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CRITICAL REVIEW

Design, simulation and optimization of conformal cooling channels in injection molds: a review

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Abstract

The manufacturing of conformal cooling channels (CCC's) is now easier and more affordable, owing to the recent developments in the field of additive manufacturing. The use of CCC's allows better cooling performances than the conventional (straight-drilled) channels, in the injection molding process. The main reason is that CCC's can follow the pathways of the molded geometry, while the conventional channels, manufactured by traditional machining techniques, are not able to do so. Some of the parameters that can be significantly improved by the use of CCC are cooling time, total injection time, uniform temperature distribution, thermal stress, warpage thickness. However, the design process for CCC is more complex than for conventional channels. Computer-aided engineering (CAE) simulations are important for achieving effective and affordable design. This review article focuses the main aspects related to the use of CCC's in injection molding, as follows: Sect. 1 presents an introduction, which focuses on the most important facts about the topic of this paper. Section 2 presents a comparison between straight cooling channels and conformal cooling channels. In Sect. 3, the theoretical background of injection molding is presented. In Sects. 3 to 7, the manufacturing, design, simulation and optimization of CCC's are presented, respectively. Section 7 is about coupled approaches, in which several systems, methods or techniques are used together for better efficiency.

Keywords Conformal cooling · Injection molding · Computer-Aided Engineering · Design Optimization

1 Introduction

Injection molding is a widely used, advanced manufacturing technology, for low-cost and high reliability manufacturing of engineering parts. The injection molding process comprises several stages:(1) injection, (2) packing, (3) cooling, and (4) ejection [1]. The cooling step (step 3) is the most dominant stage in terms of time, as it takes approximately 73–80% of the entire cycle time [2]. In the classic injection molding process, straight holes are drilled into solid dies, for the cooling of the hot molten plastic inside the cavity to occur. This cooling process takes a major portion of the manufacturing cycle, leading to a high cost of manufacture. To improve the cooling performance and reduce the cooling time, the cooling characteristics of the mold material should be improved. The thermal properties of the material and the cooling channels are two key factors that determine the cooling characteristics [3]. Injection molding is a major part of the plastic industry, consuming a large percentage of the total amount of plastics [3]. Plastic injection molding is a versatile process for obtaining different complex sizes and shapes of high-quality products, ranging from thermoplastic to thermosetting materials, by means of the application of heat and pressure [4]. To obtain a better quality plastic part, the design of the injection molding tooling, especially the design of die core and cavity is very important. It also plays an important role in the economic aspects of the business. Figure 1 shows a generic distribution of time in the total injection molding process.

In Fig. 1, it can be seen that the cooling time has a significant impact on the quality of the manufactured products. At present, with increasing competition in the plastic product business worldwide, the manufacturing cost became a major factor for competitiveness. One way of decreasing the manufacturing cost is to reduce the cycle time of the production process. Several review papers on the topic of conformal cooling

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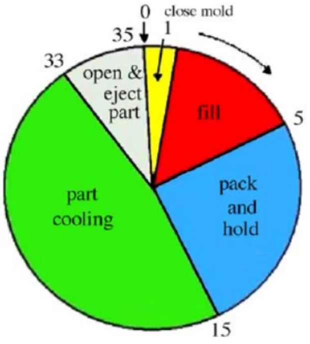


Fig. 1 Typical distribution of times in an injection molding cycle [5]

channels have been found in the literature. For example, the articles [6, 7] present a review, which focuses on aspects related to the design and fabrication of CCC's. Another review paper focus on the design and optimization [8] in injection molds. However, no review article that aims to review both design, optimization, simulation and manufacturing aspects related to CCC's in injection molds was found. Although some knowledge presented in this paper has already been presented in other review papers [6–8], the aims and scope of the present paper, which are related to design optimization of conformal cooling channels, were not found anywhere.

2 Conformal cooling channels vs straight cooling channels

In molds, cooling channels must be employed, as to ensure temperature control and cooling of the molded part. Traditionally, cooling channels were straight—drilled by subtractive manufacturing methods. In traditional methods, CCC's were easily and economically manufactured. However, serious limitations are present regarding the geometry of the CCC's, which can limit the efficiency of the injection molding process. In fact, straight-drilled channels are not able to originate optimal cooling, because of the cavity shape, as to avoid any interference between the cavity and channel, as well as by drilling process limits their layouts. In the latter case, only straight holes can be drilled. Due to its inherent limitations, straight-drilled circular channels are not able to provide efficient cooling and pose limitations for design optimization of the cooling channels, due to the limitations in the geometry. Furthermore, the injected part can only be ejected from the mold when the cavity temperature entirely cools down to below the ejection temperature. Therefore, the cooling time depends on the highest temperature point in the cavity and on its local cooling rate. Figure 2 shows a comparison of a straight cooling channels and a conformal cooling channels.

In the case of a straight-drilled channel, such as the one shown in Fig. 2a [6], the distance between the straight channels and the curved surface of the cavity varies along the channel. This causes temperature gradients and may affect the quality of the molded part by means of differential shrinkage and warpage [10]. In the situation shown in Fig. 2a, the cooling time is determined by the longest distance of the cooling channel to the mold cavity, which is the distance at the sides. If conformal cooling channels are used, the critical distance (the longest) can be significantly reduced. This will result in a reduction of the temperature gradient and in a maximization of the quality of the injected part, including reducing warpage and better compliance with geometric tolerances that were determined in the design stage of the component. Therefore, cooling efficiency is not as high as desired when using straight-drilled cooling molds. Figure 3. shows a comparison between straight-drilled cooling channels and CC channels.

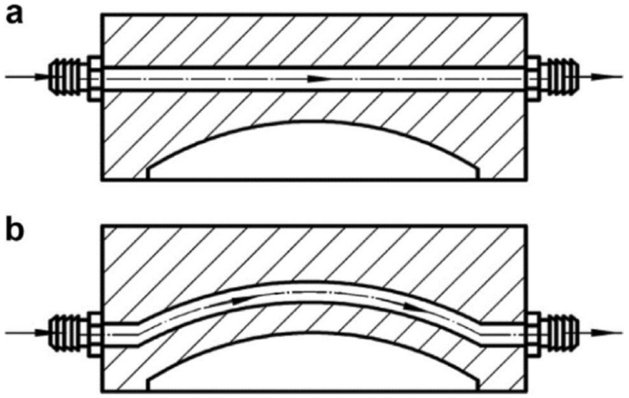


Fig. 2 Representation of cooling channels: (**a**) straight-drilled and (**b**) conformal [9] in [6]

Using CCC's is a good option for this purpose. CCC's have the potential of improving the performance of the molding dies, allowing to achieve a more uniform and faster cooling. Moreover, less warping and fewer defects occur, as channels with optimal shape can be used using additive manufacturing [5]. The thermal properties of the material and the cooling channels are two key factors that determine the cooling characteristics [3]. Once the designer decides the material of the mold, performance improvement regarding the thermal properties of the material becomes infeasible. However, the design of cooling channels can be modified and optimized, obtaining better cooling performance and lower cycle time. The layout of cooling channels in the mold may significantly affect the final performance of molded parts. For this reason, different cooling path designs in both cavity and core inserts have been designed. They are named conformal cooling channels (CCC's). In a CCC-based design, the channel path follows the contours of the injected geometry in the mold. CCC's present several advantages over conventional (straight) cooling channels, such as better

