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Warpage reduction through optimized process parameters and annealed process of injection-molded plastic parts †

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Abstract

The objective of this paper is to achieve the minimization of warpage for an injection molded part. The techniques that were implemented to minimize the warpage are the design of experiment (DOE), response surface methodology (RSM), firefly algorithm (FA), and annealing treatment. The packing time, cooling time, and melt temperature were shown to be significant parameters and FA was employed to seek these suitable values by experimental tests based on simulation software Moldex3D and injection machine. Analysis of variance (ANOVA) was used to validate experiments. Annealing treatment process was then applied to reduce more warpage phenomenon; the results showed that warpage phenomenon decreased dramatically compared with popular optimized parameter methodology. Moreover, the residual stress which was obtained by using photoelasticity showed that it has a direct relationship with warpage reduction. Therefore, the best solution of warpage mitigation can be solved by popular optimum process parameters and also annealing treatment.

Keywords: Warpage; Design of experiment; Response surface methodology; Firefly algorithm; Photoelasticity

1. Introduction

Everywhere in daily life plastic products have become part of our daily routine such as the covers of cellular phones, laptop housings, food boxes, and pen or pencil frames. The main reasons that plastic products have become popular to consumers are that they are lightweight, easy to form the parts, have low manufacturing costs when compared with other processes, and so on. The plastic injection molding (PIM) is one of the plastic forming processes which can produce good plastic products, provide high productivity, short cycle times for production, and perfectly meet complex requirements such as thin shell features and smooth product surfaces. During the injection molding process, the molding conditions are one of the causes of the quality problems of plastic parts. One of the most important problems is a distorted part referred to as warpage [1]. Thus, warpage reduction is a topic of interest for many researchers in seeking the best solution for avoiding this defect. Currently minimized warpage is a main topic in optimized injection molding process conditions [1-22].

Many publications of research about optimized plastic injection molding (PIM) parameters for reducing warpage occurrence have concentrated on computer-aided engineering (CAE) simulation, finite element and volume analysis, empirical practice experiments, and also a class of evaluation algorithm optimization methods. Subramanian et al. [2] used finite element volume analysis through C-MOLD simulation software to minimize warpage of the injection-mold part as a compact disc (CD) optical pickup. There was also use of complex methods for integration with simulation software to seek suitable process parameters such as injection location and bridge rib. The result illustrated that the thickness of the rib is the most effective constraint for avoiding warpage problems. Ozcelik et al. [1] and Kurtaran et al. [3] tried to mitigate warpage problems via genetic algorithm to find the perfect process conditions. Packing pressure, mold temperature, melt temperature, packing time, and cooling time are the terms of the most important process parameters. The results of both researcher groups found that packing pressure has the most effect on warpage, followed by mold temperature, melt temperature, packing time and cooling time respectively. Erzurulu et al. [4] used Taguchi optimization method running on CAE simulation to minimize warpage and sink index because this method can reduce experimental test array better than the usual design of the experiment, especially the full factorial design experiment. This research considered mold and melt temperature, packing pressure, rib cross-section types, and rib layout angle. The results indicated clarify that the different rib cross-section types and rib layout dramatically affected warpage and sink index problems. Chiang et al. [5] concentrated on a thin shell product to avoid shrinkage and warpage prob-

