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ORIGINAL ARTICLE

Optimization and Simulation of Plastic Injection Process using Genetic Algorithm and Moldflow

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Abstract The use of plastic-based products is continuously increasing. The increasing demands for thinner products, lower production costs, yet higher product quality has triggered an increase in the number of research projects on plastic molding processes. An important branch of such research is focused on mold cooling system. Conventional cooling systems are most widely used because they are easy to make by using conventional machining processes. However, the non-uniform cooling processes are considered as one of their weaknesses. Apart from the conventional systems, there are also conformal cooling systems that are designed for faster and more uniform plastic mold cooling. In this study, the conformal cooling system is applied for the production of bowl-shaped product made of PP AZ564. Optimization is conducted to initiate machine setup parameters, namely, the melting temperature, injection pressure, holding pressure and holding time. The genetic algorithm method and Moldflow were used to optimize the injection process parameters at a minimum cycle time. It is found that, an optimum injection molding processes could be obtained by setting the parameters to the following values: $T_{\mathrm{M}} = 180$ °C; $P_{\mathrm{inj}} = 20$ MPa; $P_{\mathrm{hold}} = 16$ MPa and $t_{\mathrm{hold}} = 8$ s, with a cycle time of 14.11 s. Experiments using the conformal cooling system yielded an average cycle time of 14.19 s. The studied conformal cooling system yielded a volumetric shrinkage of 5.61% and the wall shear stress was found at 0.17 MPa. The difference between the cycle time obtained through simulations and experiments using the conformal cooling system was insignificant (below 1%). Thus, combining process parameters optimization and simulations by using genetic algorithm method with Moldflow can be considered as valid.

Keywords Conformal cooling · Parameters optimization · Genetic algorithm · Moldflow · Cycle time

1 Introduction

The increasing use and development of plastic components in the manufacturing of household appliances, automotive components, electronic products, health-care equipment, and aircraft components has caused the needs for plastic raw material to increase amidst the decrease in the availability of such natural raw materials as steel and other metals. High mass-producibility, shape stability at room temperature, high shapeability, and good surface quality are factors that are responsible for the increase in plastic raw material. Plastic injection molding is widely used in plastic products manufacturing because the process enables fast mass-production [1]. In today's plastic products manufacturing, there are growing demands for lighter and cheaper plastic products that require no finishing process. One of the most important factors that contribute to the production of cheaper plastic products is plastic processing cycle time. Reducing the cycle time will result in higher productivity and much lower production costs. Yet, cutting down cycle time, that is removing products from the molds while still at a very high temperature, may also pose

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product defect risks. Thus, reducing plastic injection time without causing any product defects is a difficult challenge.

A number of studies have been attempted to reduce injection molding process cycle time. Some of them involved optimization of design and process parameters. A study by SACHS, et al [2] proved that compared to the conventional cooling system, the conformal cooling system indicated shorter cycle time. In the study, the molds were made of stainless steel powder by means of a three-dimensional printing (3DP) process. The study also found that mold temperature is more uniform using the conformal cooling system than using the conventional cooling system. Simulation using the finite element method was conducted in order to optimize the conformal cooling channel. The simulation yielded a reducing cycle time, improvement of the surface finish and more uniform heat distribution [3].

Some researchers used Moldflow software to simulate and optimize plastic injection molding processes [4, 5]. Their recommendation can be offered for an optimum shrinkage and warpage involving low cycle time and cost efficient way. Many studies were conducted using Taguchi method to optimize plastic injection molding process parameters and to improve the products quality [6–9]. According to their conclusions, to optimize shrinkage, tensile strength, and cycle time the most significant factor is melting temperature, followed by cooling time and injection pressure. Moreover, another researchers integrated Moldflow software and Taguchi method to simulate and optimize plastic injection molding process parameters to minimizing warpage defect on thermoplastic [10]. Another study was conducted in which Artificial Neural Network is used for modeling the plastic injection molding process and combined with the Genetic Algorithm method to optimize the process parameters. The study resulted in an optimum cycle time [11].

This study attempted to obtain the optimum plastic injection process cycle time by using the conformal cooling system. In order to do so, the molding process parameters were optimized by the Genetic Algorithm method and the Moldflow simulation.

