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A Design Optimization Methodology applied to conformal cooling channels in injection molds: 2D Transient Heat Transfer Analysis

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Abstract: Fabricating conformal cooling channels has become easier and more cost-effective because of recent advances in additive manufacturing. Conformal cooling channels (CCCs) give better cooling performance than regular (straight drilled) channels during the injection molding process. The main reason for this is that CCCs may follow the paths of the molded shape, but regular channels cannot. CCCs can be used to decrease thermal stresses and warpage while also decreasing cycle time and producing a more uniform temperature distribution. Computer-aided engineering (CAE) simulations are crucial for establishing an effective and cost-effective design. This article focuses on the design optimization of an injection mold, with the goal of optimizing the location of cooling channels to reduce ejection time and increase temperature distribution uniformity. It may be inferred that the created technique is effective and appropriate for the objectives of this work.

Keywords: Conformal cooling; injection molding; computer aided engineering; design optimization

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1. Introduction

The Finite Element Method (FEM) was first introduced by Turner et al. [1]. There are uncertainties, though, because it views the powder bed as a continuum. Even though the model can incorporate temperature-dependent material properties and phase changes to improve the model's accuracy, it still has uncertainties because it treats the powder bed as a continuum and frequently ignores the effects of hydrodynamics, such as surface tension, which leads to significant errors in predicting melt pool behavior [2]. The FEM technique is now widely used to predict the layer surface temperature, residual stresses, porosity, and geometric distortion of parts made using the PBF process [3]. Other numerical simulations, such as the Finite Volume Method (FVM) and the Lattice Boltzmann Method (LBM) methods, are primarily used to investigate melt pool hydrodynamics. Commercial software used for problem solving includes ANSYS, ABAQUS, COMSOL, FLUENT/CFX, and custom-built codes. In addition, the Monte Carlo (MC) method is used to simulate heat absorption in the powder bed and ray tracing of the energy source.   A comprehensive examination of existing numerical simulation methods should compare mesh-based continuum approaches such as the FEM and the FVM with discrete mesh free methods such as Discrete Element Method (DEM), the LBM, the Optimal Transportation Method (OTM), and Smoothed Particle Hydrodynamics (SPH) [4]. In finite element modeling (FEM), a continuum domain is divided into a finite number of elements, resulting in a two-dimensional (2D) or three-dimensional (3D) mesh. By using this approach, the space search for a differential equation solution is restricted to solving a finite number of algebraic equations [5].   Solutions that can be manufactured using additive manufacturing were produced by the work. Additive manufacturing is the process of creating parts by fusing materials together layer by layer. It is also referred to as rapid prototyping, 3D printing, or freeform fabrication. Although there are many different types of additive manufacturing (AM) processes, Powder Bed Fusion (PBF) is a widely used method in many industries because it can work with a wide range of materials, including metals, ceramics, and polymers [6]. Researchers have developed numerous methods and algorithms to optimize CCC's. Spiral, zigzag, profiled, and vascularized cooling channel designs have been proposed. Optimization-based studies used several optimization methods [7-9]. The study [10] finds the best control cooling settings using SA. This work optimizes a simulated injection molding model using the cooling system as the main control parameter. Optimization methodologies already developed include Simulated Annealing (SA), Powell's conjugate direction [11], evolutionary algorithms [12,13], Response Surface Methodology [12], and CONMIN [13] (constrained minimization methodology established in [14]). Transient thermal analysis using boundary element technique improved traditional cooling performance [14,15-17]. A similar study as the present one was already published for 3D analysis [18]. A similar mold was already simulated in ANSYS Mechanical APDL and ANSYS Workbench for 2D [19] and 3D [20] analysis. Design optimization was also done in a similar mold, in 3D analysis [21]. This study used MATLAB to coordinate optimization and ANSYS Mechanical APDL 2020 R2 to parametrize cooling channels and calculate temperatures on the 2D natural convection heat transfer problem. This work seeks the best dimensions for a mold with conformable channels for injection molding. The optimization routine lowers the temperatures of the component and its temperature gradients. This work originates a mold with pre-optimized channel placement that performs better than standard molds.

