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2
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Multi-Objective Optimization of Gate Location and Processing Conditions in Injection Molding Using MOEAs: Experimental Assessment

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Abstract. The definition of the gate location in injection molding is one of the most important factors in achieving dimensionally accuracy of the parts. This paper presents an optimization methodology for addressing this problem based on a Multi-objective Evolutionary Algorithm (MOEA). The algorithm adopted here is named Reduced Pareto Set Genetic Algorithm (RPSGA) and was used to create a balanced filling pattern using weld line characterization. The optimization approach proposed in this paper is an integration of evolutionary algorithms with Computer-Aided Engineering (CAE) software (Autodesk Moldflow Plastics software). The performance of the proposed optimization methodology was illustrated with an example consisting in the injection of a rectangular part with a non-symmetrical hole. The numerical results were experimentally assessed. Physical meaning was obtained which guaranteed a successful process optimization.

Keywords: Multi-Objective Evolutionary Algorithms · Gate Location · Moldflow

1 Introduction

Injection molding is a complex but efficient polymer processing technique for producing a variety of plastics parts. It is especially adequate to produce products with low dimensional tolerances and complex shapes. It consists in reproducing the required geometry previously machined in the mold by injecting molten polymer into the mold cavity. The quality of the injection moulding parts are affected by different processing parameters, machine control system (e.g., injection cycle times and injection and holding pressures), cooling system (e.g., cooling channels geometry and cooling liquid temperature), gates and runners (e.g., geometry and location) and cavities (e.g., geometry and total flow length). An important factor is the gate location, since it influences the way the polymer flows into the mold cavity, affecting the existence or not of weld lines and its eventual location, the shrinkage, mold filling pattern, dimensional tolerances, degree and direction of orientation, pressure distribution in the cavity, sink marks, gas traps and short shots, warpage and residual stress. Thus, the definition of the number, type, and location of the gate(s) is of high importance. These concepts will be explained in section 2.

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For optimizing gate location it is necessary the integration of tools, such as, simulation software able to take into account the referred processing parameters and optimization methodologies. There are in the literature various optimization strategies using different methodologies to optimize gate location in injection molding.

Pandelidis and Zou (1990) optimized gate location based on the combination of simulated annealing with a hill-climbing method [1]. The optimization effect is restricted by the determination of some weighting factors used by the authors. Young (1994) used a genetic algorithm to optimize gate location for the case of the molding of a liquid composite based on the minimization of the mold-filling pressure, the uneven-filling pattern and the temperature difference during mold filling [2]. Lee and Kim (1996) proposed an automated selection method for gate location, in which a set of initial gate locations were proposed by a designer and, then, the optimal location of the gate was defined using the adjacent node evaluation method [3]. The scheme can be used for complicated parts, but it requires an extensive number of design evaluations to obtain the best gate location. In their work, Douglas et al. (1998) designed a mold by combining process modelling and sensitivity analysis [4]. The gate location and injection pressure profile were optimized through minimizing the filling time. The extension of the proposed methodology to more complicated geometries is not obvious. Lam and Jin (2001) proposed the optimization of gate location based on the flow path concept [5]. For complicated parts, such as ones including holes, ribs and/or boss, the appropriate boundary is not easy to select automatically by computer being the user input required. Courbebaisse and Garcia (2002) suggested a shape analysis to estimate the best gate location of injection molding [6]. This methodology can only be used for simple flat parts with uniform thickness but it is easy to use and is not time-consuming. Shen et al. (2004) optimized the gate location by minimizing a weighted sum of filling pressure, filling time difference between different flow paths, temperature difference and over-pack percentage [7]. A hill-climbing algorithm was used to search the optimal gate location. Zhai et al. (2005) developed an efficient search method based on pressure gradient (PGSS) to optimize the location of two gates for a single molding cavity [8]. The weld lines were subsequently positioned to the desired location by varying runner sizes [9]. Li et al. (2007) proposed a different objective function to evaluate the warpage of injection molded parts [10]. The quality of the warpage was defined from the "flow plus warpage" simulation outputs of Moldflow software and the optimization is made by using simulated annealing. Wu et al. (2011) developed a study where the combination of different classes of design variables are considered simultaneously, together with both the length and the position of the weld line as design constraints [11]. This study adopted an enhanced genetic algorithm, called Distributed Multi-Population Genetic Algorithm (DMPGA), combining with a commercial Moldflow software and a master–slave distributed architecture. However, only runner size, molding conditions and part geometry are taken into consideration.

The above methodologies proposed to optimize gate location have some important limitations, namely, the capacity to handle with multi-objectives simultaneously, the linkage with the simulation codes and the complexity of the part geometry.