2 Research Methodology

2.1 Plastic Injection Molding Process

Manufacturing plastic products by means of injection molding requires a continuous process. Injection process started as mold is closed. Then, the plastic powder in the hopper enters the barrel. At this point, the screw is rotating while moving backward as the plastic powder in the barrel is being heated up gradually until its melting point is reached. Then the screw moves forward which is called the feeding stroke. As the screw is moving, the molten plastic is poured into the mold, filling the cavity through the injection machine nozzle, sprue, runner and gate. When the molten plastic is entering the cavity, a high pressure is needed in order to put the plastic material into the mold. Thus, injection pressure is defined as the pressure accompanying the melting of the plastic and its flow to the cavity during plastification process. As the mold cavity is being filled with plastic material, a high pressure is applied in the cavity to prevent the molten plastic from escaping the parting line. A clamping unit is also fastened and kept tight for a certain length of time. At this point, the screw remains motionless. This process is called holding pressure process. With an injection molding process, one production cycle consists of three main phases. In the first phase, known as injection or filling step, molten plastic is fed into the mold. During the second phase, also called the holding step, molten plastic is added until it reaches the desired weight. The third phase, or the cooling phase, is the phase in which plastic temperature is lowered to an ambient temperature. All these phases are interrelated and affected by a number of factors such as raw material characteristics, injection molding machine condition, mold design, process parameters, and final product quality, i.e., product appearance and strength.

Of all the processes involved in plastic molding, the cooling process is the most time-consuming. The next process is solidification. As solidification is taking place, mold temperature is lowered by flowing coolant (normally water) into the mold. The cooling time depends on how much time is needed by the injection machine to transfer heat from the cavity to the coolant. When product has cooled down and solidified, mold is opened by unfastening the clamping unit and pulling out the movable plate, on which the core plate is placed. At the same time, the screw moves backward as the barrel is filled with the material from the hopper. Then the ejector rod in the machine pushes the ejector plate and ejector retainer plate into the mold, forcing the product out of the core. After this demolding or ejection process, the mold closes again and the cavity is filled again with molten plastic, and the entire process starts all over again.

2.2 Cooling Time

Cycle time is the total time required to mold a plastic product. It starts when mold is closed, then the molten plastic begins to flow into the mold and ends when the product is solidified and removed from the mold. Cycle time is divided into mold closing time, injection time, solidification time, cooling time, mold opening time, and product ejection time. Cooling time is a very important part of plastic injection cycle time and is defined as the length

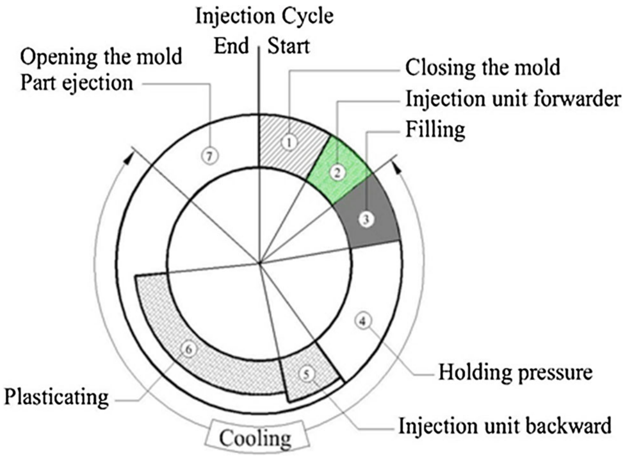

Fig. 1 A typical of a plastic injection cycle

of time needed to cool plastic material. During cooling process, plastic material: 1) solidifies, 2) reaches a level of hardness at which the product is ejectible from the mold (Fig. 1 [12]).

To calculate cooling time, the following equation can be applied [13].

$$t_c = \frac{s^2}{\pi^2 \alpha_p} ln\left(\frac{8}{\pi^2}\frac{T_W - T_M}{T_W - T_E}\right) \tag{1}$$

where s is the product thickness, t_c is the cooling time, T_E is the ejection temperature, T_M is the melting temperature, T_W is the mold wall temperature, and α_p is the heat transfer coefficient.

2.3 Injection Mold Cooling System

Cooling process plays such an important role in plastic products manufacturing that a large number of studies have been conducted on plastic injection mold cooling system design.

As Fig. 2 [2] shows, a conformal cooling channel is designed to follow the contour of the product mold, allowing a faster and more uniform cooling process. However, the system has its limitation in that it is difficult to make the cooling channel using conventional machining processes. A number of Rapid Prototyping (RP) applications, can be combined with the use of CAE software to design and produce a conformal cooling system [14]. Another study reported that the conformal cooling system was manufactured by using conventional machining processes. However, such a system was applied for the manufacturing simple cube-shaped products. According to the study, the conformal cooling channel was made by making straight drilled holes on a some sides and covering the other sides that were not needed [15]. Another cooling system was proposed in a study by DANG and PARK [16].