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lems by using the response surface methodology associated with sequential approximation optimization (SAO) method to handle the optimal value of machining parameters (such as mold temperature, packing time, packing pressure, and cooling time). The main effects that were obtained from this result were the sufficient time of packing and cooling beneficial for minimizing shrinkage and warpage problems. Gao et al. [6, 7] had researched the effective warpage optimization method by using Kriging model and Surrogated-based process optimization that is an adaptive method based on the Kriging model. Two years of development research for minimizing warpage concluded that packing time was the most important factor and Surrogated-based process optimization can provide the reduction of warpage at 38 % compared with the minimal warpage value of specimens. Ozcelik et al. [8], Hakimian et al. [9], and Zheng et al. [10] have been continually studying warpage phenomena by using the Taguchi experimental method. There was consideration of various machine parameters such as mold temperature, melt temperature, packing pressure, packing time, cooling temperature, fiber glass percentage, and V/P switchover and using Moldflow simulation software without empirical tests to seek the factors which affected warpage problems. The results show that packing pressure has the most important effect on warpage followed by other factors. Farshi et al. [11] and Kitayama et al. [12] applied sequential approximate optimization for mitigating warpage problems. Outcomes from these pieces of research were melt temperature and packing pressure profiles being the main effects and also during warped consideration, cycle time and residual stress during PIM were of concern because they had an effect in terms of quality products. Many researchers used neural network modeling research group methodology to minimize warpage defects of PIM process such as the researches of Yin et al. [13], Shi et al. [14], and Chen et al. [15]. They considered melt temperature, injection velocity, packing pressure, packing time, cooling time, and mold temperature that affected the warped product. The advantages of this research are short run time for verifying the warpage model and the research concluded that packing time was the most significant for warpage phenomenon. For practical experiment research cluster, there was research about machining parameters involved in warpage elimination. For example, Chaing et al. [16] investigated warpage of electronic battery cover parts that had a thin-wall part characteristic and verified practical results through simulation software and experimental results. The demonstration of this research result illustrated that melt temperature is a main process parameter for eliminating warpage occurrence based on Acrylonitrile-butadiene-styrene (ABS) and Polycarbonate + Acrylonitrile-butadiene-styrene (PC+ ABS) materials. Larpsuriyakul et al. [17] were concerned with the warpage problem of plastic labeling parts that were produced by PIM process. This research solved the warpage problem of production of packaging because there were injection tests to search for suitable process parameters especially several of mold temperature to reduce warpage under acceptable values. Sánchez et al. [18] defined the relationship between cooling factors and warped parts. The emphatic solution of this research was cooling time factor that was the significant key to reducing warpage problem. Wang et al. [19] studied the warpage problem of the rapid heat cycle molding process that had a new design screw structure and was external gas assisted. It can be noticed that warpage problem is still mainly affected by packing time and cooling time even if this research did not use conventional injection molding as previous researches mentioned. And Wang et al. [20] concentrated warpage prediction of strip-like plastic parts by using thermal finite element analysis associated with experimental tests to define it. The result found that stress relaxation, or equivalently, strain creep impacted warpage predicted phenomenon. Yang [23] created Firefly algorithm for solving optimal values problems and many researchers applied this algorithm to optimize various problem fields such as using Firefly algorithm to seek process parameters of vehicle routing problems of a newspaper distribution system [24], electric discharge machining (EDM) and abrasive water jet machining (AWJM) [25], and the multi-pass turning operations problem [26]. Sudsawat et al. [27] used Firefly algorithm to find optimal process setting of PIM for warpage and volume shrinkage reduction. While it has rarely been found that this algorithm has been used to optimize injection molding machine parameters, therefore, the first step of the purpose of this research was to employ Firefly algorithm associated response surface methodology to find suitable parameters in PIM process to minimize warpage through Moldex3D simulation software and empirical tests.

All literature reviews as previously mentioned were purposed deeply to provide good performance for warped elimination and all the researches provided the results with the most process parameter adjustments through software simulations based on finite element volume analysis theories, experimental corollary, and also non-conventional algorithm optimization methods. Another main factor that impacted directly on warpage problem is residual stress on the plastic injection product. There were many researches that concentrated on the effect of residual stress. For instance, researcher groups of Chen et al. [28], Tang et al. [29], Acevedo-Morantes et al. [30], and Kim et al. [31] had the same consideration of cooling temperature and time analysis that affected residual stress of the plastic injection part. There was a strong conclusion that the warpage of injection molded parts during post-manufacturing thermal cycling occurred because of the residual stress effect that formed during the cooling stage. Also Guevara-Morales et al. [32] presented that the processing parameters that were of the most influence on residual stress and warpage have been signed as an indicator of residual stress phenomenon and vice versa. Some researchers concentrated on residual stress of plastic transparent materials in the injection molding process; Lee et al. [33] and Weng et al. [34] tried to mitigate residual stress by using numerical simulation and creating a predicted model. The result presented that maximum residual stress occurred exactly at or near the gate and the processing parameters formed the highest influence that might be directly affecting warpage phenomenon. From solving residual stress researches, it can clearly be concluded that if the research aim really wants to mitigate warpage problem, then this must be indicated also through residual stress on a specimen. Thus, heat treatment is another good choice to improve plastic product quality especially warpage defeat [35] such as Prashantha et al. [36] who used polypropylene injection molding by using the Taguchi design of experiment to optimize process parameters, then there was a comparison before and after the annealing process of warpage occurrence. Digital Photoelasticity has become one of the most popular methods to investigate residual stress via birefringence measurement system. Ramesh et al. [37] researched automation of white light photoelasticity by using color image processing hardware to evaluate equivalent wavelength of red, green and blue (RGB) planes to define material stress fringe values to define residual stress on a specimen. Ramesh et al. [38] tried to separate the data acquisition techniques in digital photoelasticity. One of the outcomes from this research was a technique that used a direct evaluation of total fringe order to seek residual stress of transparent materials, especially the three fringe photoelasticity (TFP) method. This method utilized the RGB values for total fringe order determination before it was employed into the stress-optic laws to define residual stress on plastic parts.