Therefore, in the present work an automatic optimization methodology based on Multi-Objective Evolutionary Algorithms (MOEA) is used to define the processing conditions and the gate location in injection molding of a complicated part containing a hole [12]. For that purpose a MOEA is linked to an injection molding simulator code (in this case Moldflow). The proposed optimization methodology was applied to a case study where the processing conditions and the gate location are established in order to create a balanced filling pattern, achieved by weld line length minimization, to maximize part quality, guaranteed by difference between the shrinkage at the end of the flow and the pre-defined design value and to minimize the cycle time to provide low costs on part production. Finally, the optimization results were assessed experimentally. This article follows two previous papers [14, 15] with additional contribution subjected to the following tasks. First, Moldflow substituted C-Mold as the simulator program used in the other studies. Also, the way to connect Moldflow to the RPSGA algorithm is more sophisticated than with C-Mold. In this case AutoIt program was used to mimic human interface with MoldFlow because input variables and output results are not allowed to be changed/saved by command line. Second, the robustness of the optimization methodology was tested by using injection molding gate location as a case study. Finally, to our knowledge, the experimental assessment of the gate location optimization results is a relevant step in the literature.

This paper is organized as follows: first the optimization methodology used is described, specifying how the MOEA interacts with the simulation software Moldflow; second, a case study based on the use of a rectangular part to be injected with a non-symmetrical hole is presented and, finally, gate location optimization results are shown and compared with experimental measurements.

2 Optimization Methodology

2.1 Injection Molding Process

Injection molding is a process of polymer transformation involving several steps, which are performed in an order that is repeated at each cycle, such as plasticizing, packing and cooling. A typical injection molding machines (see Figure 1) have four units: power supply unit, injection unit, clamping unit and control unit. The main concern in injection molding is to produce plastic parts of the desired quality, which are related with mechanical characteristics, dimensional conformity (shrinkage, warpage) and appearance (sink marks, weld lines).

For this study it is important to clarify the concepts of shrinkage, warpage and weld lines. Shrinkage is defined as the reduction in the size of a molded component in any direction after it has been ejected from the mold do to the cooling. Warpage occurs when there are variations of internal stresses in the material caused by a variation in shrinkage. A weld line is formed when separate melt fronts travelling in opposite directions meet. Instead, a meld line occurs if two emerging melt fronts flow parallel to each other and create a bond between them. Thus, the meeting angle is used to differentiate weld lines and meld lines. If the meeting angle is smaller than 135 degrees produces a weld line. If the angle is greater than 135 degrees it will produce a meld line. In the first case, a weld line surface mark will appear in the part, but when the meeting angle reaches 120 - 150 degrees it will disappear. Weld lines are considered to be of lower quality than meld lines, since relatively less molecular diffusion occurs across a weld line after it is formed. Therefore, weld lines are the weakest areas on the part and are the potential failure locations (Moldflow reference [13]).

The major factors affecting part quality are polymer properties, mold design and operating conditions. Some of these variables will be considered later in the optimization methodology.

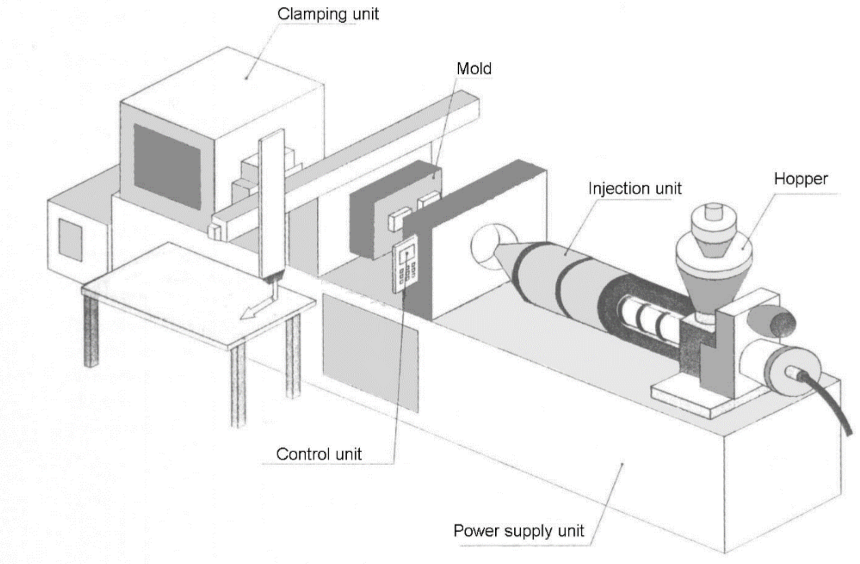

Fig. 1. Functional units of the injection molding machine

2.2 Integrated Methodology

A methodology, integrating modelling of the injection molding process and an optimization strategy based on MOEA, is proposed [14, 15]. The aim being to define the best injection gate location and injection molding operating conditions in order to minimize the cycle time, the differential shrinkage and the weld line location and length, using as example the production of an injection part with a hole (see Figure 3).