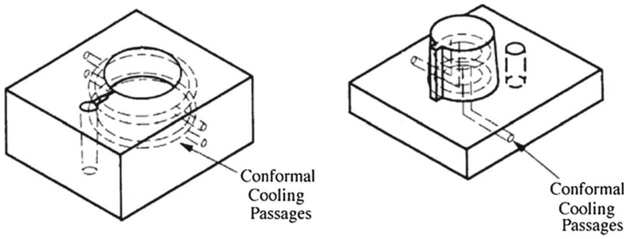

Fig. 2 Conformal cooling system

As DANG and PARK reported, the channel was made by using a milling process. The channel was designed to follow the product contour and then sealed to form a channel. Simulations using the Moldflow software yielded a warpage reduction of 15.7%. The model used many inserts and therefore was difficult to design and expensive to make.

2.4 Parameters Optimization Using Genetic Algorithm Method

Process parameters optimization is recognized as one of the most important steps that can improve injection molding product quality [17]. Researchers have attempted different approaches to determine the optimum plastic injection molding parameters that can reduce production preparation time and obtain consistent product quality.

Inspired by Charles Darwin's theory of evolution, genetic algorithm (GA) method is an algorithm used to find optimum values. In searching solutions to a problem, the algorithm keeps on evolving until an optimum solution is generated. First, a GA works by generating several random solutions, which, most probably would not yet be applicable. The algorithm will then evolve continuously until it yields better solutions. Each solution generated represents a chromosome and an individual consists of one chromosome. A group of individuals constitutes a population and each population will generate other populations until a certain number of generations are produced or a satisfactory fitness level has been reached for the population. Before executing GA, the values of the variables needed to process the algorithm must first be established. In general, GA optimization process follows the following procedures: determining initial population, evaluation, selection, crossover and mutation. The first generation is obtained by randomly generating populations with pre-defined chromosomes. In order to yield the desired solutions and the number of chromosomes in a population, the process needs a set of requirements must be met. If the number of chromosomes used is too small, the individuals that can be used in the crossover and mutation process will be very limited, rendering the entire process futile. Conversely, too many chromosomes will also slow down GA processes. It is recommended that the number of chromosomes be higher than the number of genes in a single chromosome. However, the nature of the problem should also be taken into account for too many genes is also not recommended [18].

2.5 Research Framework

A critical study on several researches related to the application of conformal cooling channels has been conducted by SHAYFULL, et al [14]. Based on the study, reduced injection molding cycle time can be achieved by simulating and experimenting conformal cooling channel. However, only a limited number of studies have been conducted on the application of conformal cooling system made by conventional machining processes, the focus of which is limited to simulations.

In this study, optimization was attempted to injection process parameters and conduct a simulation of injection molding process. Relations among parameters were determined by using DOE (design of experiment) approach and were processed further with Moldflow simulation. In addition, Moldflow simulation was used to verify at the minimum cycle time obtained the possibility of the volume shrinkage and the wall shear stress exceeding the maximum limits. The simulation results will be used to establish a relation between independent variables and response variable which will be used by GA for process parameters optimization. The main target of the study was to obtain a minimum cycle time, while maintaining volumetric shrinkage and wall shear stress below the limits established.

The study followed the following stages:

(1) Designing and making plastic injection mold including their conformal cooling channel;
(2) Conducting simulations using Moldflow to obtain cycle times with parameter combinations determined by DOE;
(3) Optimizing process parameters using GA method;
(4) Conducting simulations using Moldflow to verify the optimization results;
(5) Conducting experiments on the plastic injection molding machine and analyzing the process.

2.6 Product Data

The study focused on the production of 0.7 L rubber collecting cups. The cups were made of PP (Polypropylene) thermoplastic material. Cups were produced by using single-cavity molds with two plates. After the product image had been generated, the next step was to design the mold. All the product data had to be gathered for the designing process. The data were also needed to set injection molding process parameters. The material for the product was PP AZ564 thermoplastic from Sumitomo Chemical Co. Ltd. This type of material has good fluidity, which enables plastic products to be processed at a low melting temperature and injection pressure. Products made of this material have good plasticity and surface quality. The plastic material data are shown in Table 1.

