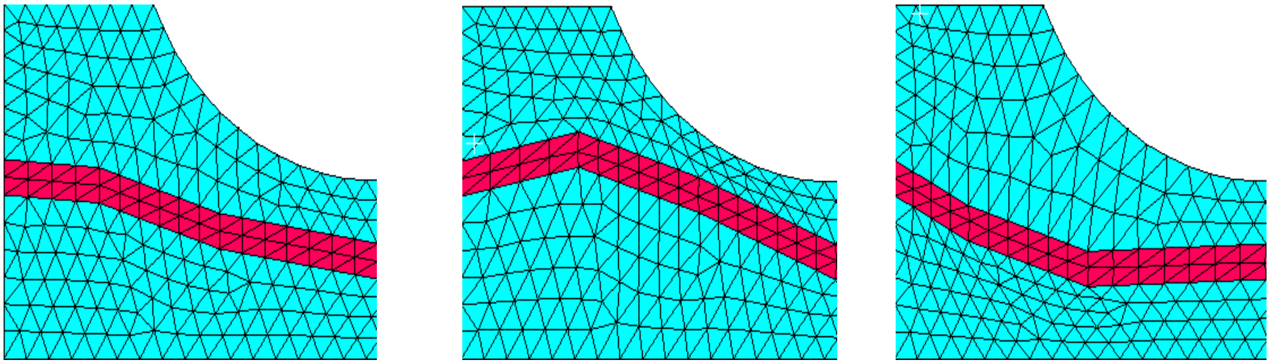


Figure 4: Temperature contours for the mesh shown in Figure 3B.



A B C

Figure 5: The mesh is moved using shape variables generated by Altair HyperMorph®. A) Undeformed configuration, with the cooling channel shown in red. B) Snapshot of a deformed configuration based on a single shape variable. C) Snapshot of a deformed configuration on the other extreme based on the same shape variable.