EAs are based on the principles of natural selection of survival of the fittest individual by mimicking some of the concepts of this natural process. The selection, crossover and mutation concepts are used by the EA to explore the search space in order to find an optimal solution or a set of optimal solutions. The initial population of chromosomes represents the gate location and/or the set of operative processing variables, which is generated randomly within the feasible search space. Then, these solutions are evaluated using the modelling routine (Autodesk Moldflow 2010 software). The performance of each one of the solutions (chromosomes) proposed by the MOEA is quantified using as objectives the minimization of the cycle time, the differential shrinkage and the length and location of the weld line. A MOEA was used to optimize the process [16]. The Reduced Pareto Set Genetic Algorithm (RPSGA) proposed previously was used for that purpose. First, the population is random initialized, where each individual (or chromosome) is represented by the binary value of the set of all variables. Then, each individual is evaluated by calculating the values of the relevant objectives using the modeling routine. Finally, the remaining steps of a MOEA are to be accomplished. To each individual is assigned a single value identifying its performance on the process (fitness). If the convergence objective is not satisfied (e.g., a predefined number of generations), the population is subjected to the operators of reproduction (i.e., the selection of the best individuals for crossover and/or mutation) and of crossover and mutation (i.e., the methods to obtain new individuals for the next generation). The solution must result from a compromise between the different objectives. Generally, this characteristic is taking into account using an approach based on the concept of Pareto frontiers (i.e., the set of points representing the trade-off between the objectives) together with an MOEA. This enabled the simultaneously accomplishment of the several solutions along the Pareto frontier, i.e., the set of non-dominated solutions. The performance of this algorithm was tested in a set of problems and its efficiency well demonstrated [12].

Figure 2 shows the interface for integrating Autodesk Moldflow 2010 and the GA-based optimization routine. First, coordinates of injection point are sent to Moldflow Adviser by an AutoIt script which mimics the user interface with computer. Next, geometric Moldflow Adviser file is renamed to geometric Moldflow Synergy file and an AutoIt script is executed to remesh the part and define processing conditions to be used in the simulation. A Fill+Pack+Warp analysis is done through command files provided by Moldflow Synergy software. When the analysis is finished, an AutoIt script is executed in order to obtain differential shrinkage in two different locations and weld line/meld line results files are saved. The optimization routine will use these results to calculate the cycle time, the dispersion of differential shrinkage and the length of the weld plus meld line, as described in next section.

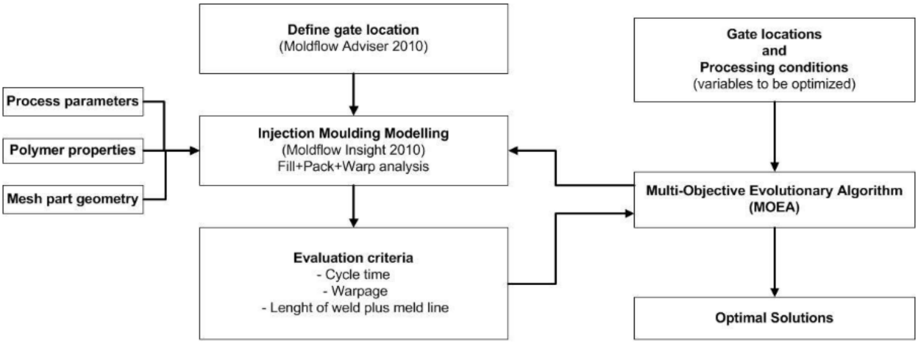

Fig. 2. Interfacing between optimization routine and Moldflow software

3 Case Study

3.1 Problem Description

To demonstrate the validity of the proposed optimization methodology, the study of the gate location of a rectangular molding with a hole, as represented in Figure 3, was used. The molding has a thickness of 1.5mm, a width of 60 mm and a length of 140 mm. The finite element mesh used has 940 triangular elements and 525 nodes (see Figure 3). The part is molded in a polypropylene, PPH 5060, from TOTAL Petrochemicals. The polymer properties used in the simulations were obtained from the Moldflow database (Moldflow 2010): melt density of 0.73406 g/cm^3, solid density of 0.90032 g/cm^3, melting temperature of 230 ºC, ejection temperature of 60 ºC, maximum shear stress of 0.25 MPa, maximum shear rate of 100000 1/s, specific heat of 2700 J/kg ºC, thermal conductivity of 0.17 W/m ºC, elastic module of 1400 MPa and Poisson ratio of 0.42. The material selected for the mold was a P20 steel. Concerning the processing conditions only the mold open time was maintained constant and equal to 5 seconds.