Table 1 Material thermoplastic

Parameter	Value
Code	AZ564
Manufacturer	Sumitomo Chemical Co. Ltd.
Material structure	Crystalline
Melting temperature	180-260°C
Max. shear stress	0.30 MPa
Melting density	0.78 g/cm^3
Shrinkage factor	0.5%
Part dimension	∅ 136×100 mm
Standard thickness	1 mm
Projection area	147.93 cm^2
Part weight	50 g

2.7 Conformal Cooling Channel Design

Based on the designed dimensions, a detailed design drawing of insert components for the core and cavity was made. The parting line for core and cavity inserts is made exactly at the center of the cooling channel hole, so that a hole was made by putting together half-circular channels of mating components (Fig. 3). Made through a milling process, mold with conformal cooling channel had holes that function as core and cavity mountings. Milling process was applied to cavity block and core plate, where cavity inserts and core were placed. Cooling fluid input and output holes were also made through milling process.

In the making of cooling system, particular attention had to given to the reference used for setting up the machine. The hole where guide pin component mounting was placed was used to determine the central reference. Alignment of axes also had to be carefully considered in the making of core-cavity and insert core-insert cavity.

2.8 Plastic Injection Machine Data

The machine used to produce rubber collecting cups was Hwa Chin 160SE. The machine is equipped with a mold cooling, of which temperature is adjustable. Injection process parameters are set by using a control panel. General machine specifications are presented in Table 2.

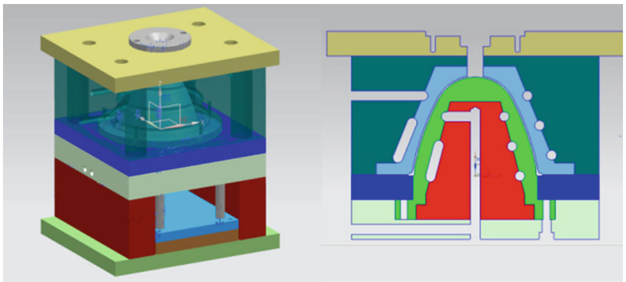

Fig. 3 Mold design with conformal cooling system

Based on the study by PARK and DANG [19], cooling process time is affected by cooling channel shape and Eq. (1) can be expressed as Eq. (2). Eq. (2) serves as an objective function in the optimization process. Optimization process is defined as a process to minimize cooling time t_C:

$$t_C = \frac{\left[\left(T_M - T_E\right) \times c_{P_m} + i_m\right] \times \rho_m \times \frac{s}{2} \times a}{T_{W-}T_{water}}$$
$$\left\{\frac{1}{2\pi \times \lambda_{ST}} \times ln\left[\frac{2a \sinh\left(2\pi \times \frac{b}{a}\right)}{\pi \times d}\right]\right\} + \frac{1}{0.031395 \times \pi \times Re^{0{,}8}} \qquad (2)$$

where a is the distance between holes, $a = 30$ mm, b is the distance between cooling hole and product surface, $b = 15$ mm, d is the cooling channel diameter, $d = 10$ mm, c_{pm} is the specific heat at melting condition, $c_{\mathrm{pm}} = 2.8$ kJ/(kg·°C), i_{m} is the latent heat of fusion of polymer, $i_{\mathrm{m}} = 71$ kJ/kg, Re is Reynold number, $Re = 2500$, T_{water} is the cooling water temperature, λ_{ST} is the mold thermal conductivity, $\lambda_{\mathrm{ST}} = 29$ W/(m·°C), and ρ_{m} is the melt density, $\rho_{\mathrm{m}} = 0.9$ g/cm^3. In the cooling process, the heat from the molten plastic was absorbed by the coolant (in this case water at 25 °C flowed through the cooling channel), and the environment. Flowing through the cooling channel at a speed of 1 m/s, cooling fluid then entered cooling channel holes. Heat transfer occurred through forced convection between the cooling system and the cooling channel surface, which happened at the same time as heat was also absorbed by the environment [20]. The outer surface of the mold was considered as adiabatic. Thus, the heat lost from the surface would not exceed 5% of the total heat lost during injection process [21]. The approach adopted might have simplified the problem. Yet, the facts indicated that 95% of the molten plastic heat was absorbed by coolant through the cooling channel.

