Applied Thermal Engineering 64 (2014) 462–470

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Optimal design of heating system for rapid thermal cycling mold using particle swarm optimization and finite element method

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HIGHLIGHTS

- PSO and FEM are integrated together to design the heating system for RTCM mold.
- The PSO–FEM process is performed automatically by instruction commands.
- Optimal design parameters can be effectively obtained using the PSO–FEM method.
- Experiments are conducted to verify the effectiveness of the PSO–FEM method.
- RTCM process can dramatically improve the surface quality of molded parts.

ARTICLE INFO

Article history:
Received 21 August 2013
Accepted 26 December 2013
Available online 4 January 2014

Keywords:
Rapid thermal cycling molding
Optimal design
Particle swarm optimization
Finite element method

ABSTRACT

Heating efficiency and cavity surface temperature distribution are two key factors for the design of heating system in rapid thermal cycling molding (RTCM) mold. Aiming at high heating efficiency and uniform cavity surface temperature distribution, an optimization method combining particle swarm optimization (PSO) with finite element method (FEM) is proposed to design the heating system for RTCM mold in this work. The proposed optimization design method is applied to design the electric-heating system for an RTCM blow mold of automotive spoiler to verify its effectiveness. The results demonstrate that the method can be used to effectively obtain the optimal design parameters compared with the simulation-based trial and error design method. Based on the optimal results, the RTCM spoiler blow mold with electric heating is constructed. Then, both infrared thermal imaging system and numerical simulation method are used to evaluate the mold thermal response and cavity surface temperature distribution. It is found that the simulated results are in good agreement with the measured ones. The blow molding experiments conducted using the constructed RTCM mold show that the surface quality of molded spoilers is dramatically improved.

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1. Introduction

Injection molding and blow molding are two major plastics processing categories, with the products used in many industries, including automotive, household appliance, consumer electrics, etc. Both injection molding and blow molding are cyclic processes involving four essential stages, which are the melt filling, melt packing, part solidification and part ejection for the former and the parison formation, parison inflation, part solidification and part ejection for the latter. It is a common practice in the regular molding process that the mold temperature is maintained at a low level. The low mold temperature can not only shorten the cycle time, but also make the molding process more stable. However, this will result in premature solidification of the skin layer of the filled melt or inflated parison in its initial contact with cavity surface, which will decrease the replicability of the molded part to the glossy mold cavity surface and thus result in poor part surface quality, such as welding line, flowing mark and sink mark on the injection molded part surface as well as roughness, sunken points and orange peel on the blow molded part surface. If high surface quality is required for the molded parts, such as automotive spoiler, LCD TV panel and other exterior parts, the defects must be eliminated via some secondary operations, such as sanding, polishing and painting. These operations not only increase the production cost, but also are harmful to the environment and human health. Elevating the mold temperature above the plastics thermal

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1359-4311/$ – see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.applthermaleng.2013.12.062

distortion temperature during molding can be considered as an effective manner to solve the aforementioned molding problems. However, this will extend the part cooling time and hence lower the productivity to a great extent.

If the mold cavity is kept above the thermal distortion temperature of the plastic used for a certain period of time in its initial contact with the filled plastics melt or inflated parison surface and then the molded part is cooled down quickly for ejection, namely rapid thermal cycling molding (RTCM), the aforementioned process contradiction between the part quality and productivity can be solved effectively. To alternately change the cavity temperature without large increase in molding cycle time, rapid mold cooling system and heating system are highly required. For the cooling system, the cooling method using water is sufficient to rapidly cool the mold. However, it is not an easy work to develop an effective heating system for rapidly heating the mold in a short time, especially for the mold with large volume. In the past several years, some rapid mold heating methods were proposed. Typically, Yao et al. [1] constructed a multilayer mold, comprising a metallic heating layer, a mold base, and an oxide insulation layer in between. With this special mold structure, the mold cavity surface can be heated from 25 to 250 °C in 2 s. However, the complex structure and weak mechanical strength among layers of the mold restrict its applications. Chen et al. [2], Huang et al. [3] and Park et al. [4] developed the induction heating technique for rapid mold heating. Although this method has quite high efficiency, it is difficult to achieve uniform cavity surface heating for the mold with complex cavity shape. Wang et al. [5] built a dynamic mold temperature system using steam heating. This system can efficiently and uniformly heat the mold, but the cost of auxiliary equipment is quite high. Other rapid mold heating methods, including infrared heating [6], high-frequency proximity heating [7,8], and hot air-assisted heating [9] were also reported in open literature. However, a lot of work has to be done further for the industrial applications of these methods.

