e-Polymers **2009**, no. 127

http://www.e-polymers.org
ISSN 1618-7229

Gate location optimization scheme for plastic injection molding

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(Received: 05 September, 2008; published: 13 November, 2009)

Abstract: Gate location of injection molding is vital to achieve high quality plastic part. The determination of gate location is an important issue in mold design. A computationally efficient scheme based on flow path is proposed to locate the optimum gate for achieving balanced flow. The range of filling time is employed as objective function. Comparisons were made between the flow path search scheme and the existing adjacent node evaluation scheme, and between the objective function of the range of filling time and the existing standard deviation of filling time. The two examples investigated indicated that the search routine based on the concept of flow path is more efficient computationally and the range of filling time is a better objective function to reflect the uniformity of fill.

Introduction

Injection molding, which is characterized by high production rates and dimensional precision, is one of the most widely employed manufacturing processes for the fabrication of plastic products. During this process, the polymer undergoes a complex thermo-mechanical history, which introduces molecular orientation, residual stresses, and strains into the final products. This results in highly anisotropic mechanical behavior, shrinkage, and warpage. The quality of injection-molded parts is the result of interaction between the material properties of the polymer, the part geometry, the design of the injection mold and the processing parameters.

Injection mold design and processing parameters determination based on past experience with trial-and-error fine tuning is time consuming. It offers no guarantee of an optimal solution. In the past three decades, CAE simulation has been developed for the prediction of the quality of injection-molded parts before physically fabricating a mold or the part. However, CAE simulation requires the mold designer to run the simulation, evaluate the design, and subsequent redesign based on experience, until a satisfactory design is obtained. This manual design process also does not guarantee an optimal design solution. Thus, there is increasing interest in the utilization of design optimization techniques for mold design.

Design optimization can be employed in the injection molding processes to determine the processing parameters and mold geometry so as to meet the product or processing objectives. Molding conditions [1-3], part wall thickness [4] and cooling system [5,6] can be selected as design variables and the performance measures include part warpage and filling pattern. Lam et al [7, 8] have developed the flow path concept for cavity balancing. An automatic flow path generation routine was developed and the flow front within a cavity was altered by varying the wall thickness of the part along the flow path so as to achieve balanced flow.

Gate is one of the most important design parameters of injection mold design and has a large bearing on the quality of the part. Bociaga [9] pointed out that the molded piece produced is reliable only when the mold is filled with a material introduced in the laminar flow mode, whereas the mode of flow is affected by the way a molten polymer is conveyed into the mold and particularly by the shape, size and location of mold runners and gates. Gate thickness was found to affect considerably the mechanical and thermal properties of polyethylene. As the gate thickness was increased, the tensile strength, yield stress, Young modulus, hardness and softening temperature decreased, whereas the impact strength and the unit strain at maximum tensile stress rose. Later, he [10] investigated the structure and the degree of crystallinity of product made by mold with different gate designs. Senthilvelan et al [11] correlated fiber orientation with injection gate location of molded gears.

Determination of the gate locations is an important issue in mold design. Kim et al [12] found that a properly determined gate location will lead to better resin flow and shorter hesitation time, and a guideline was induced by investigating resin flow patterns depending on several gate positions obtained by numerical analyses of a simple strip with a hinge. Park et al [13] elucidated the relationship between mold filling time and gate location and a scheme is proposed to optimize gate location to minimize mold filling time for a given structure geometry, material properties and loading condition. Pandelidis and Zou [14] presented a gate location optimization procedure using a combined scheme of simulated annealing and hill-climbing method. The quality of a gating design was presented as an additive function of a temperature differential term, an overpack term and the frictional overheating term, with appropriate weighting. The methodology required extensive numbers of design evaluations to obtain the optimum gate location. Young [15] optimized gate location by minimizing the mold filling pressure, uneven filling pattern, and temperature difference during the mold filling process. A genetic algorithm was used to search for the optimal gate location. Computation efficiency is a major concern.