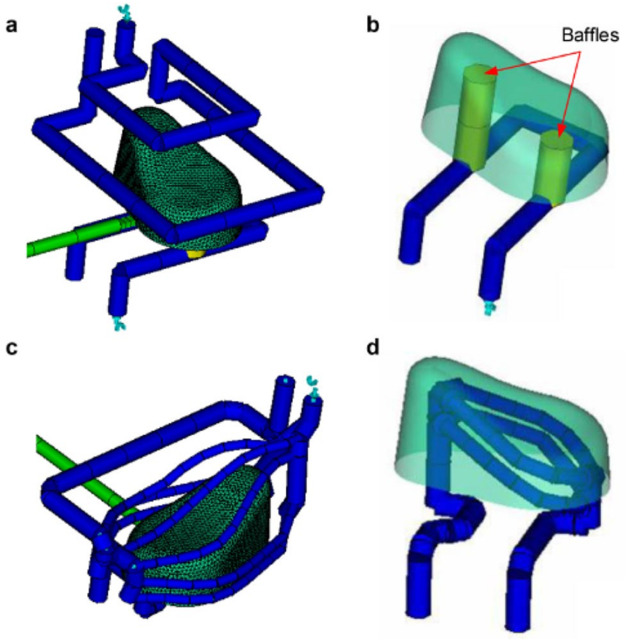


Fig. 3 Comparison of straight-drilled cooling channels and CC channels: straight-drilled cooling channels in cavity insert (**a**) and in core insert (**b**), and CC channels in cavity insert (**c**) and in core insert (**d**) (Adapted from [16], in [5])

surface temperature uniformity, fewer distortions, and steady cooling performance. These improvements make the CCC more efficient and consistent compared with the conventional channels. Other advantages of CCC designs are the reduction of the cooling time and the dependence of the decrement rate of the time on the geometry shape in the mold [12]. Different geometries with unique CCC designs presented a reduction in cycle time that varies between 15 and 50% [12–14]. It was already shown that the optimal design of CCC is important to produce parts quickly, efficiently and reliably. If design optimization is allied to a proper design strategy, significant improvements can be further obtained.

3 Theoretical background

The manufacturing of CCC shapes is often not possible using traditional machining techniques. Therefore, additive manufacturing technologies are used during its manufacturing process [1, 15, 16] in [6]. Recent developments in the field of 3D printing technology made the CCC manufacturing process more affordable and commercial. A transient heat transfer process can describe the injection molding. However, it can be assumed steady, (considering the average mold temperature as constant), after several cycles in the molding process. It is also assumed that the heat transfer balance occurs when the heat transfer rate (heat flux) from the molten polymer to the mold material, becomes equal to the heat transfer from the mold material to the coolant and ambient air. A simplified illustration of heat fluxes is shown in Fig. 4.

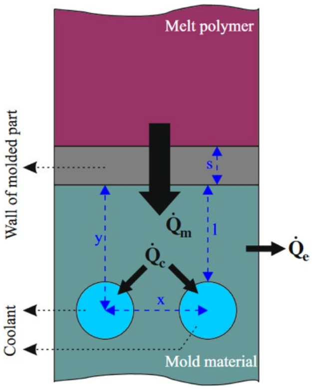


Fig. 4 Simplified diagram showing the heat fluxes [7]

The balanced equation is defined in Eq. (1) [17] in [7]

$$Q_m + Q_c + Q_e = 0 \tag{1}$$

Conduction, convection, and radiation are three different heat transfer mechanisms in the process of injection molding. The heat transfer rate (heat flux) from the molten polymer to the mold material and from the heat flux inside the mold material, are governed by the conductive heat transfer mechanism. The heat flux from the mold material to the coolant is calculated as convective heat transfer. Since during the injection molding process, the temperature of the mold material increases, the surface temperature of the mold material becomes higher than the ambient air. Therefore, the heat flux from the mold material to the ambient air occurs via both radiation and convection. Equations (2)–(4) define analytically the conductive, convective, and radiative heat transfer rates, respectively [18, 19]

$$Q_{cond} = \int_0^{t_{cycle}} \frac{\lambda}{\delta}.A.\Delta T.dt \tag{2}$$

$$Q_{conv} = \int_0^{t_{cycle}} \alpha.A.\Delta T.dt \tag{3}$$

$$Q_{rad} = \int_0^{t_{cycle}} \sigma_0.\varepsilon.A.\Delta T^4.dt \tag{4}$$

where λ and δ are the thermal conductivity and thickness in Eq. (2), respectively; α is the heat transfer coefficient in Eq. (3); and $\sigma 0$ and ε are the Stefan–Boltzmann constant and emissivity in Eq. (4). Temperature and cross-section area are denoted by

T and A, respectively. To improve the cooling performance in CCC's, the aim is usually to maximize Q_c during the cooling process. The maximum value of Q_c means the minimum value of Q_e, i.e., the heat loss through the mold material boundary. In some applications, the Q_e obtained is less than 5% of the Q_m. Thus, the Q_e is negligible and the mold material boundary is assumed to be adiabatic [20, 21] in [6]. When the Q_e is neglected, Eq. (1) can be rewritten as Eq. (5) [6]:

$$Q_m + Q_c = 0 \tag{5}$$

Rao et al. [22] define the Q_m as in Eq. (6),

$$Q_m = 10^{-3}[(T_p - T_e)C_p + i_p]\rho_p \frac{s}{2}x \tag{6}$$

where Tp and Te are the molten polymer temperature and the ejection (demolding) temperature, cp is the specific heat of polymer, ip is the latent heat, ρp is the molten polymer density, s is the molded part thickness, and x is the pitch difference between cooling channels:

Also, Q_c is given in Eq. (7) [7]:

$$Q_c = 10^{-3}.t_k.\left(\frac{1}{\lambda_m.SH} + \frac{1}{\alpha.10^{-3}.d.\pi}\right)^{-1}.(T_{mw} - T_c) \tag{7}$$

where tk is the cooling time, λm is the thermal conductivity of mold material, Sh is the shape factor of the cooling channel geometry, d is the cooling channel diameter, Tmw is the wall temperature of mold material, and Tc is the supplied temperature of the coolant.

All the parameters in Eqs. (6) and (7) are known or assumed during the process, except the parameters tk and Tmw [7].

An important aspect of the injection molding process is the mold filling stage. If one considers that, during the molding filling stage, the mass flow rate is kept constant, and then the injection pressure must increase with time. If one considers the effect of viscous dissipation, then non-uniform temperature might be obtained in the molten polymer. Because the viscosity of the molten polymer is highly dependent on the shear rate and of the temperature, the axial momentum equations and the energy equations can be coupled and should be simultaneously solved. Half of the physical domain is represented in Fig. 5.