The heating efficiency and temperature uniformity on the mold cavity surface are two key factors needed to be well considered in implementing the RTCM technology because they have a direct influence on the molding cycle time and part quality. For a given mold heating method, they are mainly dependent on the heating system design. Usually the heating system is designed with the aid of finite element method (FEM), which can predict not only the required heating time for the mold cavity surface to be heated to a set temperature, but also the cavity surface temperature distribution at any time. However, this simulation-based trial and error design method is limited because the optimal design parameters are not easy to be obtained for achieving the rapid and uniform cavity surface heating. For this reason, it is necessary to optimize the heating system to obtain the RTCM mold with good comprehensive performance. Although a lot of researches have been done to optimize the cooling system for uniform and efficient cooling in injection molding [10–12], there were only a little of works referring to the optimization of the heating system in RTCM mold. Xiao et al. [13] and Wang et al. [14] used genetic algorithm to design the heating system for an RTCM mold with electric and hot water heating, respectively. This algorithm can work well, but needs the complicated encoding and decoding and the special genetic operators including crossover and mutation. Wang et al. [15,16] developed a design method for the heating system of the RTCM mold based on FEM, response surface methodology (RSM) and optimization technique. However, the levels of design variables should be well determined in the design of experiments, because the search process of the RSM model is highly dependent on the search space [17].

Particle swarm optimization (PSO) is a population-based evolutionary optimization algorithm developed by Kennedy and Eberhart [18]. Compared with other evolutionary algorithms, e.g., genetic algorithm, PSO supplies the obvious advantages of simpler implementation, higher accuracy and faster convergence rate for solving the complex optimization problems. The PSO has been used in many applications in the past few years [19–21]. In the current work, an optimal design method combining PSO with FEM is proposed for the heating system of RTCM mold to improve the surface quality of molded plastics parts. The FEM is responsible for calculating the values of objective functions and the PSO is used as the optimizer to search the optimal design parameters. The effectiveness of the proposed optimization method is illustrated by the design of the electric-heating system for an RTCM blow mold of automotive spoilers.

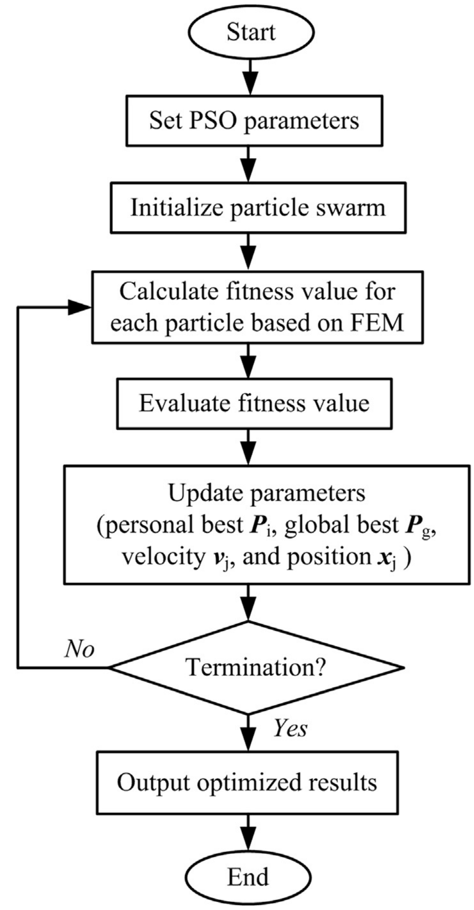

Fig. 1. Flow chart of PSO–FEM optimization.

2. PSO–FEM design method

PSO operates with a swarm of particles in the process of optimization. Each particle has its own position $\boldsymbol{x}_j = (x_j^1, x_j^2, \ldots, x_j^m)$ and velocity $\boldsymbol{v}_j = (v_j^1, v_j^2, \ldots, v_j^m)$, where j denotes the jth particle and m denotes the number of optimized variables. The former represents a potential solution to the optimization problem. In PSO–FEM design method, the objective function is formulated as the fitness function. The PSO is used to search the optimal design parameters by minimizing or maximizing the fitness function in the feasible region. The FEM, in which the design parameters are adopted as its input variables, is used as a solver of the fitness function. When the PSO optimizer is started, a swarm of particles are randomly initialized from the feasible region. In the subsequent each step of iterations, the PSO sends each particle, which represents a

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