Irani et al [16] developed a system that automated the process of gate design. Gate design was performed in two stages: a global search followed by a local search. During the global search, candidate gating plans were generated using feature connectivity information. These gating plans were evaluated and redesigned iteratively until the best cavity inlet conditions for each plan was obtained. Subsequently, the best in the trial set was perturbed locally for further improvement. The application of this approach was demonstrated by using simple geometry. The extension of this approach to complicated geometry was not obvious.

Based on the flow path concept, Lam and Jin [17] put forward two different gate location optimization objective functions, namely by minimization (i) the standard deviation of flow path length and (ii) the standard deviation of boundary filling time respectively. It was concluded that for non-uniform thickness part, standard deviation of the filling time at the boundary nodes should be minimized. However, in the search for the optimum gate location, the optimality of all the adjacent nodes of the current node was evaluated, with a filling analysis conducted for all the adjacent nodes. As such, the search algorithm was not computational efficient.

This investigation focuses on the development of an efficient search scheme for gate location optimization. A computationally efficient search method based on flow path is developed, and a more appropriate objective function based on the range of the filling time is employed.

Flow path

For plastic injection molding, flow path is defined as the path traced by a melt particle when it is first injected into a cavity until the mold cavity has been completely filled. It may be visualized as the trajectory from the injection gate to the extremities of the cavity.

As flow path generated formed the basis for the development of the gate location optimization routine in the present investigation, the generation of flow path will be briefly described here. The details of flow path generation can be found in Jin and Lam [8].

Flow path can be deduced from the filling time contours generated from a filling analysis. It represents the steepest descent of filling time from the boundary to the gates. Instead of tracing the flow path from the injection gate to the boundary, flow path can be obtained easily by tracing from a point on the boundary back to the injection gate. During the filling phase, the previous position of the melt can be determined by the fill direction of the fastest flow rate. On a filling time contour plot, the fastest flow rate is the direction of the steepest gradient, which is exactly the path traced by the hill-climbing algorithm. Hence, from filling time contours generated by a filling analysis, the flow paths can be traced effectively and efficiently using the hill-climbing algorithm.

Optimization problem formulation

The optimal design problem is defined as follows: for a given set of molding conditions, determine the optimal gate locations to achieve high quality part. The optimization model is:

Optimize $F(x)$ such that $\forall x \in R^3$ subject to $x \in \Omega \subset R^3$

where $F(x)$ is a objective function providing a quantitative measure of part quality; x are design variables, describing the gate location in the search space Ω.

To optimize an injection-molding design for improvement of part quality, there must be quantitative measure of the part quality. There are two types of part quality measures: direct and indirect methods. Direct method can determine the measurable quantities that characterize a product. For example, a model that predicts warpage from flow simulation results would be a direct quality measure. The designer and manufacturer of a product are ultimately interested in the final measurable quantities that characterize a product. In contrast, an indirect measure of quality is a quantity that can be correlated to, but does not produce a direct measure of quality. Direct quality measures are usually more expensive to evaluate than indirect quality measures. The determination of indirect part quality measure based on flow simulation results will now be discussed.

The indirect quality measures used in this paper are those related to warpage, which is a direct measure of part quality. Part warpage is a dimensional distortion which is to be minimized for good quality part. It is a critical quality issue for most high quality injection molded parts. A mold which does not produce parts that satisfy the dimensional tolerances will lead to a costly and time-consuming mold redesign process. The flow-induced residual stresses within a part that cause warpage could be related to the unbalanced filling of the mold cavity. By minimizing unbalanced flow, warpage could be reduced or minimized. Hence, balanced flow is used as the indirect measure of quality for the present investigation. Objective function for the present investigation can be constructed as one achieves balanced flow.

For part with uniform thickness, balanced flow is achieved if all flow paths are of equal length. However, equal flow path length cannot be achieved practically. Instead, the variation between the lengths of the flow path is adopted as a measure of the uniformity of fill. The less the variation between the lengths of the flow paths indicates that the more balance is the flow. Thus, Lam and Jin [17] used the standard deviation of the flow path lengths as the objective function for gate location optimization to achieve balanced flow. However, for part with non-uniform thickness, the effect of flow paths on flow pattern cannot be reflected by the length alone. Thus, the standard deviation of filling time of the boundary nodes was used as the objective function instead for gate location optimization, and it was demonstrated to be a much better objective function than that of flow path length [17].

