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# Numerical optimization of process parameters in plastic injection molding for minimizing weldlines and clamping force using conformal cooling channel

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ABSTRACT

Weldlines are one of the major defects in plastic injection molding (PIM). Since the weldlines have an influence on not only the appearance of product but also the strength, it is important to reduce the weldlines as much as possible. The melt plastic will be quickly solidified with the low weldline temperature, which results in long weldlines. The weldline temperature is one of the important factors for the weldlines reduction. Clamping force also affect the product quality, but the relationship between the weldlines and the clamping force is rarely discussed in the literature. In this paper, the minimum weldline temperature is maximized for the weldlines reduction, whereas the clamping force is minimized for the high product quality. Therefore, a multi-objective design optimization is performed and the pareto-frontier between them is identified. Numerical simulation in PIM is generally so intensive that a sequential approximate optimization (SAO) using a radial basis function (RBF) network is used to identify the pareto-frontier. Through the numerical simulation, the trade-off between the minimum weldline temperature and the clamping force is clarified.

## 1. Introduction

Plastic injection molding (PIM) is one of the most widely used industrial technologies for producing plastic products with high productivity. In the PIM, there are several process parameters such as melt temperature, mold temperature, injection time, packing pressure, and cooling time. In filling phase, melt plastic is filled into the die cavity with the injection pressure. Then, the melt plastic is packed with an appropriate packing pressure in packing phase. Finally, the melt plastic is cooled down for the solidification in cooling phase, and the solid plastic is then ejected. Conventionally, the trial and error method is widely used to determine the process parameters. The inappropriate process parameters easily cause major defects such as warpage, weldlines, and short shot, so it is important to determine the optimal process parameters to minimize these defects. Recently, computer aided engineering (CAE) coupled with design optimization is recognized as one of the powerful tools available [1–3], and the product quality such as the warpage and the weldlines can be numerically evaluated. The numerical simulation in PIM is so intensive that response surface approach is widely used to determine the optimal process parameters. In particular, a sequential approximate optimization (SAO) that the response surface is repeatedly constructed and optimized is a popular approach [4]. Let us briefly review several representative papers for determining the optimal process parameters in PIM.

Shi et al. optimized several process parameters for minimizing the maximum shear stress of a product [5]. Kurtaran et al. optimized the process parameters for minimizing the warpage of a bus ceiling lamp base using neural network (NN) and genetic algorithm (GA) [6]. They also used the quadratic polynomial as the approximation technique [7]. Ozcelik and Erzurumlu adopted the similar approach for minimizing the warpage of thin shell plastic product [8]. Chiang and Chang performed a multi-objective optimization of process parameters for minimizing warpage and shrinkage of a cell phone shell cover [9]. Note that above researches adopt one-step optimization without iteration for determining the optimal process parameters. In the one-step optimization, the optimum process parameters completely depend on the accuracy of the response surface. In order to obtain a highly accurate response surface, a big-size design of experiment (DOE) is generally required. Gao and Wang adopted the SAO using the Kriging [10,11] in which the warpage of a cellular phone cover was minimized. Zhang

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**Table 1**
Summary of representative papers of process parameter optimization using approximation technique.