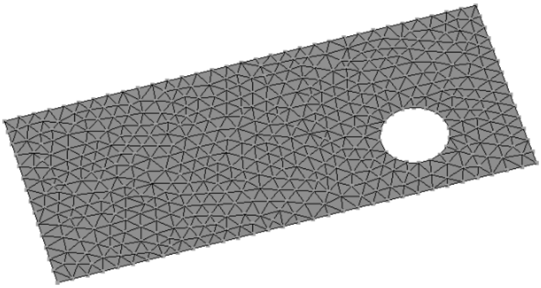

Fig. 3. Injection molding part to be used

The simulations in Moldflow are based on a hybrid finite-element/finite-difference/control-volume numerical solution of the generalized Hele-Shaw flow equation of a compressible viscous fluid under non-isothermal conditions. The polymer rheological and PVT behaviors were modelled by a Cross-WLF and the Tait modified equations, respectively. More details about the software are described in literature [17, 18, 19]. The simulations phases considered when using Moldflow are Fill, Pack and Warp analysis, including melt flow, packing, residual stress calculations and structural analysis.

3.2 Decision Variables

Two type of decision variables were considered in this study, design and operating conditions. The design variables are the injection gate location, that are defined by x and y coordinates of the node points in the mesh were they are located. Due to existing experimental restrictions only the left, right and upper boundary nodes were admitted as injection gate location. Six operating conditions were considered, filling time, melt and mold temperatures, holding time, holding pressure and cooling time. Table 1 summarizes the design variables selected and the corresponding range of variation.

Table 1. Range of variation of the decision variables

Decision variables	Range of variation
X coordinate (mm) – x	[0,140] subject to constraint
Y coordinate (mm) – y	[0, 60] subject to constraint
Fill time (s) - t_f	[1, 5]
Melt temperature (°C) - T_{inj}	[190, 270]
Mold temperature (°C) - T_w	[10, 50]
Holding pressure (MPa) - P_h	[30, 60]
Packing time (s) - t_p	[1, 20]
Cooling time (s) - t_c	[5, 20]

The RPSGA uses a real representation of the variables, a simulated binary crossover, a polynomial mutation and a roulette wheel selection strategy [12]. The following RPSGA parameters were selected: 10 generations, crossover rate of 0.8, mutation rate of 0.05, internal and external populations with 30 individuals, limits of the clustering algorithm set at 0.2 and NRanks at 30. These values resulted from a carefully analysis made in a previous work [12]. The computation time required by the MoldFlow software to evaluate a single candidate solution is approximately 5 minutes. Thus, the time necessary for a complete optimization is circa of 25 hours. This multi-objective problem used a 'budget' of 300 evaluations because of the expensive nature of evaluating candidate solutions, namely, the time taken to perform one evaluation, only one evaluation can be performed at one time and also the dimensionality of the search space is low-to-medium [20]. The proposed optimization methodology will be used for setting the injection location and to define the selected processing conditions that satisfy the objectives defined.

3.3 Objective Functions

The optimization problem consists in defining the values of the decision variables that allow the production of a part with the minimum cycle time, to minimize the production costs, the minimum of warpage due to the anti-symmetric shrinkage and the minimum of weld plus meld line length, so that weakest areas are minimized.

These objectives are defined as follows:

- Minimize cycle time, *CT*:

$$\min CT = t_f + t_p + t_c + t_o \tag{1}$$

where t_f is the filling time, t_p is the packing time, t_c is the cooling time and t_o is the mold open time.

- Minimize warpage, *WARP*:

$$\min WARP = \sqrt{\frac{{ds_1}^2+{ds_2}^2}{2}} \tag{2}$$

where ds_1 and ds_2 are the differential shrinkage values measured in longitudinal and transversal directions, respectively.

- Minimize length of weld plus meld line, *LWML*:

$$\min LWML = \sum_{i,j} \sqrt{\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2 + \left(z_i - z_j\right)^2} \tag{3}$$

where (x_*, y_*, z_*) represents the coordinates of the nodes in the finite element mesh were the weld and meld lines are located as calculated by Moldflow.