Although the standard deviation describes the overall variation of the filling time, and thus uniformity of fill, it does not reflect directly the range of the filling time. The range of filling time could also be employed to reflect the uniformity of fill, with smaller the range, the more uniform is the fill. It is possible that it could correlate better than the standard deviation for warpage. As such, the appropriateness of these two objective functions based on the standard and range of filling time respectively will be investigated.

Standerd deviation of filling time (SDT)

The details of using standard deviation of filling time as the objective function can be found in Lam and Jin [17]. The optimization problem can be stated as:

Minimize

$$F(\mathbf{X}) = \sqrt{\frac{N_{fp}\sum_{i=1}^{N_{fp}} t^2 - \left(\sum_{i=1}^{N_{fp}} t\right)^2}{N_{fp}\left(N_{fp}-1\right)}} \quad (1)$$

Subject to $\mathbf{X} \in \Omega$

where N_{fp} is the number of flow paths; t is the filling time of each flow path; $\mathbf{X}=[x, y, z]$, x, y, z are the coordinates of the corresponding gate; and Ω is the feasible search space.

Range of filling time (RT)

For the proposed new objective function using the range of the filling time, the optimization problem can be stated as:

Minimize

$$F(\mathbf{X}) = t_M - t_m \quad (2)$$

Subject to $\mathbf{X} \in \Omega$

where t_M, t_m are the maximum and minimum filling time for the polymer melt to reach the respective boundary nodes of the finite element model of the cavity; and X and Ω have the same meaning as before.

Search schemes for gate location optimization

Single-gate location optimization is considered in this investigation. The simplest method is the exhaustive search scheme (ES) that evaluates each and every candidate gate location. This method is easy to program and it guarantees that the result obtained is the global optimum. Thus, its solution is used as the reference or benchmark in this investigation. It is the most robust method with the severe limitation that it is computationally inefficient. In this paper, a methodology called flow path search scheme (FPSS) was developed. In the following section, different search methods are presented and a comparison is made.

Adjacent node evaluation scheme (ANES)

Lam and Jin [17] employed an adjacent node evaluation scheme. It chooses each node surrounding the current gate as candidate gate. The algorithm can be described as follows:

(1) Select a starting gate and evaluate the objective function F_s at the gate. g_s is the current gate.

(2) Evaluate all adjacent nodes g_s as potential gates g_1, g_2, …, g_n, and evaluate for each nodes its objective function F_1, F_2, …, F_n respectively. Select the smallest objective function value F_u and the corresponding gate g_u. If F_u<=F_s, let F_s=F_u and g_s=g_u.

(3) The searching process continues until no improvement is possible and the last chosen node becomes the optimum gate. A filling simulations is required for each g_1, g_2, …, g_n. Thus, considerable amount of computation is required.

Flow path search scheme (FPSS)

Instead of the above search algorithms, we propose here a simple but effective flow path search scheme. In order to reduce the standard deviation or the range of filling time, it is generally necessary to reduce the maximum filling time. Maximum filling time will be reduced by moving the gate location along the flow path of maximum filling time. This means that the search direction is along the flow path with maximum filling time. This proposed algorithm is interfaced with Moldflow©, the commercial software employed for simulating the injection molding filling stage. The algorithm implemented can be described as:

(1) An initial gate location is selected based on the experience of the designer.

(2) Run Moldflow© software to simulate the filling stage.

(3) Select the last-filled boundary node.

(4) Generate flow path from the last-filled node to the injection gate.

(5) Move the injection node along the generated flow path at a set distance. Subsequently run Moldflow© software to simulate the filling stage for the new design. If the filling time range is reduced, repeat the iteration from step 3.

(6) If the time difference is not reduced, check if the set distance is equal to the minimum set distance. If so, stop iteration. If not, go to step 5 but with a reduction in the set distance, say 50% of the original set distance. Fig. 1 shows the flow chart of the process.