From all previous studies, they can be summarized that warpage mitigated methodology offered two main solutions. Firstly, they concentrated on optimizing process parameters and secondly, heat treatment to relieve warpage phenomenon. These two solutions have not found that these methods were integrated to handle warpage phenomenon of plastic injection parts. Thus, this research concentrates on warpage reduction of transparent polystyrene parts by using response surface methodology associated with firefly algorithm to seek suitable process parameters including annealing process after post-injection molding process for improving the quality of plastic part occurrence by noticing residual stress via photoelasticity methodology.

2. Materials and equipment

The design specimen is according to ASTM-D638 Type 1 and the dimensions are 165 mm × 19 mm × 3.2 mm. The model, cooling system, and setting process parameters are performed with Moldex3D simulation and illustrated in Fig. 1. The material setting is general purpose polystyrene (GPPS), PG-22 that was manufactured by CHI MEI corporation; an 80-ton injection molding machine was used to performed the experiment. The electronic laboratory oven was used for annealing treatment process. The specifications of the oven are the maximum annealing temperature at 300 °C, power rating at 240 volts and 200 watts, holding power at maximum temperature at 800 watts, temperature stability with proportional integral derivative (PID) control at ±0.2 °C, using 25 minutes for heat up time to 300 °C and using 4 minutes for recovery time with door open for 60 seconds. The photoelasticity method was employed using a polariscope and pictures were recorded using a digital camera fitted with a polarized filter.

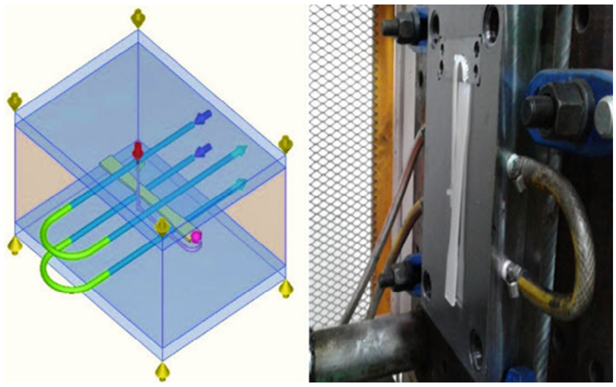

Fig. 1. The specimen and cooling system design via Moldex3D simulation and Toshiba IS80 Injection molding machine.

3. The research methodology

The methodology consisted of identification of machine parameters, screening important process parameters, response surface implement, firefly algorithm implement, creating optimal process model, and annealing treatment for warpage reduction can be concluded basically as a flow chart which is indicated in Fig. 2.

3.1 Identification of process parameters

The research goal is warpage reduction based on the identification of critical process parameters and mitigating warpage through heat treatment. The selection of machining set-up factors can be performed starting from many previous scientific research papers. Many studies [1-22] considered the relationship of several setting injection machine factors during the injection molding process on final warpage reduction. The list of related main factors that this research is interested to employ in experiment tests is: injection flow rate, injection pressure, switching over, packing time, packing pressure, melting temperature, mold temperature, and cooling time.

After there was a consideration of influent parameters that impact the injection molding process, a fractional two-levels factional was used for the initial stage of analysis. The variability parameter range was indicated based on two levels being upper and lower limits as shown in Table 1.

Then fractional two-levels run and provide a good screening performance through Moldex3D simulation software.

3.2 Screening experiment of process parameters

Factor screening is used to evaluate main and interaction ef-

Table 1. Process parameters and levels.

Screening experiment (Unit)	Symbol	Level	
		Low	*High*
1. Injection flow rate (%)	*A*	20	70
2. Injection pressure (%)	*B*	60	80
3. Switching over (%)	*C*	90	98
4. Packing time (sec)	*D*	3	15
5. Packing pressure (%)	*E*	60	80
6. Melting temperature (°C)	*F*	170	210
7. Mold temperature (°C)	*G*	55	70
8. Cooling time (sec)	*H*	20	60

Addition: Water coolant temperature is 55 °C.

