Journal of Zhejiang University SCIENCE A
ISSN 1673-565X (Print); ISSN 1862-1775 (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

Single gate optimization for plastic injection mold*

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Received Nov. 22, 2006; revision accepted Mar. 19, 2007

Abstract: This paper deals with a methodology for single gate location optimization for plastic injection mold. The objective of the gate optimization is to minimize the warpage of injection molded parts, because warpage is a crucial quality issue for most injection molded parts while it is influenced greatly by the gate location. Feature warpage is defined as the ratio of maximum displacement on the feature surface to the projected length of the feature surface to describe part warpage. The optimization is combined with the numerical simulation technology to find the optimal gate location, in which the simulated annealing algorithm is used to search for the optimum. Finally, an example is discussed in the paper and it can be concluded that the proposed method is effective.

Key words: Injection mold, Gate location, Optimization, Feature warpage
doi:10.1631/jzus.2007.A1077 **Document code:** A **CLC number:** TQ320.66

INTRODUCTION

Plastic injection molding is a widely used, complex but highly efficient technique for producing a large variety of plastic products, particularly those with high production requirement, tight tolerance, and complex shapes. The quality of injection molded parts is a function of plastic material, part geometry, mold structure and process conditions. The most important part of an injection mold basically is the following three sets of components: cavities, gates and runners, and cooling system.

Lam and Seow (2000) and Jin and Lam (2002) achieved cavity balancing by varying the wall thickness of the part. A balance filling process within the cavity gives an evenly distributed pressure and temperature which can drastically reduce the warpage of the part. But the cavity balancing is only one of the important influencing factors of part qualities. Especially, the part has its functional requirements, and its thicknesses should not be varied usually.

From the pointview of the injection mold design, a gate is characterized by its size and location, and the runner system by the size and layout. The gate size and runner layout are usually determined as constants. Relatively, gate locations and runner sizes are more flexible, which can be varied to influence the quality of the part. As a result, they are often the design parameters for optimization.

Lee and Kim (1996a) optimized the sizes of runners and gates to balance runner system for multiple injection cavities. The runner balancing was described as the differences of entrance pressures for a multi-cavity mold with identical cavities, and as differences of pressures at the end of the melt flow path in each cavity for a family mold with different cavity volumes and geometries. The methodology has shown uniform pressure distributions among the cavities during the entire molding cycle of multiple cavities mold.

Zhai *et al*.(2005a) presented the two gate location optimization of one molding cavity by an efficient search method based on pressure gradient (PGSS), and subsequently positioned weld lines to the desired locations by varying runner sizes for

* Project (No. 50675080) supported by the National Natural Science Foundation of China

multi-gate parts (Zhai *et al*., 2006). As large-volume part, multiple gates are needed to shorten the maximum flow path, with a corresponding decrease in injection pressure. The method is promising for design of gates and runners for a single cavity with multiple gates.

Many of injection molded parts are produced with one gate, whether in single cavity mold or in multiple cavities mold. Therefore, the gate location of a single gate is the most common design parameter for optimization. A shape analysis approach was presented by Courbebaisse and Garcia (2002), by which the best gate location of injection molding was estimated. Subsequently, they developed this methodology further and applied it to single gate location optimization of an L shape example (Courbebaisse, 2005). It is easy to use and not time-consuming, while it only serves the turning of simple flat parts with uniform thickness.

Pandelidis and Zou (1990) presented the optimization of gate location, by indirect quality measures relevant to warpage and material degradation, which is represented as weighted sum of a temperature differential term, an over-pack term, and a frictional overheating term. Warpage is influenced by the above factors, but the relationship between them is not clear. Therefore, the optimization effect is restricted by the determination of the weighting factors.

Lee and Kim (1996b) developed an automated selection method of gate location, in which a set of initial gate locations were proposed by a designer and then the optimal gate was located by the adjacent node evaluation method. The conclusion to a great extent depends much on the human designer's intuition, because the first step of the method is based on the designer's proposition. So the result is to a large extent limited to the designer's experience.

Lam and Jin (2001) developed a gate location optimization method based on the minimization of the Standard Deviation of Flow Path Length (SD[L]) and Standard Deviation of Filling Time (SD[T]) during the molding filling process. Subsequently, Shen *et al.(*2004a; 2004b) optimized the gate location design by minimizing the weighted sum of filling pressure, filling time difference between different flow paths, temperature difference, and over-pack percentage. Zhai *et al*.(2005b) investigated optimal gate location with evaluation criteria of injection pressure at the end of filling. These researchers presented the objective functions as performances of injection molding filling operation, which are correlated with product qualities. But the correlation between the performances and qualities is very complicated and no clear relationship has been observed between them yet. It is also difficult to select appropriate weighting factors for each term.