The gate locations obtained during the iteration process may not coincide with the nodes of the pre-assigned finite element mesh. However, the mesh could be adjusted easily so that there is a node corresponding to the location of the injecting gate. This can be achieved by moving the node nearest the gate location to the gate location. The nodes adjacent to the gate are moved in such way that the geometry of the elements connected to the gate node remains unchanged and with acceptable distortion for elements immediately surrounding the elements connected to the gate. This mesh adjustment scheme avoids the regeneration of mesh, but with acceptable accuracy.

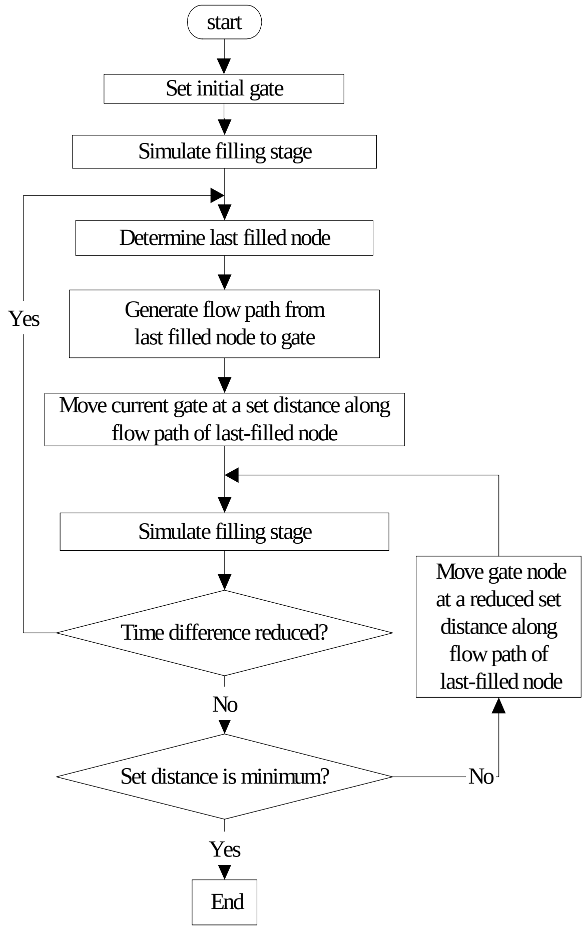


Fig. 1. Flow chart of the optimization scheme.

Case study

Two examples are presented here to illustrate the effectiveness of the proposed methodology.

Example1: a rectangle plate

The first example is a 200×40×2 mm rectangular plate. This example is chosen for verification purposes since the optimal gate location to achieve balanced flow should be at the center of the plate purely by symmetrical consideration.

This numerical model has 203 nodes and 336 elements. The mesh size was chosen based on consideration of computational effort and solution accuracy of the gate locations. Finer mesh would result in gate location which is closer to the actual optimal location. The maximum error is directly related to the mesh size. PS (Styron 478, Dow Chemical USA) was employed as the polymer material and its viscosity is calculated by Cross-WLF model:

$$\eta(\dot{\gamma},T,P)=\frac{\eta_0(T,P)}{1+(\frac{\eta_0\dot{\gamma}}{\tau^*})^{1-n}} \tag{3}$$

whereas,

$$\eta_0(T,P)=D_1\exp\left(-\frac{A_1(T-T^*)}{A_2+(T-T^*)}\right) \tag{4}$$

$$T^*(P)=D_2+D_3P \tag{5}$$

$$A_2=\overline{A}_2+D_3P \tag{6}$$

n, τ^*, D_1, D_2, D_3, A_1, A_2 are material constants, and its values are adopted as 0.3455, 10300Pa, 1e+012Pa·s, 373.15K, 0, 25.921 and 51.6K respectively. The molding conditions adopted were:

mold temperature = 50 ºC; melt temperature = 200 ºC; injection rate = 1E-03 m^3s^{-1}; pack time = 6s; and pack pressure =100 MPa.

