Topology optimization applied to the design of cooling channels for plastic injection

D A Muñoz¹, J P Arango¹, C González¹, E Puerto² and M Garzón²

¹ Universidad Pontificia Bolivariana, Medellín, Colombia
² PM-Tec S.A.S. Bogotá, Colombia

E-mail: diego.munoz@upb.edu.co

Abstract. In this paper, topology optimization is applied to design cooling channels in a mold of structural steel. The problem was implemented in COMSOL multiphysics, where two physics were coupled, heat transfer and solid mechanics. The optimization objective is to maximize the conduction heat flux in the mold and minimize the deformations when the plastic is injected. In order to find an optimal geometry for this objective, a density-based method was implemented into the nonlinear program (NLP) for which feasible results were found.

1. Introduction
Nowadays, topology optimization is becoming popular as a design method for thermofluid systems [1]. Traditional designs are based in engineering intuition or in trial and error approaches [2]. Topology optimization brings a non-intuitive design for this kind of systems maximizing or minimizing process variables changing geometric configurations, which affect the physical phenomena. The classic shape of cooling channels for plastic molds are horizontal, parallel or straight ducts because the traditional manufacturing machines. However, this design results in inefficient cooling channels for which heat transfer in the mold is not well removed [3]. Additionally, volumetric contraction, superficial depression or warp can appear causing detrimental mechanical and optical properties [4,5]. On the other hand, long cooling periods translate into low process profitability and limited tool life due to risk of thermal fatigue in the mold [6]. For efficient heat transfer and mechanical resistance in the mold, we use topology optimization with a density-based method for the design of the system [2]. In the density-based method, the algorithm determines the optimal material distribution of a material in a given design domain [1]. In this work, the solid material is distributed in order to maximize heat conduction flux and minimize mechanical deformations with the help of a density field, which takes a value of 1 for solid and 0 for void. This paper is organized as follows. In Section 2 the governing equations are presented. In Section 3, the results are discussed. Finally, in Section 4 we summarize the conclusion of this work.

2. Thermo-mechanic model and governing equations

2.1. Heat transfer modeling
The heat transfer in the solid inside the mold is modeled with equation (1), which consists in the Fourier’s law [7]:
\[ k \nabla^2 T + Q = 0 , \]  

(1)

Where \( k \) is the thermal conductivity of the solid material, \( T \) is the temperature, and \( Q \) is the heat generation. The objective function related to the heat transfer is shown in equation (2) [7]:

\[ A = \int_{W} k(\nabla T)^2 \, dW , \]

(2)

Where \( W \) is the design domain, surface or volume. The thermal conductivity is modeled as function of the density variable \( \gamma \). In equation (3), the material interpolation is shown [7]:

\[ k(\gamma) = k_s \gamma^p , \]

(3)

Where \( k_s \) is the thermal conductivity of the solid phase and \( p \) is a penalty factor to improve the convergence of the numerical method. This interpolation allows to decide where the material must appear and where it is not required. The aim is to find the distribution of the control variable to determine the optimal material distribution to improve heat transfer conduction.

2.2. Solid mechanics modeling

The solid mechanics modeling for the deformations in the mold is shown in equation (4), which corresponds to the stresses in the design domain [8]:

\[ \nabla \cdot \mathbf{S} = 0 . \]

(4)

The objective function chosen for solid mechanics is shown in equation (5) [8]:

\[ B = \int_{W_s} W_s \, dW , \]

(5)

Where the variable \( W_s \) is the deformation energy. The density variable was coupled for solid mechanics through the Young’s modulus, \( E_0 \), which measures the ability of a material to stretch or compress [8]:

\[ E(\gamma) = E_0 \gamma^p . \]

(6)

In equation (6), \( \gamma \) is also the control variable and \( p \) is other penalty factor to improve the convergence of the numerical method. In this case, the distribution of design variable is computed to keep a mold structure which is able to reduce deformation when the plastic is injected.