A new objective function is presented here to evaluate the warpage of injection molded parts to optimize gate location. To measure part quality directly, this investigation defines feature warpage to evaluate part warpage, which is evaluated from the "flow plus warpage" simulation outputs of Moldflow Plastics Insight (MPI) software. The objective function is minimized to achieve minimum deformation in gate location optimization. Simulated annealing algorithm is employed to search for the optimal gate location. An example is given to illustrate the effectivity of the proposed optimization procedure.

QUALITY MEASURES: FEATURE WARPGE

Definition of feature warpage

To apply optimization theory to the gate design, quality measures of the part must be specified in the first instance. The term "quality" may be referred to many product properties, such as mechanical, thermal, electrical, optical, ergonomical or geometrical properties. There are two types of part quality measures: direct and indirect. A model that predicts the properties from numerical simulation results would be characterized as a direct quality measure. In contrast, an indirect measure of part quality is correlated with target quality, but it cannot provide a direct estimate of that quality.

For warpage, the indirect quality measures in related works are one of performances of injection molding flowing behavior or weighted sum of those. The performances are presented as filling time differential along different flow paths, temperature differential, over-pack percentage, and so on. It is obvious that warpage is influenced by these performances, but the relationship between warpage and these performances is not clear and the determination of these weighting factors is rather difficult. Therefore, the optimization with the above objective function probably will not minimize part warpage even with perfect optimization technique. Sometimes, improper weighting factors will result in absolutely wrong results.

Some statistical quantities calculated from the nodal displacements were characterized as direct quality measures to achieve minimum deformation in related optimization studies. The statistical quantities are usually a maximum nodal displacement, an average of top 10 percentile nodal displacements, and an overall average nodal displacement (Lee and Kim, 1995; 1996b). These nodal displacements are easy to obtain from the simulation results, the statistical values, to some extents, representing the deformation. But the statistical displacement cannot effectively describe the deformation of the injection molded parts.

In industry, designers and manufacturers usually pay more attention to the degree of part warpage on some specific features than the whole deformation of the injection molded parts. In this study, feature warpage is defined to describe the deformation of the injection parts. The feature warpage is the ratio of the maximum displacement of the feature surface to the projected length of the feature surface (Fig.1):

$$\gamma = \frac{h}{L} \times 100\%, \tag{1}$$

where γ is the feature warpage, h is the maximum displacement on the feature surface deviating from the reference platform, and L is the projected length of the feature surface on a reference direction paralleling the reference platform.

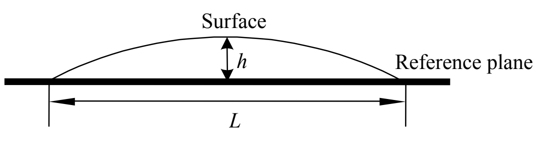

Fig.1 The definition of feature warpage

For complicated features (only plane feature discussed here), the feature warpage is usually separated into two constituents on the reference plane, which are represented on a 2D coordinate system:

$$\gamma_x = \frac{h}{L_x} \times 100\%,\ \gamma_y = \frac{h}{L_y} \times 100\%, \tag{2}$$

where γ_x, γ_y are the constituent feature warpages in the X, Y direction, and L_x, L_y are the projected lengths of the feature surface on X, Y component.

Evaluation of feature warpage

After the determination of target feature combined with corresponding reference plane and projection direction, the value of L can be calculated immediately from the part with the calculating method of analytic geometry (Fig.2). L is a constant for any part on the specified feature surface and projected direction. But the evaluation of h is more complicated than that of L.

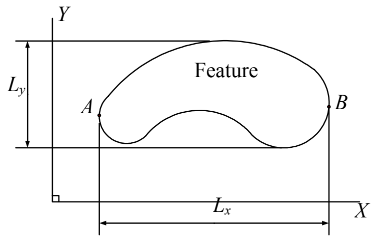

Fig.2 The projected length evaluation

Simulation of injection molding process is a common technique to forecast the quality of part design, mold design and process settings. The results of warpage simulation are expressed as the nodal deflections on X, Y, Z component (W_x, W_y, W_z), and the nodal displacement W. W is the vector length of vector sum of $W_x \cdot \boldsymbol{i}$, $W_y \cdot \boldsymbol{j}$, and $W_z \cdot \boldsymbol{k}$, where $\boldsymbol{i}$, $\boldsymbol{j}$, $\boldsymbol{k}$ are the unit vectors on X, Y, Z component. The h is the maximum displacement of the nodes on the feature surface, which is correlated with the normal orientation of the reference plane, and can be derived from the results of warpage simulation.