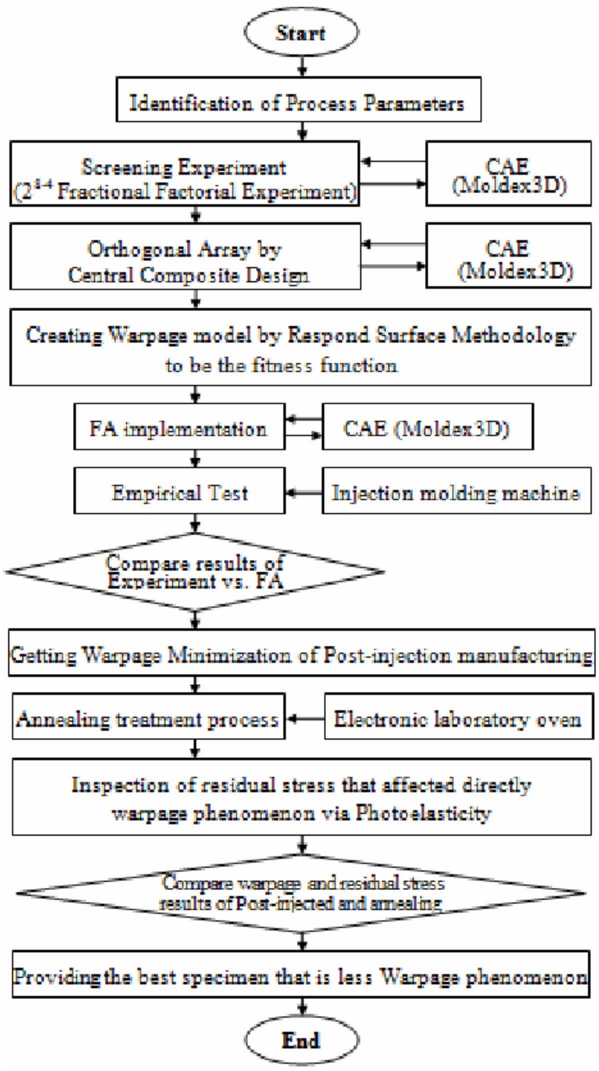

Fig. 2. Flow chart of methodology.

fects without impacting the final second quadratic regression model. For example, Tsai et al. [39], Mathivanan et al. [40], Zhang and Jiang [41] applied fractional two-levels for experimental design to present the initial step of screening ex-

Table 2. Screening experiment 2^{8-4} fractional factorial experiment through Moldex3D simulation software.

Run order	Factors								Warpage (mm.)
	A	*B*	*C*	*D*	*E*	*F*	*G*	*H*	
1	70	60	98	3	80	10	55	60	0.56
2	20	60	98	3	80	210	70	20	0.84
3	20	60	98	15	60	170	70	60	0.50
4	20	80	98	15	80	170	55	20	0.47
5	20	60	90	3	60	170	55	20	0.70
6	70	60	98	15	60	210	55	20	0.63
7	20	80	98	3	60	210	55	60	0.69
8	70	80	90	15	60	170	55	60	0.45
9	70	80	90	3	80	210	55	20	0.86
10	20	80	90	3	80	170	70	60	0.57
11	70	60	90	3	60	210	70	60	0.70
12	70	80	98	15	80	210	70	60	0.51
13	20	80	90	15	60	210	70	20	0.62
14	70	60	90	15	80	170	70	20	0.38
15	70	80	98	3	60	170	70	20	0.67
16	20	60	90	15	80	210	55	60	0.56

Table 3. Central composite design (CCD) as face centered composite design type.

Factors	Symbol	Level				
		-*α*	-1	0	1	*α*
Packing time (sec)	*D*	3	3	9	15	15
Melt temp (°C)	*F*	170	170	190	210	210
Cooling time (sec)	*H*	20	20	40	60	60

perimental analysis.

The procedures of this step are an indication of the design space, next the implementation of Moldex3D simulation experiments and then the effected parameters are automatically optioned. The fractional factorial design of screening 8 factors with two-levels each is shown in Table 2, then all the design experiments set for processing parameters in Moldex3D simulation to investigate warpage phenomenon. The warpage results are screened for providing influent parameters through analysis of variance (ANOVA).