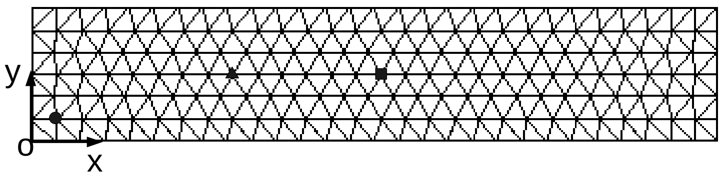


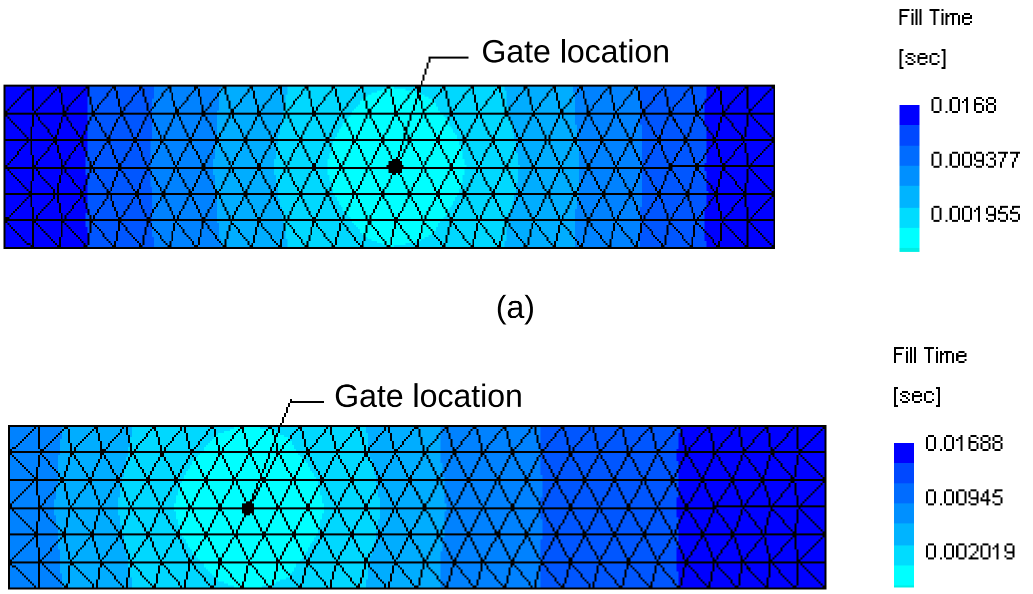
Fig. 2. The initial and optimum gate locations (● initial gate location ▲, ■ approximate optimum gate location for SDT and RT respectively)

The initial gate (7.55, 6.66) was located at the lower left hand corner of the plate, as shown in Fig. 2. The resin flow of this gate design is unbalanced. Unbalanced flow causes overpacking and so the part exhibits excessive warpage of 0.83 mm. Flow path search scheme (FPSS), and adjacent node evaluation scheme (ANES) were applied respectively to search for the optimal gate location, with standard deviation of filling time and range of filling time as objective function respectively. The results obtained separately using the exhaustive search algorithm (ES) were used as the benchmark. The coordinates of the optimum gate locations obtained are shown in Table1.

From Table 1, for both objective functions, the optimal gate locations obtained by FPSS and ANES are very close or identical to that obtained by ES. Satisfying results are achieved by both schemes. Both ANES and ES determine the gate location based on the initial finite element nodes, thus the optimum gate location is identical with each other. FPSS determines the gate location based on flow path with mesh adjustment. As a result, the generated gate may not coincide with the initial finite element nodes. Thus, there is a slight difference between the optimum results of FPSS and ES. The optimum gates obtained by FPSS and ES are within the tolerance of the length of a triangular element as expected. Though both FPSS and ANES can achieve good results, FPSS is of higher efficiency, requires 40% less iterations when compared with ANES.

Tab. 1. Optimum Results of the Rectangular Plate.

		RT			SDT		
		FPSS	ANES	ES	FPSS	ANES	ES
Coordinates of Optimal Gate Location	X(mm)	100.2	101.8	101.8	56.7	58.9	58.9
	Y(mm)	22.1	20.0	20.0	21.4	20.0	20.0
Number of Iterations		30	51	203	19	31	203
Warpage (mm)		0.64	0.64	0.64	0.67	0.67	0.67



(a)

(b)

Fig. 3. Melt front advancement of a rectangle plate. (a) RT optimum design (b) SDT optimum design.