To calculate h, the deflection of ith node is evaluated firstly as follows:

$$W_i = W_{ix}\cos\alpha + W_{iy}\cos\beta + W_{iz}\cos\gamma - (\omega_{iA}W_A + \omega_{iB}W_B), \tag{3}$$

where W_i is the deflection in the normal direction of the reference plane of ith node; W_{ix}, W_{iy}, W_{iz} are the deflections on X, Y, Z component of ith node; α, β, γ are the angles of normal vector of the reference; A and B are the terminal nodes of the feature to projecting direction (Fig.2); W_A and W_B are the deflections of nodes A and B:

$$\begin{cases} W_A = W_{Ax}\cos\alpha + W_{Ay}\cos\beta + W_{Az}\cos\gamma, \\ W_B = W_{Bx}\cos\alpha + W_{By}\cos\beta + W_{Bz}\cos\gamma, \end{cases} \tag{4}$$

where W_{Ax}, W_{Ay}, W_{Az} are the deflections on X, Y, Z component of node A; W_{Bx}, W_{By} and W_{Bz} are the deflections on X, Y, Z component of node B; ω_{iA} and ω_{iB} are the weighting factors of the terminal node deflections calculated as follows:

$$\omega_{iA} = 1 - L_{iA} / L,\ \omega_{iB} = 1 - \omega_{iA}, \tag{5}$$

where L_{iA} is the projector distance between ith node and node A. Ultimately, h is the maximum of the absolute value of W_i:

$$h = \max\{|W_1|,|W_2|,\ldots,|W_k|\}. \tag{6}$$

In industry, the inspection of the warpage is carried out with the help of a feeler gauge, while the measured part should be placed on a reference platform. The value of h is the maximum numerical reading of the space between the measured part surface and the reference platform.

GATE LOCATION OPTIMIZATION PROBLEM FORMATION

The quality term "warpage" means the permanent deformation of the part, which is not caused by an applied load. It is caused by differential shrinkage throughout the part, due to the imbalance of polymer flow, packing, cooling, and crystallization.

The placement of a gate in an injection mold is one of the most important variables of the total mold design. The quality of the molded part is greatly affected by the gate location, because it influences the manner that the plastic flows into the mold cavity. Therefore, different gate locations introduce inhomogeneity in orientation, density, pressure, and temperature distribution, accordingly introducing different value and distribution of warpage. Therefore, gate location is a valuable design variable to minimize the injection molded part warpage. Because the correlation between gate location and warpage distribution is to a large extent independent of the melt and mold temperature, it is assumed that the molding conditions are kept constant in this investigation. The injection molded part warpage is quantified by the feature warpage which was discussed in the previous section.

The single gate location optimization can thus be formulated as follows:

Minimize: $\min f(\boldsymbol{X}) = \gamma$;
Subject to: $g(\boldsymbol{X}) = p / p_0 - 1 \le 0,$
$\boldsymbol{X} \in X_i,\ \ i = 1, 2, ..., N,$

where γ is the feature warpage; p is the injection pressure at the gate position; p_0 is the allowable injection pressure of injection molding machine or the allowable injection pressure specified by the designer or manufacturer; $\boldsymbol{X}$ is the coordinate vector of the candidate gate locations; X_i is the node on the finite element mesh model of the part for injection molding process simulation; N is the total number of nodes.

In the finite element mesh model of the part, every node is a possible candidate for a gate. Therefore, the total number of the possible gate location N_p is a function of the total number of nodes N and the total number of gate locations to be optimized n:

$$N_\mathrm{p} = \frac{N(N-1)\cdots(N-n-1)}{n!}.$$

In this study, only the single-gate location problem is investigated.

SIMULATED ANNEALING ALGORITHM

The simulated annealing algorithm is one of the most powerful and popular meta-heuristics to solve optimization problems because of the provision of good global solutions to real-world problems. The algorithm is based upon that of Metropolis *et al.* (1953), which was originally proposed as a means to find an equilibrium configuration of a collection of atoms at a given temperature. The connection between this algorithm and mathematical minimization was first noted by Pincus (1970), but it was Kirkpatrick *et al.*(1983) who proposed that it formed the basis of an optimization technique for combinational (and other) problems.