4 Results and Discussion

4.1 Optimization Results

Figure 4 shows the results obtained for an optimization run considering simultaneously the three objectives defined before (minimization of cycle time, length of weld plus meld line and warpage), the aim being to define the best values for the decision variables presented in Table 1. The figure represents all solutions of the initial population and the non-dominated solutions of the final population (10th generation). The operating conditions and objectives of the optimal solutions found are presented in Table 2.

Table 2. Solutions for gate location optimization

	Variables						**Objectives**		
Solutions	T_w (°C)	T_{inj} (°C)	t_f (s)	P_h (%)	t_p (s)	t_o (s)	*CT* (s)	*WARP* (%)	*LWML* (m)
P1	46	268	2.20	42	1.16	5.00	13.36	0.815	0.0331
P2	28	268	4.30	56	12.7	10.1	32.06	0.800	0.0216
P3	46	269	2.84	44	6.57	6.39	20.80	0.800	0.0219
P4	38	265	2.61	47	1.49	5.30	14.20	0.820	0.0103
P5	40	265	2.44	46	1.00	5.35	13.79	0.820	0.0216
P6	46	268	2.27	42	1.21	5.40	13.88	0.815	0.0216
P7	44	264	1.37	44	3.02	6.23	15.62	0.815	0.0106

There is a clear improvement from the initial population to the 10th generation, since the optimal solutions found have better values for the objectives considered. Also, there is not a solution that, simultaneously, provides the better (minimum) values for all three objectives. Therefore, three cases will be analyzed considering each one of the objectives as the most important.

If cycle time is considered the most important objective, the solution with lower cycle time is P1 in Figure 4. In this case *CT* is equal to 13.36 s, *WARP* is equal to 0.815 % and *LWML* is equal to 0.0331 m that is the highest value found for the length of weld plus meld line. Therefore, this solution is unsatisfactory when the length of weld plus meld line is considered. The injection molding machine must operate with a fill time of 2.2 s, melt and mold temperatures of 268 ºC and 46 ºC, respectively, holding pressure of 42 MPa, packing time of 1.16 s and cooling time of 5 s.

Figure 5 (A) shows the gate location and the filling pattern, while Figure 5 (B) shows weld line location for solution P1 as calculated by Moldflow. Since gate location is positioned in the top left corner of the part the two melt fronts will meet in the bottom right corner of the hole (were the weld line is plotted in Figure 5 (B)). In this case, the flow pattern design does not reach the top, bottom and left cavity boundaries uniformly, as shown by the filling pattern in Figure 5 (A). However, no weld lines were formed, since the meeting angles of the flow fronts are kept higher than 135 °. The line shown in Figure 5 (B) represents both a weld and a meld line, but that does not represent a problem for the molded part since the weld line does not reach the external boundary of the part. Figure 5 (C) shows the warpage distribution for solution P1. The value of WARP represents the standard deviation of differential shrinkage values measured on the boundary midpoints in horizontal and vertical directions. For the present case means that the distances between these points after part production only differs of 0.815 % when compared with the distances in the mold cavity.

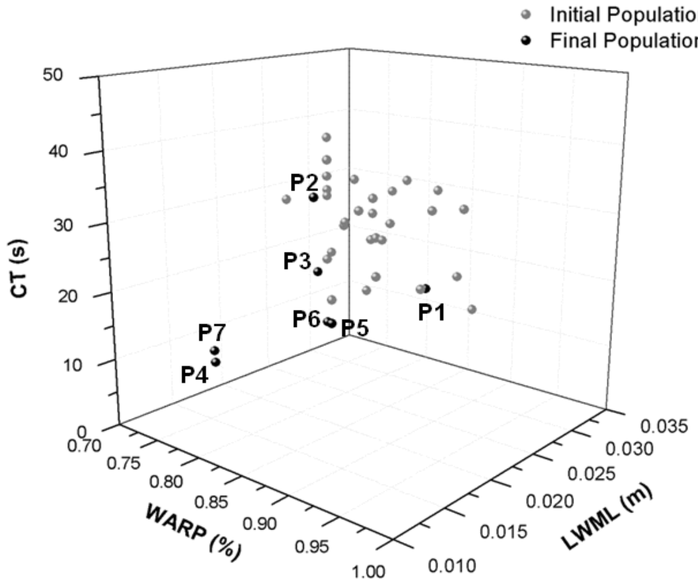

Fig. 4. Optimization results for three objectives in the objectives domain. Black symbols: Pareto frontier at 10th generation; grey symbols: initial population (CT – cycle time, WARP – warpage, LWML – length of weld plus meld line).