2. Procedure

2.1. Geometry and numerical procedure

The geometry of the analyzed 2D model is presented in Fig. 1 (left). Fig. 1 (right) shows the geometry analyzed, with black lines showing the sets of nodal points used in ANSYS APDL for optimization purposes. To perform optimization, 16 variables/geometric parameters were defined in the ANSYS Mechanical APDL 2020 R2 project.

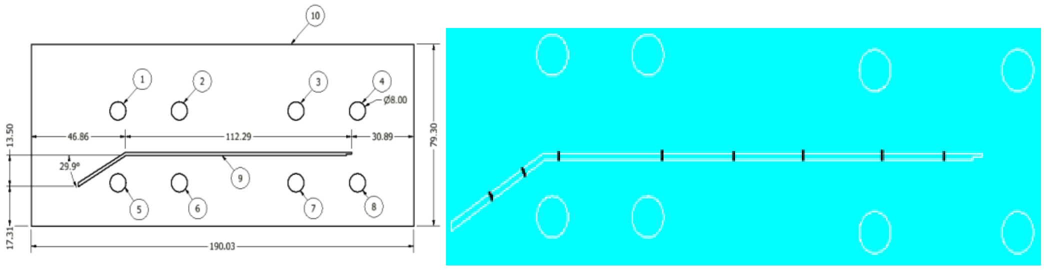

Figure 1. Set drawing: simplification of the 2D model (left) and model analyzed in ANSYS Mechanical APDL 2020 R2. The black lines represent the lines across which nodal points were considered for the calculation of the objective function (right).

The Finite Element Model Updating approach given in this section is based on collaboration between ANSYS and MATLAB: ANSYS is used for Finite Element Method (FEM) computations, while MATLAB is used for optimization. Simulated Annealing is the optimization method. The MATLAB global optimization toolbox's `simulannealbnd` function is used to manage the optimization process. The MATLAB software used in this study was a modification/improvement of previous versions [22-26]. The MATLAB software runs the basic FEM model, which is represented by the APDL input file input.txt. The objective function is calculated using the temperatures of important nodal points following the run (Fig. 1, right). The optimization function in MATLAB then sets new values for the design variables and runs ANSYS again. Each iteration generates an output file that MATLAB uses to calculate the objective function and that serves as a reference for MATLAB to assess the feasibility of each variable's value and the whole set of variables on the minimization of the objective function. This technique is repeated automatically until the solution converges and the optimal values of the design variables are found for the best (lowest) value of the objective function. The used objective function is shown in Eq. (1):

$$\text{obj}=\text{w}_1\frac{[T_{\max}]_o}{[T_{\max}]_i}+\text{w}_2\frac{[T_{\min}]_i}{[T_{\min}]_o} \tag{1}$$

The interaction between ANSYS and MATLAB is shown in Fig. 2:

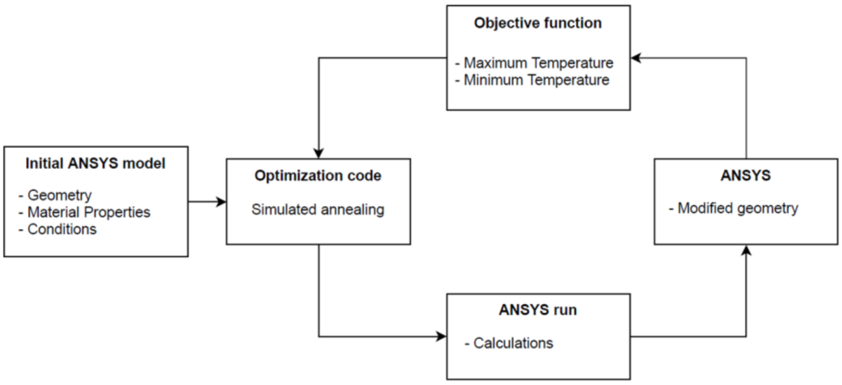

Figure 2. Interaction between ANSYS and MATLAB, adapted from [22].

The main MATLAB code first launches ANSYS to begin the thermal analysis of the models created using FEM, using the ANSYS input file containing all the instructions. The MATLAB code creates a new input file from the original ANSYS input file. This step is done to prevent having to alter the original input file, which could be required for further optimization steps. During the optimization procedure, the modified input file is updated, changing the values of the variables upon each iteration.