To apply the simulated annealing method to optimization problems, the objective function f is used as an energy function E. Instead of finding a low energy configuration, the problem becomes to seek an approximate global optimal solution. The configurations of the values of design variables are substituted for the energy configurations of the body, and the control parameter for the process is substituted for temperature. A random number generator is used as a way of generating new values for the design variables. It is obvious that this algorithm just takes the minimization problems into account. Hence, while performing a maximization problem the objective function is multiplied by (−1) to obtain a capable form.

The major advantage of simulated annealing algorithm over other methods is the ability to avoid being trapped at local minima. This algorithm employs a random search, which not only accepts changes that decrease objective function f, but also accepts some changes that increase it. The latter are accepted with a probability p

$$p = \mathrm{e}^{-\Delta f/(kT)},$$

where Δf is the increase of f, k is Boltzman's constant, and T is a control parameter which by analogy with the original application is known as the system "temperature" irrespective of the objective function involved.

In the case of gate location optimization, the implementation of this algorithm is illustrated in Fig.3, and this algorithm is detailed as follows:

(1) SA algorithm starts from an initial gate location $\boldsymbol{X}_{\text{old}}$ with an assigned value T_k of the "temperature" parameter T (the "temperature" counter k is initially set to zero). Proper control parameter c ($0<c<1$) in annealing process and Markov chain N_{generate} are given.

(2) SA algorithm generates a new gate location $\boldsymbol{X}_{\text{new}}$ in the neighborhood of $\boldsymbol{X}_{\text{old}}$ and the value of the objective function $f(\boldsymbol{X})$ is calculated.

(3) The new gate location will be accepted with probability determined by the acceptance function

$$P_{\text{accept}} = \min\{1, \exp[-k(f(\boldsymbol{X}_{\text{new}}) - f(\boldsymbol{X}_{\text{old}}))/T_k]\}.$$

A uniform random variable P_{unif} is generated in [0,1]. If $P_{\text{unif}}<P_{\text{accept}}$, $\boldsymbol{X}_{\text{new}}$ is accepted; otherwise it is rejected.

(4) This process is repeated for a large enough number of iterations (N_{generate}) for T_k. The sequence of trial gate locations generated in this way is known as Markov chain.

(5) A new Markov chain is then generated (starting from the last accepted gate location in the previous Markov chain) for a reduced "temperature" $T_{k+1}=cT_k$ and the same process continues for decreasing values of "temperature" until the algorithm stops.

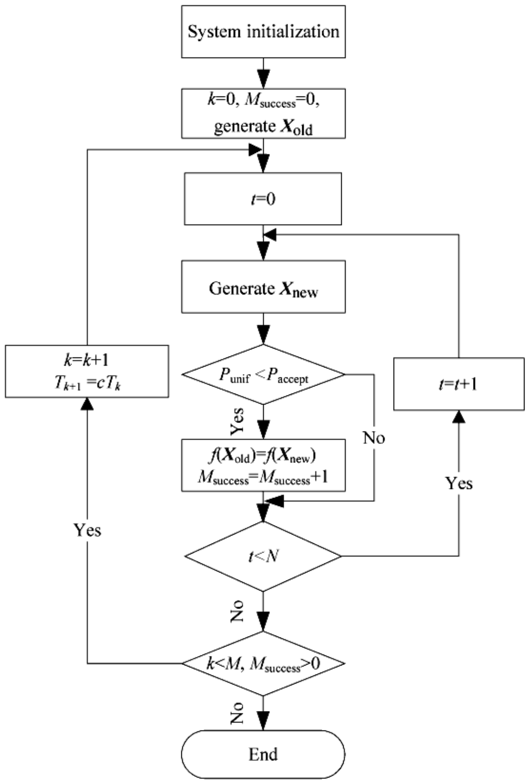

Fig.3 The flow chart of the simulated annealing algorithm

APPLICATION AND DISCUSSION

The application to a complex industrial part is presented in this section to illustrate the proposed quality measure and optimization methodology. The part is provided by a manufacturer, as shown in Fig.4. In this part, the flatness of basal surface is the most important profile precision requirement. Therefore, the feature warpage is discussed on basal surface, in which reference platform is specified as a horizontal plane attached to the basal surface, and the longitudinal direction is specified as projected reference direction. The parameter h is the maximum basal surface deflection on the normal direction, namely the vertical direction, and the parameter L is the projected length of the basal surface to the longitudinal direction.

Fig.4 Industrial part provided by the manufacturer

The material of the part is Nylon Zytel 101L (30% EGF, DuPont Engineering Polymer). The molding conditions in the simulation are listed in Table 1. Fig.5 shows the finite element mesh model of the part employed in the numerical simulation. It has 1469 nodes and 2492 elements. The objective function, namely feature warpage, is evaluated by Eqs.(1), (3)~(6). The h is evaluated from the results of "Flow +Warp" Analysis Sequence in MPI by Eq.(1), and the L is measured on the industrial part immediately, L=20.50 mm.