The considered computational domain is the mold cavity. The axial momentum equation can be represented by [23]:

$$\frac{\partial p}{\partial z} = \frac{1}{r}\frac{\partial}{\partial r}(r\tau_{rz}) \tag{8}$$

Where

$$\tau_{rz} = \mu\frac{\partial V_z}{\partial r} \tag{9}$$

And

$$\mu = m\left|\frac{V_z}{\partial r}\right|^{n-1} e^{-b(T-T_{ref})} \tag{10}$$

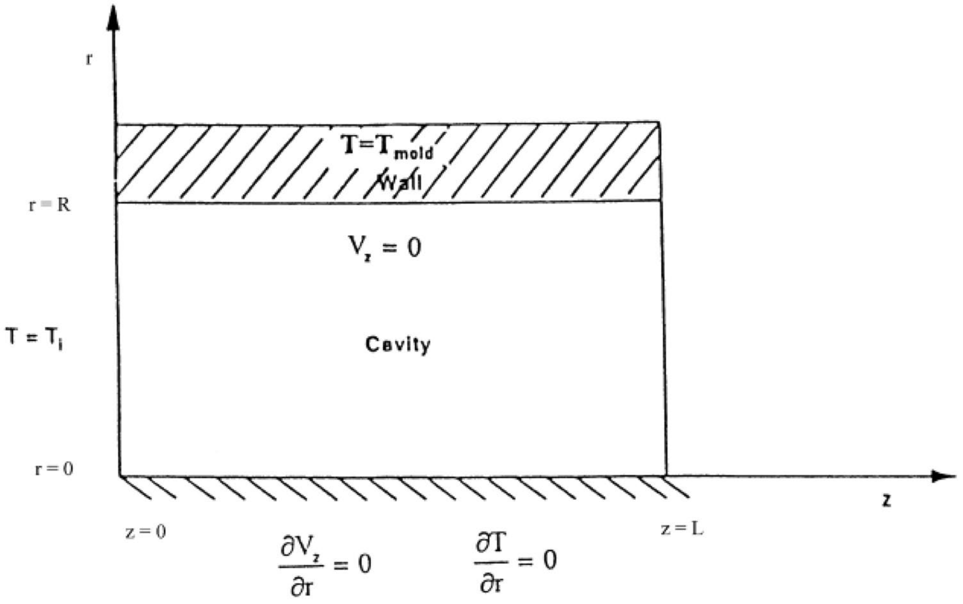
In the case $\frac{\partial V_z}{\partial r} = 0$, then $\mu = \mu_0 e^{-b(T-T_{ref})}$

μ_0 is the zero-shear rate viscosity and $T_{ref} = 160°$.

The Energy equation, neglecting the effect of axial conduction, can be expressed by [23]:

$$\rho C_p V_z \frac{\partial T}{\partial z} = k\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + \mu\left(\frac{\partial V_z}{\partial r}\right)^2 \tag{11}$$

Fig. 5 Half of the physical domain for non-isothermal filling [23]



The phenomenon of heat transfer at the mold cavity-molten polymer interface is complex. It depends on several factors, such as surface roughness, geometry, mold coating and polymer composition.

The condition usually considered under the conditions of contact heat transfer rate is the one that considers that the heat flux must be conserved across the discontinuity [24]:

$$q^{||} = h(T_{melt} - T_{mould}) \tag{12}$$

The thermal contact resistance coefficient, h, is experimentally determined [24].

After the temperature and velocity profiles at any location of the z-axis are obtained, the average melt temperature can be calculated, using the concept of mixing-cup temperature [25]. The respective equation (Eq. (13)), is shown below.

$$T_{avg} = \frac{\int_0^R \rho.2.\pi.r.dr.V_z.C_p.T}{\int_0^R \rho.2.\eta.r.dr.V_z.C_p} \tag{13}$$

In injection molding, the theoretical aspects related to heat transfer are very important. One important equation is energy balance. Let us consider the active portion of the mold. An energy balance can be written, as in Eq. (14) [26]:

$$\rho_m C_m l_m \frac{dT_m}{dt} + \frac{h\pi DK_m}{2K_m W + h\pi Dl_m} = \frac{\rho_p C_p l_p (T_{melt} - T_{eject})}{t_{cycle}} \tag{14}$$

The active portion of the mold is considered to be the zone located between the surface and the cooling lines. The first term of Eq. (14) represents the thermal mass of the tool, as well as the build-up of heat with increasing tool temperature. The second term in Eq. (14) represents the heat transfer by conduction through the mold, and then convecting into the cooling fluid. The right-hand side of Eq. (14) represents the heat source. The heat source is considered to be the cooling down of the plastic. The first-order ordinary differential equation, represented by Eq. (14), has a solution in the form of Eq. (15) [26]:

$$T_m(t) = T_{m0} + (T_{ms} - T_{m0})e^{\frac{-t}{\tau}} \tag{15}$$

where T_{ms} is the cycle-averaged mold temperature at steady-state and τ is the time constant of the system.

Equations (16) and (17) give the expressions for cycle averaged mold temperature and the time constant, respectively. The definition of conformal cooling (CC) can now be formally written, by requiring τ to be lesser or equal to one injection cycle time [26]:

$$T_{ms} = T_c + \frac{\rho_p C_p l_p (2K_m W + h\pi Dl_m)(T_{melt} - T_{eject})}{h\pi DK_m t_{cycle}} \tag{16}$$

$$\tau = \frac{\rho_m C_m l_m (h\pi Dl_m + 2K^m W)}{h\pi DK^m} \tag{17}$$

If one considers the heat transfer to have no losses, the expression for the time constant, represented by Eq. (17), reduces to the form shown in Eq. (18)[26]:

$$\tau = \frac{\rho_m C_m l_m^2}{K_m} \tag{18}$$

Equation (18) considers the case where the heat transfer coefficient is infinity, which is equivalent to consider the heat transfer to the molten fluid to be 100% efficient [26].

4 Manufacturing of CCC

In conventional cooling channels, traditional machining techniques, such as drilling, boring tools and electrical discharge machining (EDM), create the paths. These are straight channels in the mold, usually in the shape of hollow cylinders. The main design limitations of the conventional channels are related to the outer perimeters of the mold and the cavity inserts. Conventional cooling channels can provide satisfying cooling time and performance for simple geometries. Nevertheless, undesired occurrences, such as higher cooling time, higher non-uniformity and warpage, are prone to happen. Defects are more likely to occur in complex geometries, due to the straight pathways not being able to achieve efficient cooling through the entire mold cavity [27–29] in [6]. Ferreira and Mateus studied rapid soft tooling for plastic injection molding. The main purpose of that study was to propose several original approaches for the integration of advanced processing technologies on injection molding [30].