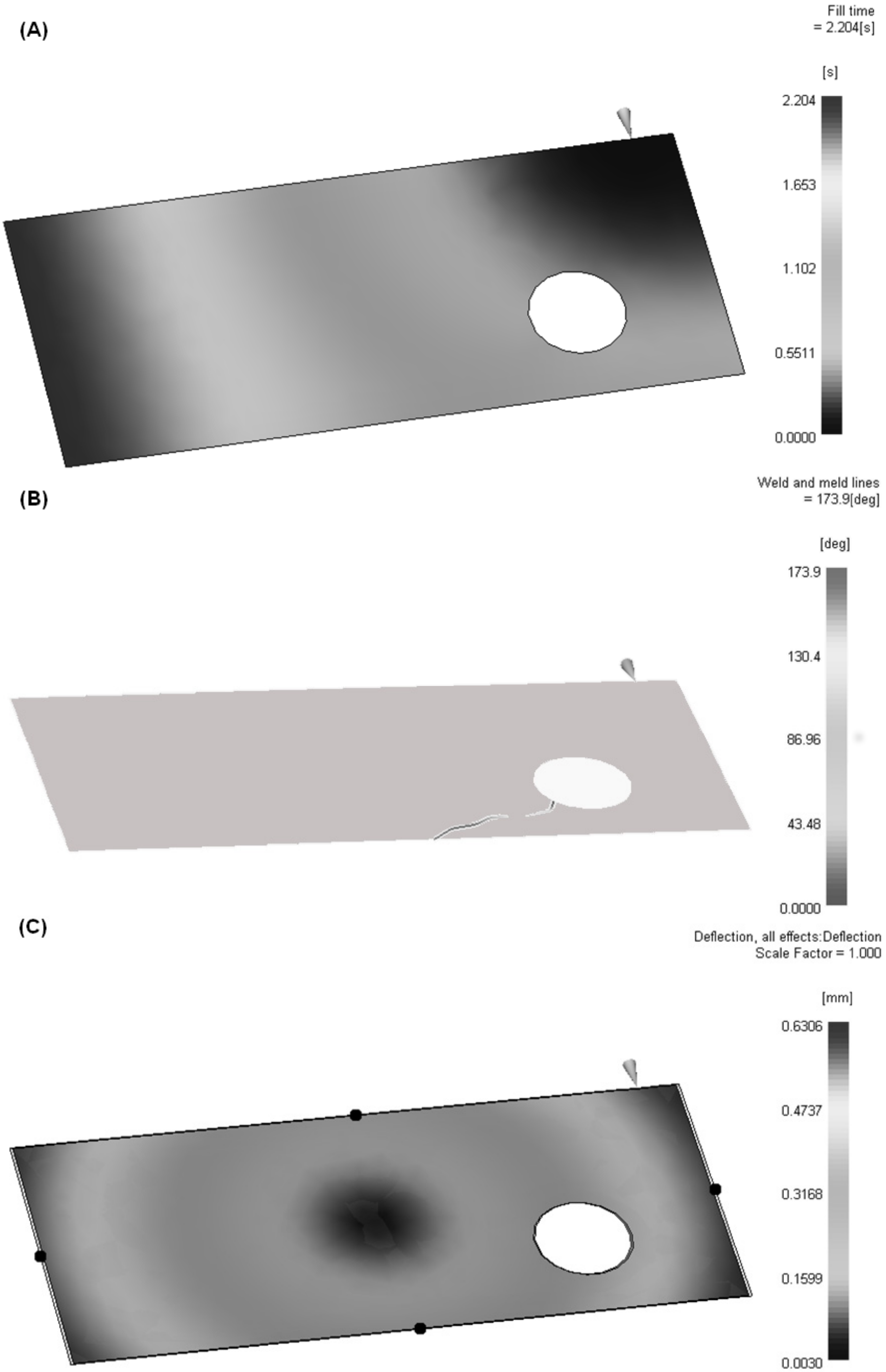

Fig. 5. Filling pattern (A), weld/meld line position (B) and warpage distribution (C) for solution P1