From Table 1, we can observe that the optimal gate location for the objective function of range of filling time is near the centre of the plate, i.e. (100, 20) within the tolerance of an element as expected. The optimal gate location obtained with the standard deviation of filling time as objective function is near (59, 20), which is far away from the optimum location from symmetry consideration. The optimum gate locations obtained by these two different objective functions are shown in Fig. 2. The fill patterns of these optimum designs are shown in Fig. 3(a) and 3(b) respectively. It can be observed that the flow pattern for the gate design obtained with SDT as objection function is unbalanced, whereas the flow pattern for the gate design obtained with RT as objective function is rather balanced. As shown in Table 1, the warpage of the part produced by the optimal gate design obtained with RT as objective function (0.64) is smaller than that obtained with SDT as objective function (0.67). So the range of filling time is a better objective function than the standard deviation of filling time.

Example 2: the hubcap

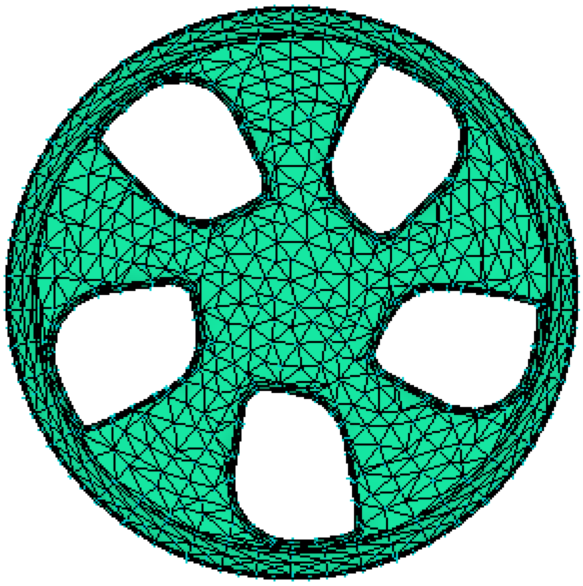


Fig. 4. Part geometry of hubcap.

A more complicated component, that of a hubcap, is used here to demonstrate the effectiveness of the proposed scheme. The dimension of the part is 400×400 mm, with thickness varying from 3-5 mm. There are 1084 nodes and 1961 elements in the finite element mesh model as shown in Fig. 4. The material used is PS (Styron 478, Dow Chemical USA), and a same Cross-WLF model is employed to calculate its viscosity during simulaiton. The molding conditions adopted are: mold temperature = 50 ºC; melt temperature = 200 ºC; injection rate = 1E-03 m^3s^{-1}; pack pressure =100 Mpa; and pack time is 10 s. By choosing the initial gate near the rim (359.82, 258.73, 30.02), the part exhibits excessive warpage (1.86 mm) due to overpacking in the rim area. The problem is obvious in the plots of filling time distribution in Fig. 5(a), which shows that the flow is unbalanced because of the gate location. This is the major cause of overpacking leading to excessive warpage.

Flow path search scheme, adjacent node search scheme and exhaustive search scheme are employed to obtain the optimum gate location, with RT and SDT as objective function respectively. Through the searching process, the optimum gates are automatically located. The optimum results and efficiency of the search scheme is shown in Table 2.

From Table 2, it can be observed that for this part, the optimum gate locations obtained by both objective functions and all the three search schemes are close to the centre of the part, i.e. at (200.00, 200.00, 37.24). Thus, for this example, the advantage of RT over SDT is not obvious. It appears that only at situation where the ratio of length to width of the part is high, the possibility is higher for the optimum gates obtained with the two objective functions to be far from each other. For part with the ratio of length to width approaching one as in this example, the optimum gate locations obtained by RT and SDT may coincide with each other.

In this example, the number of iteration for FPSS is only 60% of that for ANES for both objective functions. This demonstrates that FPSS is much more efficient than ANES. Fig. 5(b) shows the filling time contours with optimized gate located at

(213.87, 200.26, 37.28). A balanced flow in the cavity is achieved. As shown in Table 2, the warpape of the optimized design was reduced to 1.64 mm, a 11.8% reduction compared with the initial gate location under the same molding condition.