Table 2 Specification of plastic injection machine

Specifications	Value	Unit
Clamping force	160	t
Screw diameter	42	mm
Injection pressure	1440	kg/cm^2
Theoretical shot volume	276	cm^3
Shot weight	248	g
Injection rate	180	cm^3/s
Screw revolving speed	0-276	r/min
Clamping stroke	500	mm
Space between tie bars	450-460	mm
Mold platen dimensions	660-660	mm
Range of mold height	150-500	mm
Hydraulic ejector stroke	130	mm
Machine size	4.5×1.2×1.8	m

3 Parameters Optimization and Analysis

3.1 Simulation Design for Injection Process Optimization

The simulation-based optimization process required a simulation design (combination of parameters) to obtain a model of relations among injection process parameters. The parameters observed were melting temperature, injection pressure, holding pressure and holding time. These parameters are called independent variables or controllable factors. The dependent or response variable that was observed in order to find out its correlation with the independent variables was process cycle time. Other responses, such as volumetric shrinkage and wall shear stress were recorded in order to observe their fluctuations with different combinations of parameters.

Combinations of parameters were generated through full factorial designs with 4 factors and 2 levels, namely low level (-) and high level (+) for each factor. Thus, the total number of set parameters is 16 ($2^4 = 16$). The four factors and their levels are shown in Table 3.

The next stage was to perform simulation using Moldflow for each set parameter (see Table 4). The 1st run order with $T_{\mathrm{M}} = 180$°C, $P_{\mathrm{inj}} = 26$ MPa, $P_{\mathrm{hold}} = 16$ MPa and $t_{\mathrm{hold}} = 8$ s yielded a cycle time response of 14.11 s, volumetric shrinkage of 4.87% and wall shear stress of 0.25 MPa. Simulation continued until the 16th run order. All the resulting responses were recorded.

Table 3 Factors and level for DOE

Factors	Level	
	Low (-1)	High (+1)
Melting temperature T_{M}	180°C	260°C
Injection pressure P_{inj}	20 MPa	26 MPa
Holding pressure P_{hold}	16 MPa	22 MPa
Holding time t_{hold}	8 s	12 s

Table 4 DOE and response from Moldflow simulation

	Parameter				Response		
Run order	Melting temperature (°C)	Injection pressure (MPa)	Holding pressure (MPa)	Holding time (s)	Cycle time (s)	Volumetric shrinkage (%)	Wall shear stress (MPa)
1	180	26	16	8	14.11	4.87	0.25
2	180	20	22	12	14.54	4.50	0.16
3	260	26	16	8	19.92	5.53	0.20
4	260	26	16	12	20.35	5.40	0.08
5	260	26	22	12	20.44	5.23	0.20
6	180	20	22	8	14.11	4.50	0.15
7	260	20	22	12	20.35	5.23	0.19
8	260	20	16	8	19.92	5.53	0.19
9	260	20	22	8	19.92	5.24	0.19
10	260	20	16	12	20.35	5.40	0.07
11	180	26	22	8	14.63	4.74	0.25
12	260	26	22	8	19.92	5.24	0.19
13	180	26	16	12	14.54	4.80	0.24
14	180	26	22	12	14.54	4.72	0.24
15	180	20	16	8	14.54	4.72	0.24
16	180	20	16	12	14.54	4.40	0.15

Linear regression analysis of the cycle time response data was made in order to find the correlation between cycle time and the affecting factors. From the analysis, a linear regression equation was obtained that was used to predict optimum cycle time response. Table 5 shows the results of the linear regression analysis of cycle time against process parameter variables. The coefficient of determination (R^2) calculated for this model was 99.8%. In other words, the cycle time prediction model was appropriate. However, individually, there were 2 interaction factors that did not give any significant effect. They were injection pressure and holding pressure. This was because the P value of the two factors was higher than 0.05 (α or level of significance).

As illustrated in the main effect chart (Fig. 4), factor that most significantly affected cycle time was melting temperature, as evident from the magnitude of the line gradient in the chart. In conclusion, the higher the melting point, the longer the injection process cycle time, for it would take a longer time to cool the product to a certain temperature. Then, as shown by the chart in Fig. 4, the effect of holding time was very insignificant. Injection and holding pressures had no effect at all.