CCC's were also studied by Meckley and Edwards. Their study aimed to reduce cooling time and to increase part quality. The authors compared the differences in the mold and melt temperatures between CCC and traditional straight cooling channels. The materials used for injection were high-density polyethylene and polycarbonate [11]. Hopkins and Dickens demonstrated the effect of using CCC in both heating and cooling of a single injection molding tool. The results of the study demonstrated the potential of 3D printing technology to achieve successful manufacture of complex geometries [31]. One of the advantages of using conformal heating or cooling channels, manufactured by rapid tooling methods, is the improvement of thermal control. An important problem that may arise in the manufacture of such tooling is the difficulty of sealing the channels quickly and inexpensively. In 2008, Yoo performed research on that topic [32]. Altaf et al. presented a technique for manufacturing CCC, using rapid prototyping techniques. The cooling channels were built in an aluminum filled epoxy mold. This study provided insights into the manufacturing method of conformal channels. This type of channels is not possible to be manufactured by traditional drilling or machining process [33].

5 Design of CCC

The geometry of conventional cooling channels is shown in Fig. 6 (left) and of conformal cooling channels (CCC's), is shown in Fig. 6 (right).

The use of cooling channels conformal to the molding cavity improves the control of mold temperature and part dimensions. This has been reported by a research group at MIT in the 1990s [26]. Mold surface temperature, pressure drop, mold material strength, were considered as design parameters in their study. Dang and Park adopted an algorithm for obtaining the temperature distribution through molding thickness and presented a conformal channel with an array of baffles, for obtaining uniform cooling over the whole free-form surface of molded parts [9]. In [35], the authors presented U-shaped milled groove conformal channels and proposed an optimization process, to get an optimal conformal channels configuration. The authors succeeded in providing insights regarding the use of CCC's to provide more uniform cooling and reducing the cycle time in the injection molding process. In 2014, Khan et al. studied the comparative effect of conventional, series, parallel and additive parallel cooling channels. The study was focused on cooling time, total cycle time, volumetric shrinkage and temperature variance. AMI software was used [36]. In 2011, Wang et al. presented an automatic method for the design of CC circuits. The work was performed by establishing a relationship between CC and the shape of the final plastic part [37]. Choi et al. confirm the higher degree of freedom of CCC's by performing design for application in 3D printing, and concentrating on a principle of branching law. The goal was to improve the cooling efficiency in injection molds. The authors used an algorithm based on a Voronoi diagram and on a binary branching algorithm, in order to create the design of CCC's [38]. A similar technique was also adopted by Park and Pham. The authors designed cooling channels for individual surfaces. Then, the authors combined them to form an overall CCC system for the whole part [39]. Two years later, the authors designed CCC for an automotive part, using the algorithm they had developed in their previous studies. In this article, the authors performed an optimization to minimize the cooling time with boundaries ensuring a realistic design for the cooling system [40]. Wang et al. presented an approach whose aim was to generate spiral channels for CC using an algorithm. Their algorithm was used to generate evenly distributed spiral channels in the injection mold, with the help of boundary distance maps [41]. In 2011 Au and Yu presented a methodology named visibility-based cooling channel generation for automatic preliminary cooling channel design. This is a more geometric and theoretical method, rather than a method adopted in practical scenario [42]. After that, in 2017, the authors presented a modification of the cooling channel distance-based on adjustment direction and adjustment amount [43]. A new methodology named Morpho Cooling was proposed by Agazzi et al. for the design of cooling channels in injection molds. This technique provided better results in cooling in terms of higher uniformity of temperature and lesser part warpage [44].

6 Simulation of CCC

There has been much research in the field of design and modelling of CCC's in injection molding tooling. Different simulation packages have been used to analyze the tool and channel designs. In 2005, Moldflow analysis in

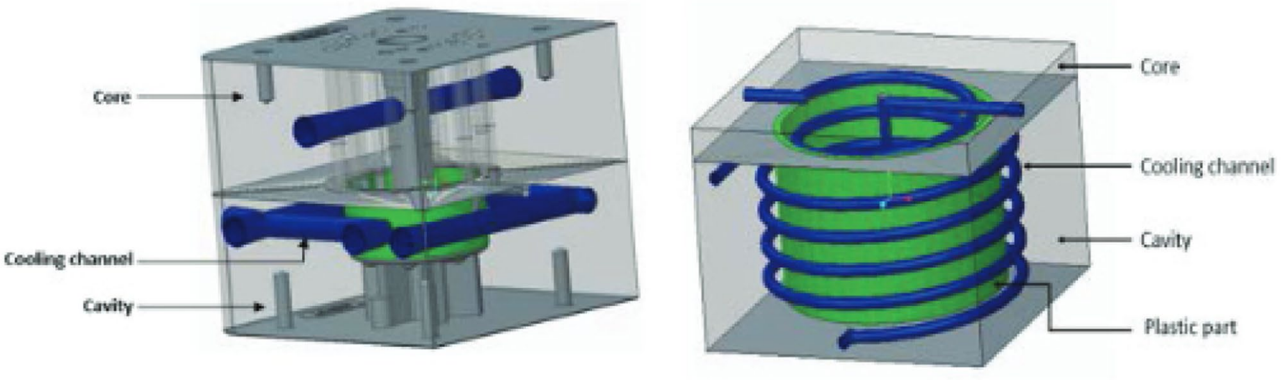


Fig. 6 conventional cooling channels (left) and CCC's [34]

I-DEAS™ was used by Dimla et al., to find the best position of the runner [45]. ABM Saifullah and SH Masood analyzed 'part cooling time' using the ANSYS thermal analysis software [46]. In 2009, the same research group used the MPI simulation software for the analysis of parts and compared results for conventional and square section CCC; concluding conformal channels render 38% less cooling time than conventional ones [47]. Gloinn et al. from Ireland performed FEM analysis to determine mold temperature using ABS polymer as molten material and cooling water inlet [48]. Another study was conducted, in 2007, using Moldflow Plastic Insight 3.1 to research the thermal effects of cooling channel design on the injection molding process [49]. The authors proposed a novel scaffold for the design of uniform CC. Using the same simulation software, Wang et al. verified the advantages of a cooling circuit; modelling part temperature only [50]. In 2017, the comparative effect of conventional, series, parallel and additive parallel cooling channels was studied by Khan et al. regarding cooling time, total cycle time, volumetric shrinkage and temperature variance using AMI software [51]. Though there have been many studies regarding the analysis of CCC, the number of studies that are focused on the design parameters of CCC's for several types of designs is very limited. Most of the designs have been applied based on the designers' experiences. According to the author's knowledge, any blend of any type, as well as the match between the design parameters, cross-section size and the respective experimental analyses, is rare. Nevertheless, some preliminary information could be gathered from the literature that renders a basis for further research in this project. For example, a simple relationship between four parameters, for the design of CCC using additive manufacturing is found by Mayer [52]. Previous literature shows that the use of different cross-section for channels other than circular might provide better cooling efficiency. Some research has been conducted regarding the analyses of cooling channels with variable distance, for application in molding tools [43]. For redesigning the existing model, originally built with straight channels, with CCC's, the authors performed a study in which a comprehensive solution for conformal channel design was derived. Parameters such as channel diameter, pitch distance and wall to channel distance were considered by the authors.