| Refs. | Process parameters in PIM | | Approximation technique | Objective function |
|---|---|---|---|---|
| Shi et al. [5] | Mold temperature<br>Melt temperature | Injection time<br>Injection pressure | Back propagation neural network | Maximum shear stress |
| Kurtaran et al. [6] | Mold temperature<br>Melt temperature<br>Packing pressure | Packing time<br>Cooling time | Back propagation neural network | Warpage |
| Kurtaran and Erzurumlu [7] | Mold temperature<br>Melt temperature | Packing pressure | Quadratic polynomial | Warpage |
| Chiang and Chang [9] | Mold temperature<br>Packing pressure | Packing time<br>Cooling time | Quadratic polynomial | Warpage<br>Shrinkage |
| Gao and Wang [10] | Melt temperature<br>Mold temperature | Injection time<br>Packing pressure | Kriging | Warpage |
| Gao and Wang [11] | Melt temperature<br>Mold temperature | Packing profile | Kriging | Warpage |
| Zhang et al. [12] | Mold temperature<br>Melt temperature | Injection time | Quadratic polynomial | Warpage |
| Deng et al. [13] | Mold temperature<br>Melt temperature | Injection time<br>Packing pressure | Kriging | Warpage |
| Zhao et al. [14] | Mold temperature<br>Melt temperature<br>Injection time | | Fast Strip Analysis | Cativy pressure<br>Melt temperature<br>Cooling time |
| Li et al. [15] | Packing profile | | Radial basis function | Shrinkage |
| Shi et al. [16] | Mold temperature<br>Melt temperature<br>Injection time | Packing pressure<br>Packing time<br>Cooling time | Back propagation neural network | Warpage |
| Xia et al. [17] | Packing pressure<br>Packing time<br>Injection pressure | Melt temperature<br>Injection time<br>Cooling time | Gaussian process | Warpage |
| Cheng et al. [18] | Diameter of runner<br>Packing pressure<br>Packing time | Cooling time | Back propagation neural network | Volume shrinkage<br>Total volume of runner system<br>Cycle time |
| Shi et al. [19] | Mold temperature<br>Melt temperature<br>Injection time | Packing time<br>Packing pressure<br>Cooling time | Back propagation neural network | Warpage |
| Kitayama et al. [20] | Pressure profile in injection and packing phase<br>Mold temperature | <br>Melt temperature | Radial basis function | Warpage |
| Zhao et al. [21] | Injection time<br>Melt temperature<br>Packing pressure | Packing time<br>Cooling temparature<br>Cooling time | Kriging | Volume shrinkage<br>Sink marks |

et al. and Deng et al. adopted the mode-pursuing sampling method for the SAO and the warpage of a scanner frame was minimized [12,13]. Zhao et al. developed the fast strip analysis (FSA) for the surrogate model and the pareto-optimal solutions among three objectives were determined [14]. Other representative papers using the SAO on the process parameters in PIM can be found in Refs. [15–21]. The summary is listed in Table 1.

Weldlines which are formed when two or more melt fronts meet are also one of the important product qualities in PIM. Since the weldlines influence not only the appearance of products but also the strength, it is preferable to reduce the weldlines as much as possible. Li et al. used the Taguchi method to examine the effects of process parameters on the weldlines [22], and they clarified that the melt temperature, the injection velocity and the injection pressure had an influence on the weldlines. Chen et al. controlled the weldline positions by changing the gate location [23]. Wu et al. adopted distributed multi-population GA to optimize the process parameters for minimizing the warpage of LCD panel under the weldlines constraint [24]. Deng et al. optimized the process parameters for minimizing four objective functions (the temperature distribution, the shear stress distribution, the weldlines, and the total volume of air traps), and the pareto-optimal solutions were determined [25]. Kim et al. optimized both the gate locations and the process parameters for minimizing the weldlines of an automotive front bumper [26]. It is found from above brief review that the process parameters in PIM affect the weldlines.

Clamping force also plays an important role in PIM. As suggested by Yin et al. [27], energy consumption is also an important issue in the PIM. Small clamping force can save the energy consumption, and will lead to high productivity. Zhai and Xie optimized the process parameters for minimizing the filling time of a toy table [28] in which the clamping force was handled as the design constraint. Kitayama and Natsume performed a multi-objective design optimization for minimizing the volume shrinkage and the clamping force of a cup [29]. Zhang et al. optimized several process parameters for minimizing the warpage and the clamping force of an oil cooler cove of diesel engine [30]. It is found from above brief review that the clamping force is also useful for improving the product quality.

Finally, the cooling channel in PIM needs to be considered. Conventionally, straight-type cooling channels are widely used. Due to the recent advancement in 3D printing technology, it is possible to produce conformal cooling channel [31–33]. Dimla et al. reported that conformal cooling channel could drastically reduce cycle time [34]. Au and Yu designed various scaffold cooling channels and evaluated the cooling performance [35] and found that the conformal cooling channel could offer a more uniform thermal distribution. Kitayama et al. have examined the cooling performance of conformal cooling channel numerically and experimentally [36] where the process parameter optimization for short cycle time and warpage reduction was performed.

The objective of this work is summarized as the following:

1 Process parameter optimization in PIM is still a crucial issue. Several process parameters are optimized for weldlines reduction and clamping force minimization.
2 Weldlines that cannot be completely eliminated in PIM are one of the major defects. The melt plastic will be quickly solidified with the low weldline temperature, which results in long weldlines. Then, we consider that the minimum weldline temperature should be maximized for the weldlines reduction.