Table 5 Regression analysis and ANOVA for cycle time

Estimated regression coefficients for cycle time

Term	Coef.	SE Coef.	F	P
Constant	0.647 5	0.512 9	1.26	0.233
Melting temperature T_M	0.071 3	0.001 0	69.26	0.000
Injection pressure P_{inj}	0.003 8	0.013 7	0.28	0.788
Holding pressure P_{hold}	0.003 8	0.013 7	0.28	0.788
Holding time t_{hold}	0.080 4	0.020 6	3.90	0.002
$S = 0.16472$	R-Sq = 99.8%		R-Sq(adj) = 99.7%	

Analysis of varians

Source	DF	SS	MS	F	P
Regression	4	130.579	32.645	1203.15	0.000
Residual error	11	0.298	0.027		
Total	15	130.877			

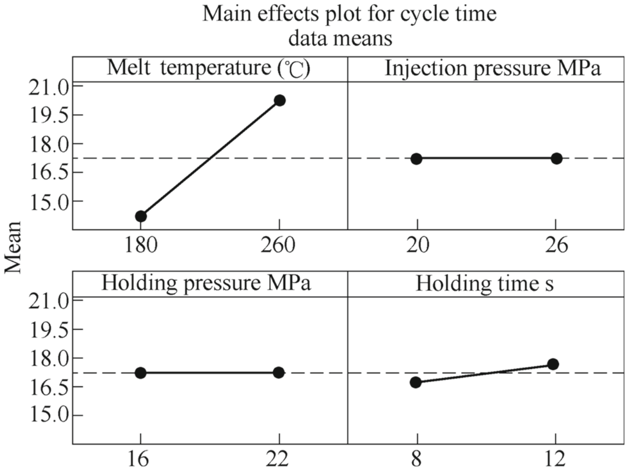

Fig. 4 Main effect plot for mean cycle time

Table 6 GA parameters for plastic injection process optimization

Parameter	Description
Number of independent variables	4
Population type	Double vector
Population size	20
Selection type	Stochastic uniform
Crossover type	Scattered
Crossover rate	0.8
Mutation type	Constraint dependent
Mutation rate	0.2
Total generation	100
# of iteration	50

Based on the regression analysis coefficient data, the model that fit with the relation between process parameters (independent variables) and cycle time (response variable) could be formulated by using the following empirical equation.

$$t_{cycle} = 0.6475 + 0.0713 \times T_M + 0.0038 \times P_{inj} + 0.0038 \times P_{hold} + 0.0804 \times t_{hold} \quad (3)$$

3.2 Optimization of Parameters Using GA

By applying GA method, optimum parameters could be obtained by optimizing the linear regression equation. This was done by minimizing cycle time as a function of process parameters. Matlab software was used to execute GA for process optimization. The input GA parameters are shown in Table 6. The limits of the parameters as set in the DOE were T_M = 180-260 °C, P_{inj} = 20-26 MPa, P_{hold} = 16-22 MPa and t_{hold} = 8-12 s.

Optimization using GA yielded the following values: cycle time=14.26 s, optimum T_M=180 °C, P_{inj}=20 MPa, P_{hold}=16 MPa and t_{hold}=8 s. These values were yielded in the 51th iteration, as shown in Fig. 5.

3.3 Simulation and Experiment of Optimum Parameters

The next step of the study was to simulate the optimum parameters obtained by GA using Moldflow software. The optimum parameters of T_M = 180 °C, P_{inj} = 20 MPa, P_{hold} = 16 MPa and t_{hold} = 8 s were simulated to obtain cooling and cycle time responses. Other parameters were also needed for simulation. These parameters are shown in Table 7. The simulation performed yielded a process cycle time of 14.11 s, volumetric shrinkage of 5.61%, and wall shear stress of 0.17 MPa.