7 Optimization of CCC

Many methodologies and algorithms for designing CCC'S have been proposed by researchers with the aim of obtaining intelligent and optimal design of CC systems [53–55]. For that purpose, several cooling channel layouts such as: spiral [56], zigzag [57], profiled [58], and vascularized [59] have been proposed. In the optimization-based studies, several optimization approaches have been applied. Some examples of optimization strategies are simulated annealing (SA) [27], Powell's conjugate direction [28], Evolutionary algorithms [60, 61], response surface methodology [60], and CONMIN [17] (constrained minimization approach developed in [62]. In terms of analysis, transient thermal analysis via boundary element method was preferred for improving conventional cooling performance [17, 63–65]. The optimization procedure can be based on a single objective of a system parameter. Different optimization strategies can be used, such as genetic algorithms, surface response methodologies, classical constrained minimization approaches, and neural networks. Multiobjective optimization procedures can also be used. In that case, the procedures are usually carried out by combining different objective functions, using different algorithms. At the end of the optimization step, the optimal design of the designed model is obtained, as well as a measure of the model's performance. After the optimization step, the second CAE step is applied. Computational analyses are carried out outside the first CAE step, to evaluate the thermo-mechanical performance of the optimal design, before the experimental studies [18]. Several optimization algorithms were developed, to improve the design of conformal cooling channels [6, 27, 66, 67]. These algorithms are illustrated in Figs. 7–10. In the work [27], the SA algorithm is used to search for the optimal control cooling parameters. This article uses the cooling system as the major control parameter to achieve an optimal design for a simulated injection-mold model. In this investigation, the cooling system parameters, such as cooling channel diameters, cooling channel spacing and cooling line equations are studied. The goal was to accurately predict product performance, in terms of warpage, employing the developed abductive network model. In the first place, the injection-mold part-line of the parameter equation is formulated utilizing the abductive network method. The intention was to limit the number of parameters in the cooling system. The optimal parameters of the cooling system can then be achieved utilizing a SA optimization algorithm, using a performance index. The ultimate goal was to obtain perfect parts. Figure 7 shows the diagram in the SA search.

First, the algorithm is given an initial temperature (Ts) and a final temperature (Te), and a set of initial process vectors (Ox). The objective function (obj) is defined based on the injection parameter performance index. The objective function can be recalculated utilizing all the different perturbed compensation parameters. If the value of the new objective function decreases in relation to its previous value, the perturbed process parameters are accepted as the new process parameters and the temperature slightly decreases in scale. The procedure is repeated until the temperature Ti approaches 0, which shows the lowering

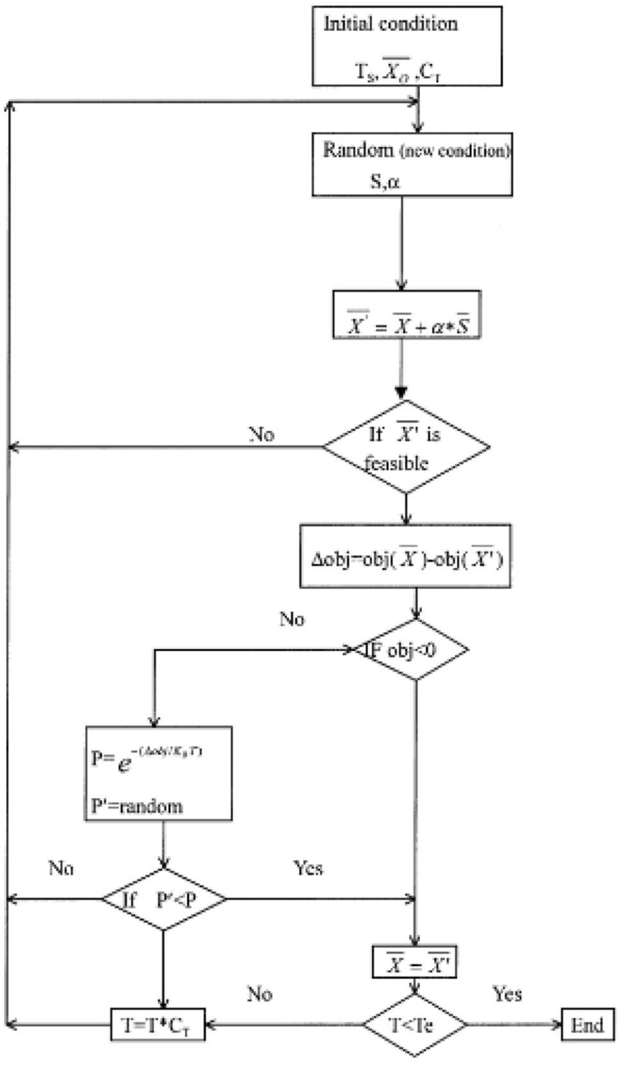


Fig. 7 Diagram of the optimization algorithm proposed in [27]

in energy to the lowest state. Once the model of the relationship among functions of the cooling system parameters and the warpage of the product is established, this model can be used to find the optimal cooling parameter to secure the minimum warpage. The optimal parameter of the process can be obtained by using the objective function to serve as a starting point. The cooling system has an important role in the injection molding process in terms of not only productivity and quality but also mold-making cost. In this paper, a CCC with an array of baffles is proposed. The goal is to get uniform cooling over the entire free-form surface of produced parts. A new algorithm for obtaining temperature distribution utilizing molding thickness, mold surface temperature and cooling time was presented in [9] and is shown in Fig. 8.

In [9], the relationship between the configuration of the cooling channels, the process parameters, the mold material, the mold thickness and the temperature distribution in the mold for a given polymer is expressed by a system of approximate equations. This relationship was obtained by the experimental design and response surface method based on a suitable physical mathematical model, finite difference method and numerical simulation. By applying this approximate mathematical relationship, the optimization process to achieve the target mold temperature, uniform temperature distribution and minimize the cooling time becomes more effective. Two case studies were conducted to test and validate the proposed method. The results show that the present approach improves the cooling performance and facilitates the mold design process compared to the trial and error-based method. In the paper [68], an artificial neural network is coupled with a genetic algorithm (ANN/GA). A new method is proposed, whose aim is to optimize the injection molding process. In this method, a back propagation (BP) neural network model is developed. The aim was to map the complex nonlinear relationship between process conditions