Table 1 The molding conditions in the simulation

Conditions	Values
Fill time (s)	2.5
Melt temperature (°C)	295
Mold temperature (°C)	70
Packing time (s)	10
Packing pressure (of filling pressure) (%)	80

MPI is the most extensive software for the injection molding simulation, which can recommend the best gate location based on balanced flow. Gate location analysis is an effective tool for gate location design besides empirical method. For this part, the gate location analysis of MPI recommends that the best gate location is near node N7459, as shown in Fig.5. The part warpage is simulated based on this recommended gate and thus the feature warpage is evaluated: γ=5.15%, which is a great value. In trial manufacturing, part warpage is visible on the sample work piece. This is unacceptable for the manufacturer.

The great warpage on basal surface is caused by the uneven orientation distribution of the glass fiber, as shown in Fig.6a. Fig.6a shows that the glass fiber orientation changes from negative direction to positive direction because of the location of the gate, particularly the greatest change of the fiber orientation appears near the gate. The great diversification of fiber orientation caused by gate location introduces serious differential shrinkage. Accordingly, the feature warpage is notable and the gate location must be optimized to reduce part warpage.

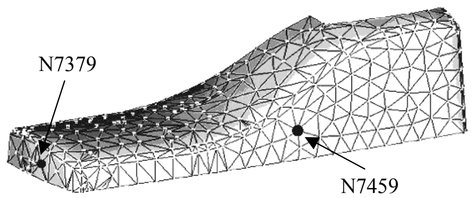

Fig.5 Finite element mesh model of the part

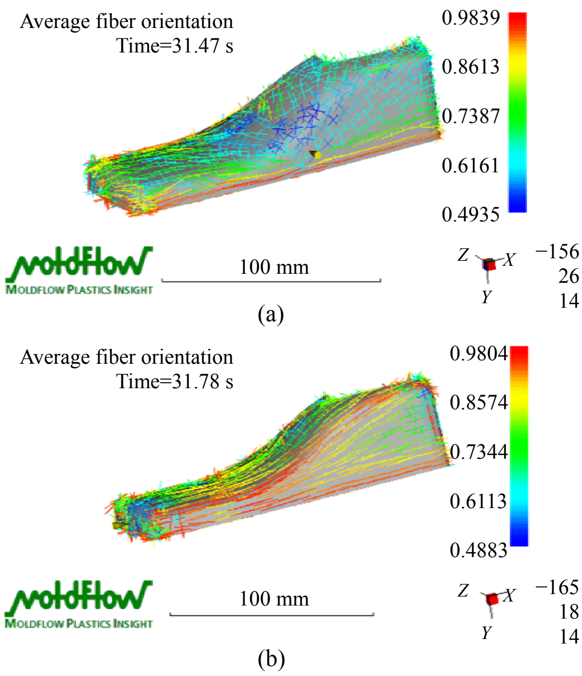

Fig.6 The orientation distribution of the glass fiber with varied gate location
(a) Gate set on N7459; (b) The optimal gate location N7379

To optimize the gate location, the simulated annealing searching discussed in the section "Simulated annealing algorithm" is applied to this part. The maximum number of iterations is chosen as 30 to ensure the precision of the optimization, and the maximum number of random trials allowed for each iteration is chosen as 10 to decrease the probability of null iteration without an iterative solution. Node N7379 (Fig.5) is found to be the optimum gate location. The feature warpage is evaluated from the warpage simulation results $f(\boldsymbol{X})=\gamma=0.97\%$, which is less than that of the recommended gate by MPI. And the part warpage meets the manufacturer's requirements in trial manufacturing. Fig.6b shows the fiber orientation in the simulation. It is seen that the optimal gate location results in the even glass fiber orientation, and thus introduces great reduction of shrinkage difference on the vertical direction along the longitudinal direction. Accordingly, the feature warpage is reduced.

CONCLUSION

Feature warpage is defined to describe the warpage of injection molded parts and is evaluated based on the numerical simulation software MPI in this investigation. The feature warpage evaluation based on numerical simulation is combined with simulated annealing algorithm to optimize the single gate location for plastic injection mold. An industrial part is taken as an example to illustrate the proposed method. The method results in an optimal gate location, by which the part is satisfactory for the manufacturer. This method is also suitable to other optimization problems for warpage minimization, such as location optimization for multiple gates, runner system balancing, and option of anisotropic materials.

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