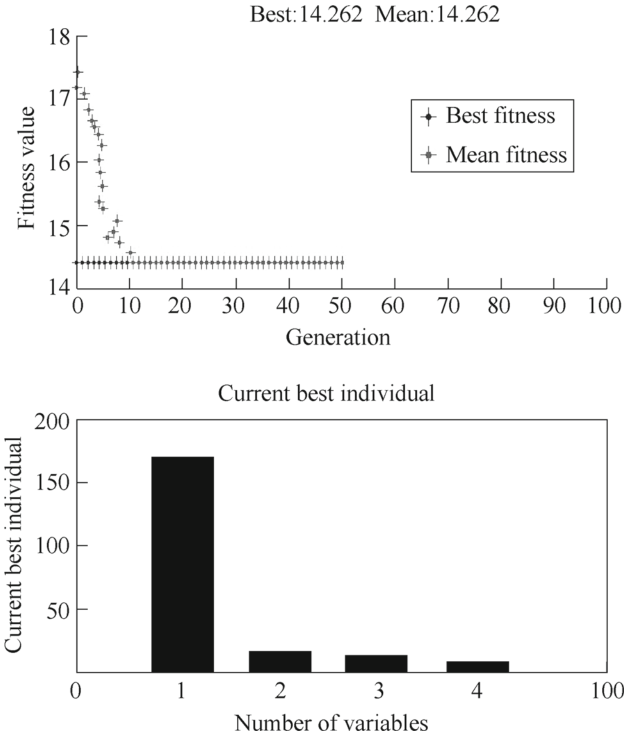

Fig. 5 Optimum cycle time and parameters

Then, experiment was carried out on the injection molding machine using the optimum parameters. Before starting the production process, the external temperature around the mold was measured and, as reported in the record, the average temperature was 30 °C. Compared to the simulated surrounding temperature of mold (32 °C), there was a difference of 2 °C. Water temperature in the cooling unit was set at 25 °C and cooling fluid flow at 1 m/s. In the experiment, cycle time was recorded and compared to the simulated results. The experiment yielded an average cycle time of 14.19 s.

Table 7 Parameters for simulation process

Parameter	Value	Unit
Melting temperature T_M	180	°C
Ejection temperature T_E	120	°C
Mold wall temperature T_W	50	°C
Injection pressure P_{inj}	20	MPa
Holding pressure P_{hold}	16	MPa
Holding time t_{hold}	8	s
Velocity of cooling water u	1	m/s
Cooling water temperature T_{water}	25	°C
Mold opening time t_o	5	s
Reynold number Re	2500	
Ambient temperature T_e	30	°C

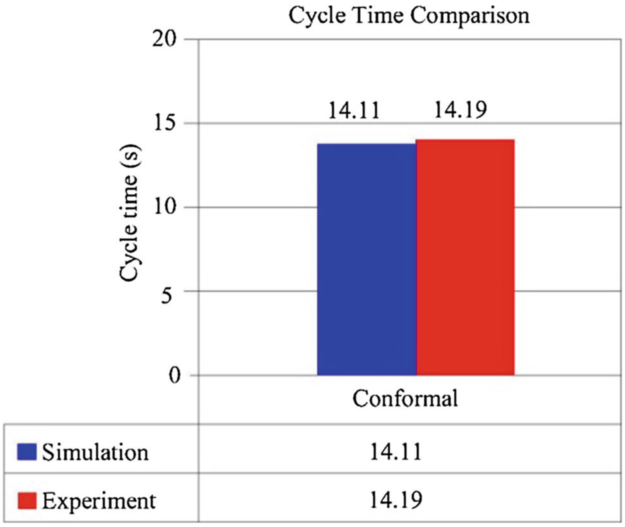

Fig. 6 Cycle time comparison

Table 8 Volumetric shrinkage and wall shear stress response from simulation

Response	Conformal	
	T_M = 220 °C	T_M = 180 °C (optimum)
Volume shrinkage (%)	5.57	5.61
Wall shear stress (MPa)	0.16	0.17

3.4 Experiment Results Analysis

Figure 6 presents an injection molding process cycle time comparison chart. The chart shows that the cycle time resulting from the simulation and experiment was almost the same. In addition, from the simulation result, volumetric shrinkage and wall shear stress did not undergo any significant change for their values were still below the allowed maximum limit of 7% for volumetric shrinkage and 0.30 MPa for wall shear stress (Table 8). The data indicated that simulation could be used as a reference before starting an injection molding process with an injection molding machine.

4 Conclusions

(1) Optimization of process parameters using Genetic Algorithm method and simulation using Moldflow could yield optimum injection molding parameters. Based on the study, the optimum parameters for rubber collecting cup injection molding process were T_M = 180 °C, P_{inj} = 20 MPa, P_{hold} = 16 MPa and t_{hold} = 8 s, with a cycle time of 14.11 s. These optimum parameters were obtained with the following conformal cooling system dimensions a = 30 mm, b = 15 mm and d = 10 mm.

(2) Experiment with a conformal cooling system yielded an average cycle time of 14.19 s. The volumetric shrinkage resulting from the conformal cooling system used was 5.61%, still below the maximum limit of 7%. The wall shear stress was 0.17 MPa, below the maximum limit of 0.30 MPa.

(3) The difference between the cycle time yielded by the simulation and experiment using a conformal cooling system was very insignificant, less than 1%. Therefore, the process parameters optimization using Genetic Algorithm method as combined with simulation using Moldflow can be considered valid.