The sequence of the MATLAB is shown in Fig. 3:

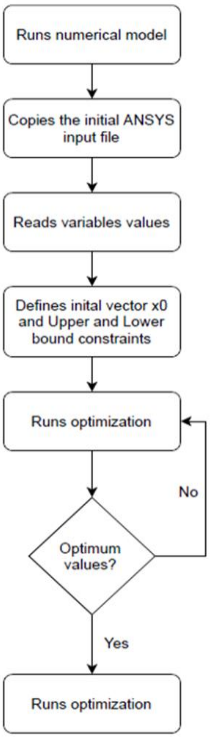

Figure 3. Sequence of Optimization code, adapted from [26] in [22-25].

The main m. file opens ANSYS and uses the ANSYS input file with all the instructions to start the thermal analysis of the models made with FEM. The original ANSYS input file, input.txt, is converted into a new file called inputmod.txt by the MATLAB application. In order to avoid having to change the original input file—which might be necessary for additional optimization steps—this step is taken. The inputmod.txt file is updated during the optimization process, altering the variable values each time it is assessed. MATLAB then finds the variables in the lines of the ANSYS input file. The main program defines the inputmod.txt vector of beginning values x0. There are upper and lower bounds on each variable. The nodal temperature measurements are then extracted by the program from the `temp.lgw` output file, which was first filled with values by ANSYS. For the temperatures of the initial model, this is done once. Then, it is performed each time the MATLAB function iterates. The optimization function is then called by the main program. When the optimization function reads the initial value vector x0, the target objective function is called. The computer code's goal is to change the model variables in the input file to get the lowest temperatures and shortest thermal gradient possible in the nodes. The boundary conditions implemented in ANSYS Mechanical APDL 2020 R2 are shown in Table 1.

Table 1. – Thermal conditions applied.

Condition	Component ID	Value [°C]	Application
Initial Temperature, varies with time	9	210	Part, 1 area
	1-8	40	Cooling channels, 8 areas
Temperature, constant	10	40	Mold, 1 area
	10	23	Boundary, 4 lines

The temperature of 210 [°C] is the temperature-melting approximation, which would be used experimentally in the injection molding machine. With respect to the cooling channels, the water is assumed to have a constant temperature of 40 [°C]

2.2. Materials

The materials used in the simulations were water, for the cooling channels, polypropylene (PP) for the injected part and P20 steel for the mold enclosure. For the cooling channels, represented by circles in fig. 1 (left), water (fluid) was used. Of these materials, only water is assumed to be in the liquid state, i.e., PP and steel are assumed to be in the solid state. The properties of the used materials are shown in Table 2.

Table 2. – Properties of Water, injected material: PP and P20 steel.

Material	Water	PP, with 10% mineral	P20 steel
Application	Cooling channels	Injected part	Mold
Density (kg/m^3)]	998.2	1050	7861
Specific heat [J / (kg.°C)]	4182	1800, Considered constant	502,48
Thermal conductivity [W/ (m.K)]	0.6	0.2, Considered constant	41,5

3. Results

Fig. 4 shows the temperature distributions in the component, generated using ANSYS Mechanical APDL 2020 r2, for both the initial (left) and optimized (right) models at t=6 s.

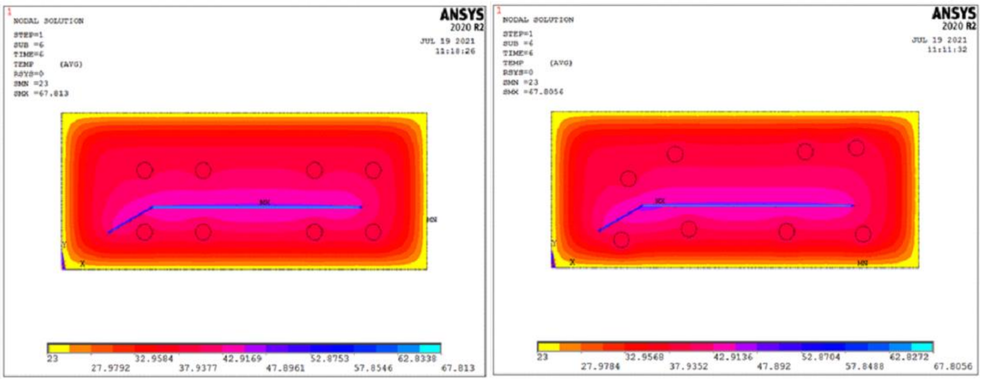

Figure 4. Distribution of temperatures obtained in the initial model (left) and in the optimized model (right), for t=6 s (left).