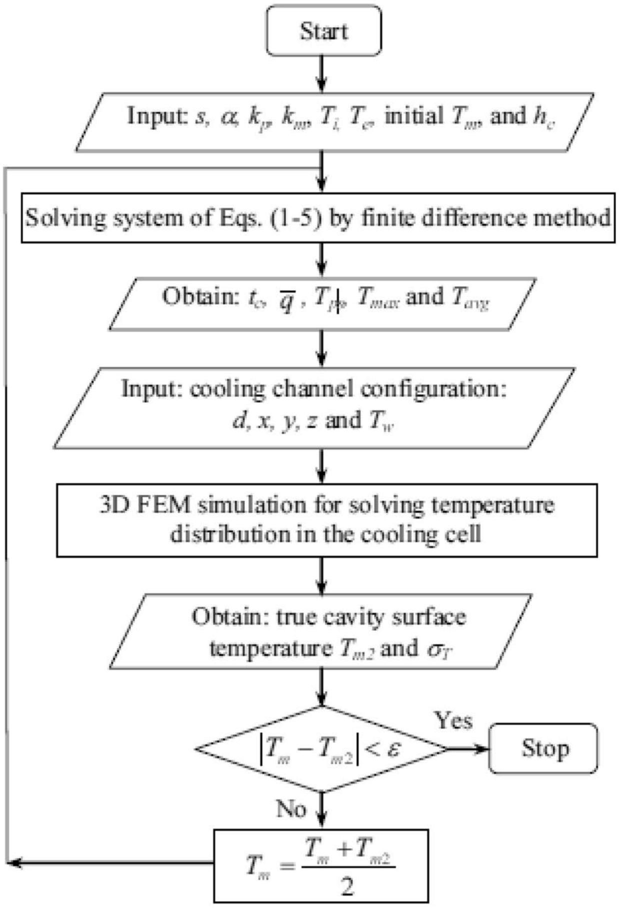


Fig. 8 Optimization algorithm proposed in [9]

and quality indexes of the manufactured parts. A genetic algorithm (GA) is used in the optimization of the process conditions, using a fitness function based on an ANN model. The combining ANN/GA method is used in the process optimization for an industrial part, with the aim of improving the quality index of the variation in volumetric shrinkage of the part. The outline of the coupled ANN/GA optimization algorithm is illustrated in Fig. 9.

In the developed algorithm, an initial population is randomly generated. The fitness function, which is based on the ANN model, is used to calculate the fitness for all the individuals of the initial generation. Then, the processes of selection, crossover and mutation are used to obtain a new generation. The process described in the previous sentence is repeated until the maximum number of generations is achieved or population convergence is achieved. The program for the optimization of the injection molding process was developed in the commercial software MATLAB. The purpose of the work [69] was to optimize the layout of the heating/cooling channels for rapid heat cycle molding with hot medium heating and coolant cooling by using response surface methodology and optimization technique. The optimization problem in [69] was solved by coupling the developed math models with the particle swarm optimization (PSO) method. The diagram of the optimization design is shown in Fig. 10.

The equations of energy in the heating and cooling processes of RHCM were reduced. Based on the equations of energy, several measurements relating to the heating/cooling media, mold structure and mold material were presented to improve the heating/cooling efficiencies. The layout of the heating/cooling channels in the mold has a great effect on the heating/cooling efficiency, temperature uniformity and mold strength. An efficient optimization methodology coupling RSM and PSO was introduced to optimize the layout of the heating/cooling channels. The half distance between the walls of two adjacent channels, the distance from the wall of the channel to the cavity surface and the diameter of the channel were selected as the design variables to describe the layout and size of the heating/ cooling channels.

8 Coupled methodologies

The additive manufacturing technologies are co-operated by computer-aided engineering (CAE) tools during both the design and simulation stage. Integrated CAE and additive manufacturing processes are also able to make the optimization of the injection molding process easier. The design of CCC's is considered to be a complex heat transfer problem with transient and 3D design conditions. For this reason, a large number of design parameters exist. The

Fig. 9 Diagram of combining ANN/GA optimization. [68]

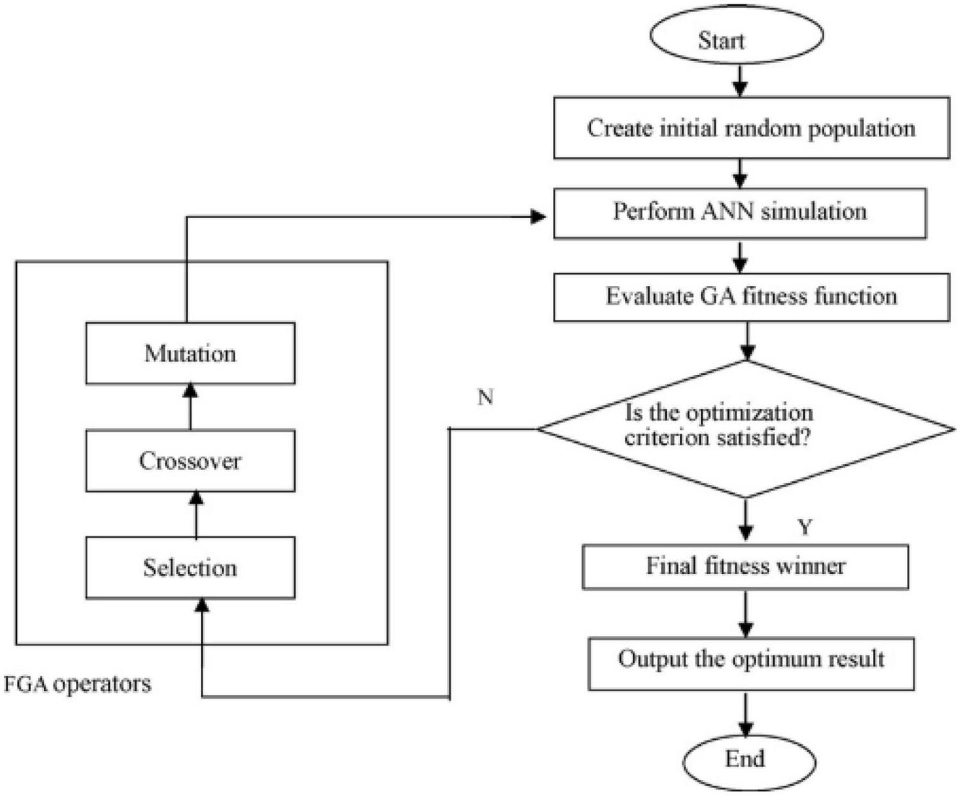
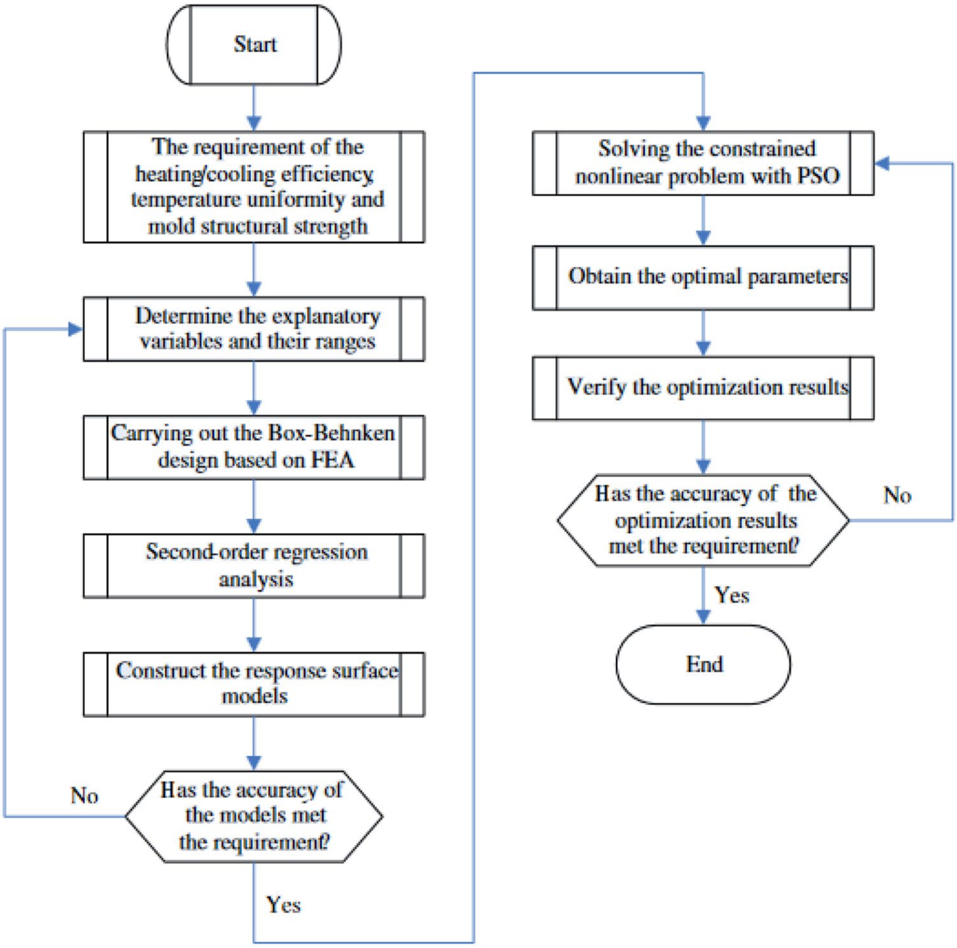