References

1. ROSATO D V, ROSATO D V, ROSATO M G. *Injection Molding Handbook*[M]. 3rd ed. Massachusetts: Kluwer Academic Publishers, 2000.
2. SACHS E, WYLONIS E, ALLEN S, CIMA M, GUO H. Production of injection molding tooling with conformal cooling channels using the three dimensional printing process[J]. *Polymer Engineering and Science*, 2000, 40(5): 1232–1247.
3. DIMLA D E, CAMILOTTO M, MIANI F. Design and optimisation of conformal cooling channels in injection moulding tools[J]. *Journal of Materials Processing Technology*, 2005, 164165: 1294–1300.
4. FARSHI B, GHESHMI S, MIANDOABCHI E. Optimization of injection molding process parameters using sequential simplex algorithm[J]. *Materials & Design*, 2011, 32(1): 414–423.
5. VISHNUVARTHANAN M, PANDA R, ILANGOVAN S. Optimization of injection molding cycle time using moldflow analysis[J]. *Middle-East Journal of Scientific Research*, 2013, 13(7): 944–946.
6. KAMARUDDIN S, KHAN Z A, FOONG S H. Application of Taguchi method in the optimization of injection moulding parameters for manufacturing products from plastic blend[J]. IACSIT *International Journal of Engineering and Technology*, 2010, 2(6): 574–580.
7. PAREEK R, BHAMNIYA J. Optimization of injection moulding process using Taguchi and ANOVA[J]. *International Journal of Scientific & Engineering Research*, 2013, 4(1).
8. LAHOTI S N, NADAR M D, KULKARNI S S. Optimization of critical processing parameters for plastic injection molding for enhance productivity and reduced time for development[J]. *International Journal of Advanced Engineering Research and Studies*, 2014, III(II): 66–71.
9. NOOR RAHBAR N, KUMAR S. Optimisation of process parameters for LDPE material in injection moulding machine using Taguchi methodology[J]. *International Journal Engineering Research & Technology* (IJERT), 2015, 4(7): 81–83.
10. HUSSIN R, MOHD SAAD R, HUSSIN R, MOHD DAWI M S I. An optimization of plastic injection molding parameters using Taguchi optimization method[J]. *Asian Transactions on Engineering*, 2012, 2(5): 75–80.

11. MEIABADI M S, VAFAEESAFAT A, SHARIFI F. Optimization of plastic injection molding process by combination of Artificial Neural Network and Genetic Algorithm[J]. *Journal of Optimization in Industrial Engineering,* 2013, 13: 49–54.
12. PÖTSCH G, MICHAELI W. *Injection Molding: An Introduction*[M]. Munich: Hanser Verlag, 2008.
13. RAO N S, SCHUMACHER G. *Design Formulas for Plastics Engineers*[M]. 2nd ed. Munich: Hanser Publishers, 2004.
14. SHAYFULL Z, SHARIF S, MOHD ZAIN A, GHAZALI M F, MOHD SAAD R. Potential of conformal cooling channels in rapid heat cycle molding: a review[J]. *Advances in Polymer Technology*, 2014, 33(1): 1–24.
15. SAIFULLAH A B M, MASOOD S H. (2007). Cycle time reduction in injection moulding with conformal cooling channels[C]//*Proceedings of the International Conference on Mechanical Engineering 2007(ICME2007)*, Dhaka, Bangladesh, December 29–31, 2007: ICME07-AM-42.
16. DANG X P, PARK H S. Design of U-shape milled groove conformal cooling channels for plastic injection molding[J]. *International Journal of Precision Engineering and Manufacturing,* 2011, 12(1): 73–84.
17. MOK S L, KWONG C K. Application of artificial neural network and fuzzy logic in a case-based system for initial process parameter setting of injection molding. *Journal of Intelligent Manufacturing*, 2002, 13(3): 165–176.
18. SUYANTO. *Genetic algorithm in Matlab*[M]. Yogyakarta: Penerbit Andi, 2005. (in Indonesian)
19. PARK H S, DANG X P. Design and Simulation-Based Optimization of Cooling Channels for Plastic Injection Mold. *New Technologies - Trends, Innovations and Research*[M]. ISBN: 978-953-51-0480-3. Rijeka, Croatia: InTech, 2012.
20. MENGES G, MICHAELI W, MOHREN P. *How to Make Injection Molds*[M]. 3rd ed, Munich: Hanser Publishers, 2001.
21. PARK S J, KWON T H. Optimal cooling system design for the injection molding process[J]. *Polymer Engineering and Science*, 1998, 38(9): 1450–1462.

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