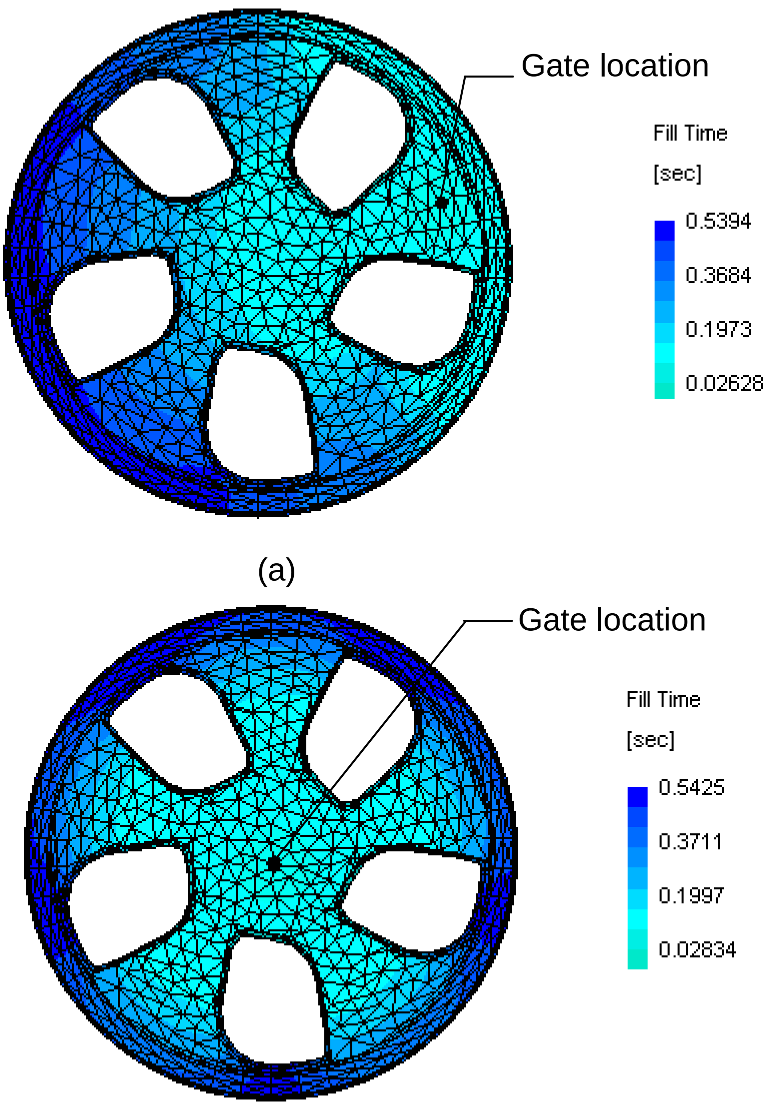


Fig. 5. Melt front advancement for hubcap (a) initial design (b) optimum design.

Tab. 2. Optimum Results of the Hubcap.

		RT			SDT		
		FPSS	ANES	ES	FPSS	ANES	ES
Coordinates of optimal gate location	X(mm)	216.51	213.87	213.87	210.54	213.87	213.87
	Y(mm)	209.06	200.26	200.26	209.46	200.26	200.26
	Z(mm)	37.29	37.28	37.28	37.27	37.28	37.28
Number of iterations		28	47	1084	29	49	1084
Warpage (mm)		1.64	1.64	1.64	1.64	1.64	1.64

Conclusions

A gate location optimization scheme is developed by minimizing the range of filling time to achieve a balanced flow in the cavity so that warpage of the part will be reduced. A new methodology for the search direction based on flow path is developed. Comparisons are made between the appropriateness of the objective function of the range of filling time and the existing standard deviation of filling time, and the efficiency of the flow path search scheme and the existing adjacent node evaluation scheme. It is concluded that flow path search scheme is more efficient and the range of filling time is a better objective function for gate location optimization.

Acknowledgements

The authors would like to acknowledge the support of the Academic Research Fund, Ministry of Education, Singapore and Moldflow Pty Ltd.

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