Fig. 10 Diagram of the optimization procedure introduced by [69]



design parameters can be evaluated via computational, thermal and mechanical simulation tools, even in large number, but it significantly increases computational processing power. The main consequences are higher computational time and costs. To decrease the drawbacks related to the cost and time of the computational processes, an analytical heat transfer model is applied to the design stage of the CCC's. The considered analytical model is usually based on the 1D heat transfer model. This model can provide brief performance outputs regarding basic insights upon the initial assessments. A simplified flow of the additive manufacturing-based CCC manufacturing is illustrated in Fig. 11 [7].

The main stages of the CAE-based CCC studies can be explained as follows: An analytical model is created for the geometry. In this step, the channel parameters, coolant characteristics, limitations, and other variables are determined in detail. Then, the 3D design of the created geometry is performed in a computer-aided design (CAD) software. The built model is individually exported for the computational thermo-mechanical analysis stage. Computational thermal simulations study the fluid dynamics and heat transfer on the designed geometry, intending to maximize the cooling performance, while the computational mechanics' simulations mostly focus on stress analysis. Mesh generation, system setup, simulation, and results are completed in both computational processes. It must be noted that both computational thermo-mechanical processes are run in parallel because all the outcomes (fluid dynamics, heat transfer, and stress) strongly affect one another. After the parallel simulations run, the first decision is made in the CAE step, before the optimization stage. The results of the computational analyses reveal findings regarding the overall thermo-mechanical performances. If the obtained results are not good enough for the designer (engineer or operator), the CAE step is redone to the 3D design part until satisfying results are obtained. The next step is the second decision-making. This step is done in the optimization step, which aims to get the optimal design for the CCC's [70] in [7]. The first experiments are done as lab-scale. These are started after the computational results are obtained and the materials are prepared. The lab-

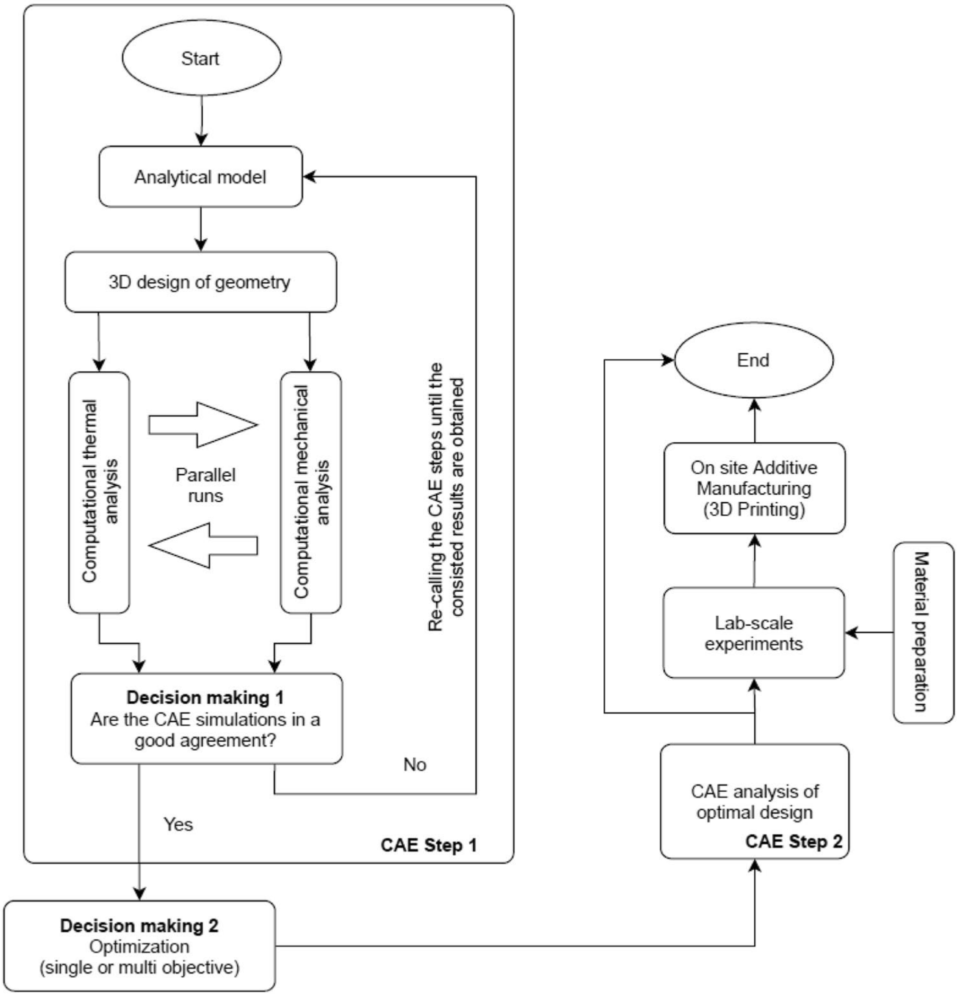


Fig. 11 The design, analysis, and optimization stages of the CCC manufacturing process [7]

scale experiments give insights regarding CCC design. This allows the missing points to be fixed employing the experiments, before the on-site real-scale additive manufacturing. The knowledge from the lab-scale experiments and the computational simulations allows performing reliable on-site real-scale manufacturing of the built design utilizing additive manufacturing technologies. The final step of the CCC manufacturing process is on-site additive manufacturing. As explained in detail, the CCC manufacturing process includes CAE and additive manufacturing processes. Both CAE and additive manufacturing are needed for reliable onsite 3D printing processes. Therefore, it can be inferred that the CAE constitutes the design and analysis stage of CCC, while additive manufacturing is about the manufacture of the CCC models via efficient and reliable methods [7].