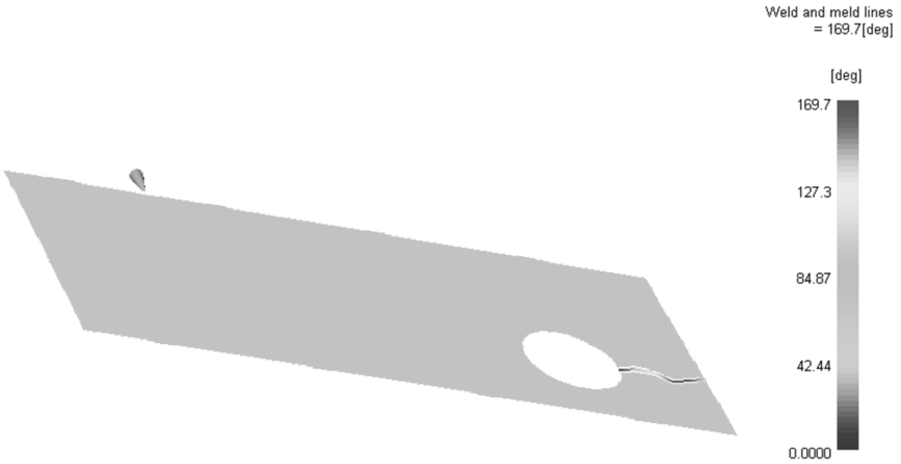

Fig. 6. Weld/meld line position for solution P2

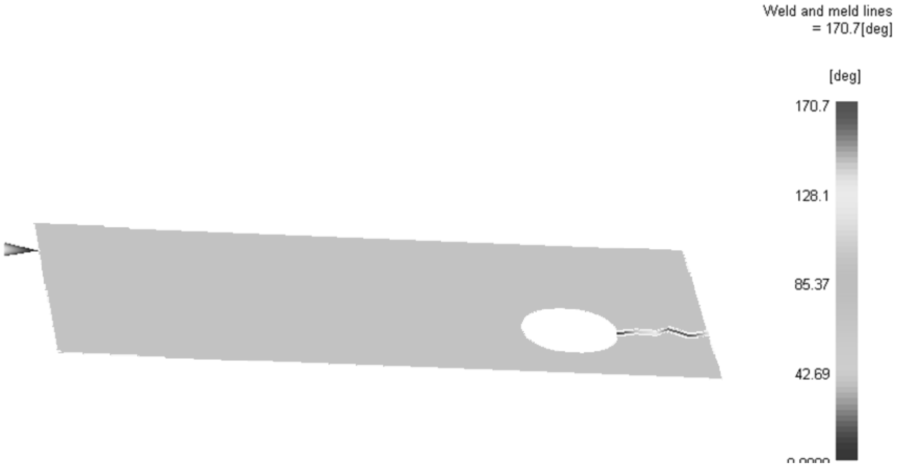

Fig. 7. Weld/meld line position for solution P3

When warpage is considered the most important objective to satisfy, two solutions were obtained with lower warpage values, i.e., solutions P2 and P3. The main difference between these two solutions is related with the cycle time, which is 32.06 s for P2 and 20.80 s for P3. Since the values of WARP and LWML are very similar, it is clear that P3 is a much better solution than P2. Concerning solutions P2, P3 and P4, only the location of the weld plus meld lines are represented, since these are the results used in the experimental assessment. Figures 6 and 7 represents the location of weld plus meld line, respectively for P2 and P3. In both cases, the gate is located in the top right corner of the part and thus the weld plus meld line appear in the bottom left corner of the hole. Also, only meld lines are formed for these two solutions in the external boundary of the part. Figure 8 presents the modelling results for solution P4, i.e., the solution with lower length of weld plus meld line. In this case only a weld line

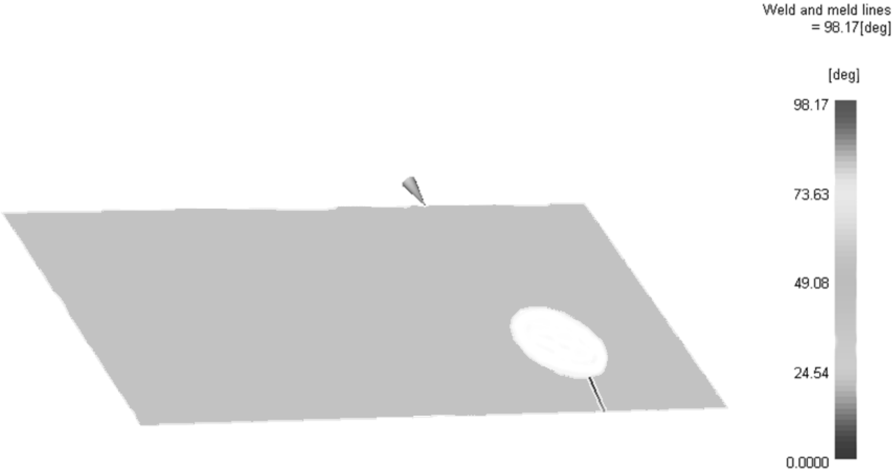

Fig. 8. Weld/meld line position for solution P4

forms on the bottom surface of the molded part (as all the meeting angles of the flow fronts are lower than 135 °), which, due to the reasons referred above, makes this a bad solution concerning this aspect. Simultaneously, this solution has the higher value for WARP (0.820 %).