2.3. Objective function

In order to couple both dynamics into a single optimization problem, a multiobjective function for topology optimization is formulated by the sum of equation (2) and (5):

\[ O.F = w_1 A + w_2 B , \]

(7)
Where \( w_1 \) and \( w_2 \) are weight factors, taking values between 0 and 1. Note that if one of the factor takes the value of 1, the other part of the objective function is not optimized, for instance, if \( w_1 = 1 \), only the effect of heat transfer is considered in the topology optimization problem.

3. Results and discussion

In order to validate the problem formulation to design cooling channels in injection plastic molds, two configurations, one 2D and other one 3D, are considered and shown in Figure 1. The 2D system considers a circular chamber where the hot plastic is injected, and the mold will be designed in the square area, while in the 3D system a more complex chamber is considered. The mold material is structural steel, with a thermal conductivity of \( 44.5 \text{ W/mK} \), Young’s modulus of \( 9205 \text{ e Pa} \), and the superficial load in the chamber is \( 100 \text{ bar} \).

In the 2D simulation, a parametric analysis was considered modifying the weight factors in the objective function, as shown in Figure 1. Note that, for high values of \( w_2 \), the fins are designed to decrease deformations without considering the heat transfer [9], as shown in the first row of Figure 2. In contrast, for high values of \( w_1 \), the fins are thinner, which increases the heat transfer area favoring the heat removal, as shown in the third row of Figure 2.

![Figure 1](image)

**Figure 1.** Geometry of chambers and molds for simulation results. (a) 2D geometry with 4908 finite elements. (b) 3D geometry with 64083.

When both weigh factors have the same input, the density profile \( \gamma \) shows “two big arms” and microchannels round this arms, as shown in the second row of Figure 2. The big arms give to the domain the ability of support high pressures when the plastic is injected, while the thin fins gives to the domain the necessary area to have a good heat exchange between the coolant and the designed mold [10]. For each 2D simulation, 4908 finite elements were considered and the computation time was around 200 minutes, using an Intel Xeon processor of \( 2.3 \text{GHz} \ 8\text{GB} \) RAM. The weight factors are listed in Table 1. The optimization method was SNOPT for the resulting large-scale nonlinear program.

The results for the 3D domain are presented in Figure 3, where the complete objective function was considered. The red solid parts of the Figure 3(b) are the cooling channels, and the temperature distribution is shown in Figure 3(a). The designed fins give more heat exchange area between the solid part and the coolant. The obtained topology is the one that allows the best configuration. The coolant is going to pass across the mold removing the heat [11]. The weight factors are listed in Table 1. For the 3D domain, 64083 finite elements were considered and the computation time was around 3 days, using an Intel Xeon processor of \( 2.3\text{GHz} \ 8\text{GB} \) RAM. The optimization method was also SNOPT for the resulting large-scale nonlinear program.
Finally, Table 1 shows the values of the function objective (7) for every case considered in the simulation results.

| Domain            | $w_1$ | $w_2$ | Value  |
|-------------------|-------|-------|--------|
| 2D domain         | 0.5   | 0.5   | 8137.2 |
| Coupled physics   | 0.5   | 0.5   | 755.1  |
| Temperature term  | 1     | 0     | 298.15 |
| Structure term    | 0     | 1     | 4.73e3 |
| 3D domain         | 0.5   | 0.5   | 755.1  |
| Coupled physics   | 0.5   | 0.5   | 755.1  |

**Figure 2.** Parametric analysis for three different sets of weigh factors. (a) simulation results for density profile $\gamma$. (b) simulation results for temperature profile.
4. Conclusions
The design of molds for plastic injection was formulated using the topology optimization method. Two physics, heat transfer and solid mechanics, coupled with topological optimization allowed to improve the traditional mold manufacture, saving raw material to find the best distribution of material, maximizing the heat transfer and minimizing deformation. The application of topology optimization was solved with the SNOPT method implemented in COMSOL multiphysics. The 3D results show the optimal configuration for the cooling channels for a complex injection chamber. This configuration allows to minimize the temperature in the solid domain guaranteeing structural resistance. The 2D simulation allowed to identify the effect of the weight factors in the objective function.

However, a third physic, the fluid dynamics, should be considered to have a most realistic design. Additionally, a more refined mesh must be considered for the 3D simulation to have a smooth design, which can be manufactured by metal 3D printing [12]. A current work is being developed to handle both problems.

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