In [71], a novel framework for the design optimization of dies with CC, is proposed. The additive manufacturing method was used. Figure 12 shows the framework used in [71].

In [71], the proposed system consists of three modules, namely process and material modeling, multiscale topology optimization, and experimental testing, calibration, and validation. An advanced numerical simulation was implemented for a typical tool with conformal cooling channels to predict cycle time, part quality and tool life. A multi-level thermo-mechanical topology optimization algorithm was developed to minimize the weight of the mold and improve its thermal performance. The technique was implemented on simple molds for validation before being applied to tools with conformal cooling in manufacturing. Finally, material modeling was performed using simulations and design of experiments to determine the material properties and their variations.

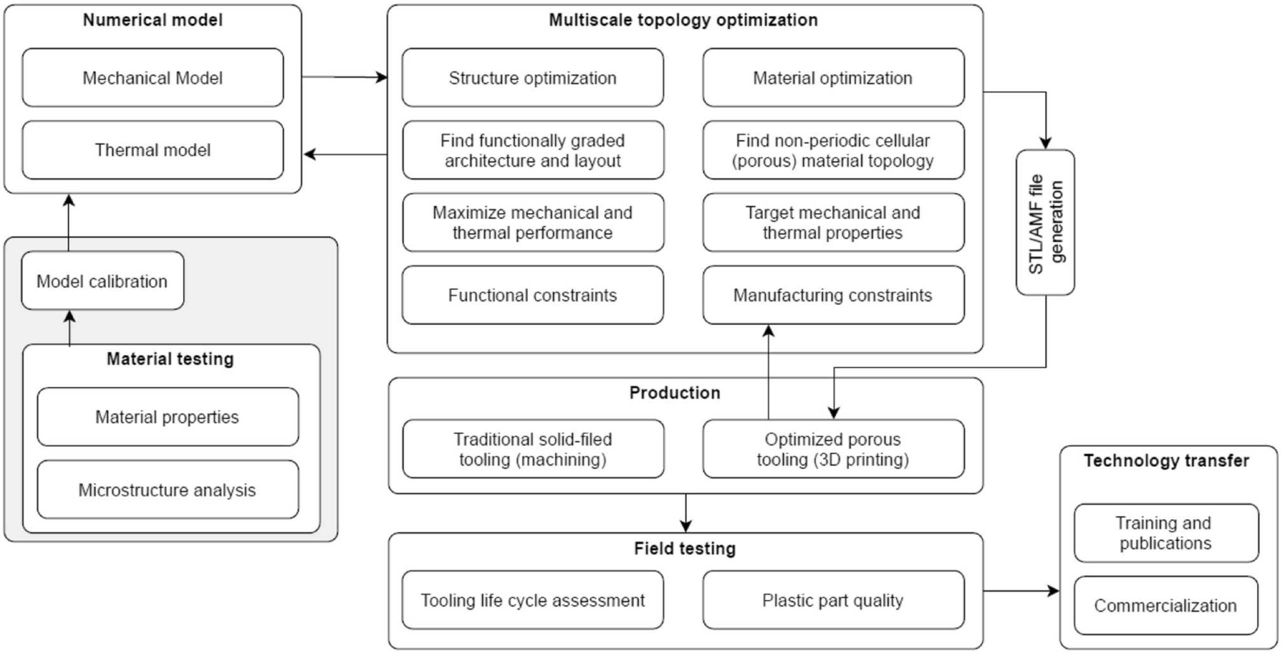


Fig. 12 Framework that couples numerical modelling, multiscale topology optimization and production [71].

9 Conclusions

The presented review study focused on the main aspects of CCC's for applications in injection molds.

In Sect. 1, an introduction, which focuses on the most important facts about the topic of this paper, is presented. The main facts about injection molding that explains its importance are explained. A brief description of the injection cycle is also presented. The importance of the use of CCC's is stated. In Sect. 2 the theoretical background of injection molding is presented. This section focuses on heat transfer phenomena for the filling stage of the injection molding. It was also presented the equation of Williams-Landel-Ferry (WLF), for the typical type behavior of molten polymeric in injection molding: Non-Newtonian fluid. It was considered that the behavior of the fluid on the mold filling stage was described by a power law. The equations regarding heat transfer are applied to injection molding, having as basis the principle of energy conservation. Section 3 presents the manufacturing of CCC's. In Sect. 3, the influence of the CCC's on several aspects of injection molds, are presented. In Sect. 4, a comparison between traditional cooling channels and CCC's, with the advantages and problems of each type of cooling channels, is presented. The manufacturing of CCC's by additive manufacturing is of special focus in this section. Most of the studies cited in Sect. 3 are focused on the manufacturing of CCC's and the optimization or determination of optimum processing parameters. The aim is to get a final plastic part with the highest quality possible, to avoid defects as much as possible. Section 4 presents the design of CCC's, with the main focus on improving the injection molding process, having in mind specific objectives, such as reduction of cooling time. The difference between Sects. 3 and 4 is that in Sect. 3, special focus is placed in the manufacturing, while in Sect. 4, the focus is placed on the design of CCC's. Section 5 presents the simulation of injection molds, using computational software. The main software used was MPI simulation software, Moldflow Plastic Insight 3.1 and Moldflow analysis in I-DEAS™. Section 6 presents optimization algorithms for CCC-related optimization in this section, four optimization algorithms for CCC-related optimization are presented. The types of optimization analyzed are: SA, RSM, ANN/GA and PSO. Section 7 is about coupled approaches, in which several systems, methods or techniques are used together for better efficiency. This section is mainly about the coupling of CAD/CAE and FEM/external software. As concluding remarks, CCC's are great solutions for injection molding applications. Although some problems may occur, especially for more complex geometries, there is a significant number of studies that aimed at minimizing the problems occurred during the manufacture of plastic parts. This review aims to be useful as a bibliographic review for researchers working in research and development projects in the topic of CCC's for injection molding. It can also be said that CCC's represent a great advancement in many aspects of injection molding, such as the possibility of manufacturing complex channel shapes, the possibility of manufacturing channels with a complex configuration that was previously subjected to design optimization or process optimization routines. The result of applying CCC's is a greater potential for achieving the goals of the injection molding process. This paper compiled the most important aspects regarding the topic of CCC's for applications in injection molding. This work aims to provide a helpful reference to the researchers who would like to work on this topic.

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Declarations

Ethics approval Not applicable

Consent to participate Not applicable

Consent for publication Not applicable

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