4.2 Experimental Assessment

The optimization results presented in the last section were experimentally compared using solutions P1 to P4 analyzed in the previous sections (Figure 4). The mold used for the experimental studies was built with four different gate locations corresponding to each of the solutions P1 to P4 (Figure 5 to 8). For the part weld lines characterization a crossed polarizer was used to obtain the locations of the weld lines. To be possible to perform experimentally the optimization/modelling results, the total cycle time was fixed in the machine. Figure 9 shows the experimental weld lines locations for the four solutions chosen. The weld lines are identified in the figure with arrows to better understand their location. As can be seen the experimental results confirm the location of the weld lines predicted by the optimization methodology (Figure 5 to 8).

Figure 10 shows the simulation vs. experimental warpage measurements. The results are graphically represented in two different plots to better distinguish the shapes of the curves due to differences in warpage scale. As can be seen the experimental results follow the same tendency of the simulated ones. Solution P1 is the only one that has a different pattern comparing to the simulated one, due to the use of a lower packing pressure in few packing time (see Table 2). In agreement with the simulation results the experimental solutions P2 and P3 have similar values. Moreover, those values are the lowest ones for warpage criteria. This can be explained by the use of a packing pressure during more time than in solutions P1 and P4. Quantitative differences between experimental and numerical results are explained by the fact that in the numerical warpage calculation the effect of differential shrinkage, differential cooling and orientation effects are taken into consideration. Simultaneously, the experimental measurements were made considering only the differential shrinkage effect.

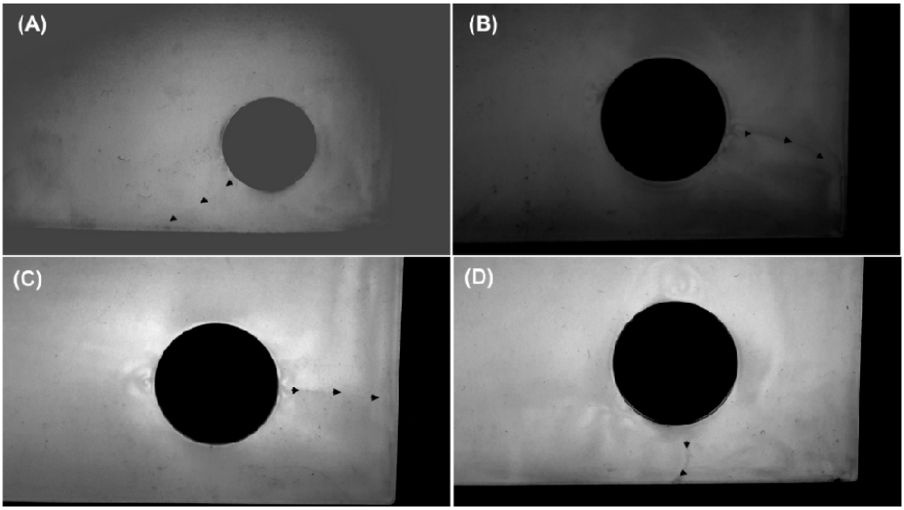

Fig. 9. Experimental weld lines location for solution P1 (A), solution P2 (B), solution P3 (C) and solution P4 (D)

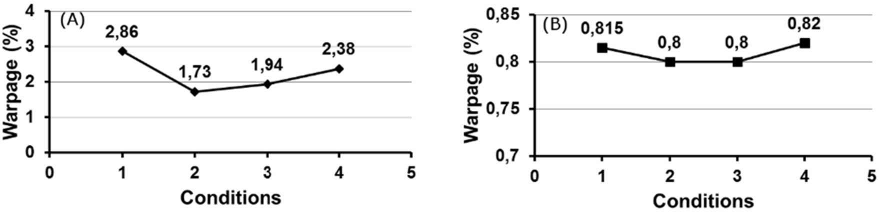

Fig. 10. (A) Experimental and (B) optimization warpage results for solutions P1 to P4

5 Conclusions

In this work, a multi-objective optimization methodology based on Evolutionary Algorithms (MOEA) was applied to the optimization of processing conditions and gate location of a rectangular molding with a hole in order to minimize the cycle time, the warpage and the length of weld plus meld line.

The methodology proposed was able to produce results with physical meaning. The optimization algorithm is able to minimize simultaneously the three objectives defined through the generation of optimal Pareto frontiers showing the trade-off between the solutions found. This allows the user the comparison between these solutions to select the best that corresponds to their design purposes.

Finally, the optimization results were assessed experimentally. The experiments obtained in an injection machine available shows identical behavior when compared with the computational ones.

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