Fig. 5 shows the temperature distributions in the component, generated using ANSYS Mechanical APDL 2020 r2, for both the initial (left) and optimized (right) models at t=30 s.

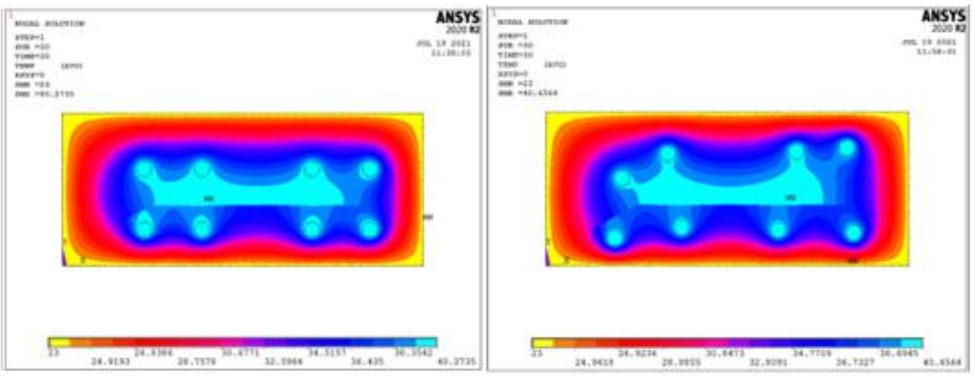

Figure 5. Distribution of temperatures obtained in the initial model (a) and in the optimized model (b), for t=30 s (left).

Fig. 6 shows the comparison of the geometry of initial and optimized models: blue circles show the initial position of the cooling channels, while the circles in gray background represent the cooling channels of the optimized model.

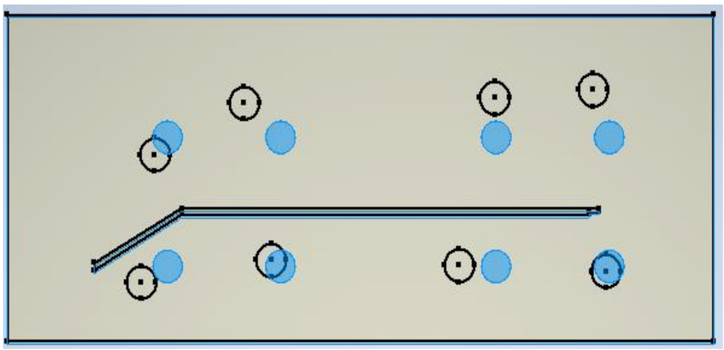

Figure 6. -Initial (in blue color) and optimized channel placement (hollow circles).

4. Conclusions

The main findings of the work are summarized next:

-The thermal behavior of the FEM model is significantly improved by optimization processes. The objective function of the optimized model is 0.5986, a 40% improvement above baseline model, for which the objective function is 1.

-Optimization significantly improves the thermal performance of the final part under free convection thermal conditions.

-The parameters evaluated the optimization code and objective function. ANSYS Mechanical APDL Finite Element Method results allowed thermal evaluation of the initial and optimized models.

-The developed optimization procedure can be applied to any part, in molds of any size and with any number of cooling channels.

-Optimization significantly improves the thermal performance of the analyzed part/component.

-The selected design variables are suitable because their values in the optimized model change significantly from those in the original model.

-In real-world applications and working conditions, a decreased temperature gradient would reduce warping and improve product quality.

-The methodology developed herein may be useful to help design engineers determine the optimal placement of cooling channels.

The invention of a methodology that helps design engineers to predict where cooling channels should be placed in order to improve the quality of manufactured parts is the most important advancement for engineering practice. The methodology used in this study has industrial applications related to injection molding. As part of their work, design engineers may also find this strategy quite helpful in choosing where to put cooling channels. In the future, conformal cooling channels will eventually be able to be produced by additive manufacturing and experimentally tested. The methodology can also be used with molds that differ in terms of ultimate component temperature, number of cooling channels, and mold size.

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Data Availability Statement: The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

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