3.3 Response surface implementation

After screening experiments, screened factors can be clarified to use in response surface method as shown in Table 3. Three main parameters as indicated in Table 3 are generated from analysis of variance (ANOVA) that evaluates main and interaction effects. Response surface methodology (RSM) is a collection of statistical techniques that is employed to define the warpage mathematical models. RSM used to evaluate the relationship between machining process parameters that influence warpage phenomenon to be a two or three-dimensional

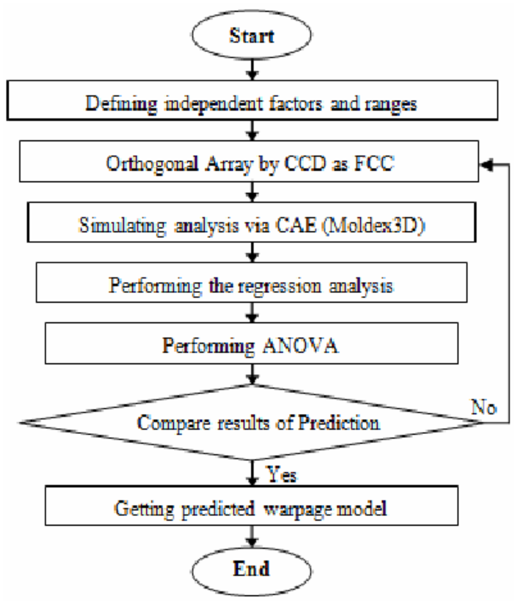

Fig. 3. Flow chart of response surface methodology (RMS).

quadratic surface [42]. Fig. 3 shows the response surface procedure in this research.

3.3.1 Central composite design

Before becoming the forecasting model stage of warpage, central composite design (CCD) is a necessary step to design and run the experiments. CCD is a full factorial design with all combinations of the important parameters and a suitable method to build the quadratic model. In this research, one kind of CCD being the central composite face-centered (CCF) is used to design experiments. This design type for this research consists of 8 cube points, 4 center points in the cube, 6 axial points, 2 center points in axial, and a circle of radius (α) equal to 1.0 according to Chaing et al. [16] as shown in the design table in Table 4. The warpage results as illustrated in Table 4 are employed to evaluate the respective impact of three main parameters and generated the second quadratic model.

3.3.2 Creating predicted model

After establishing CCF design experiments, the second quadratic model has to be created based on warpage simulation experimental results as shown in Eq. (1).

$$Y = c_0 + \sum_{i=1}^{k} c_i X_i + \sum_{i<j}^{k} c_{ij} X_i X_j + \sum_{i=1}^{k} c_{ii} X_i^2 \quad (1)$$

where X_i denotes independent variables, Y represents warpage response, k is the number of design variables, c_0 is the coefficients of constant, c_i is the coefficients of linear, c_{ii} is the coefficients of quadratic, and c_{ij} is the coefficients of cross product term.

3.3.3 Analysis of variance (ANOVA)

Filter step before Firefly algorithm methodology is the verification by analysis of variance (ANOVA); to be specific, either the warpage quadratic model was statistically reliable or otherwise. All the most influent parameters are indicated in terms of how they impact the warpage problem. The main and interaction effects are provided in analysis of variance.

Table 4. Design and results of central composite design (CCD) experiments.

Run order	Factors			Warpage (mm.)
	D	*F*	*H*	
1	3	190	40	0.66
2	9	190	40	0.43
3	9	210	40	0.52
4	9	190	40	0.43
5	9	170	40	0.36
6	9	190	20	0.48
7	9	190	60	0.42
8	15	190	40	0.42
9	3	210	20	0.86
10	9	190	40	0.43
11	9	190	40	0.43
12	15	170	60	0.33
13	15	210	60	0.51
14	15	210	20	0.56
15	15	170	20	0.37
16	3	170	20	0.65
17	9	190	40	0.43
18	3	210	60	0.69
19	3	170	60	0.56
20	9	190	40	0.43

3.4 Firefly algorithm established for optimized process parameter

Warpage polynomial equation generated from Eq. (1) is used as the fitness equation in optimization stage. Then Firefly algorithm from Yang [23] created following idealized rules of flashing patterns and behavior of fireflies algorithm is used for optimized process parameters. This algorithm has to establish the initial population of n fireflies as represented in a random searched set of solutions, the same as warpage solution and process parameters of the attractiveness, light absorption coefficient, and randomization parameters. A firefly will move forward to approve other fireflies by finding a firefly which has a high proportion of brightness that can evaluate the distance of firefly i to another attractive firefly j in Eq. (2):

$$X_i = X_i + \beta^*(X_j - X_i) + \alpha^*(\text{rand} - 0.5)) \quad (2)$$

where β and α are parameters of attractiveness and randomization by which both parameters were affected from Cartesian

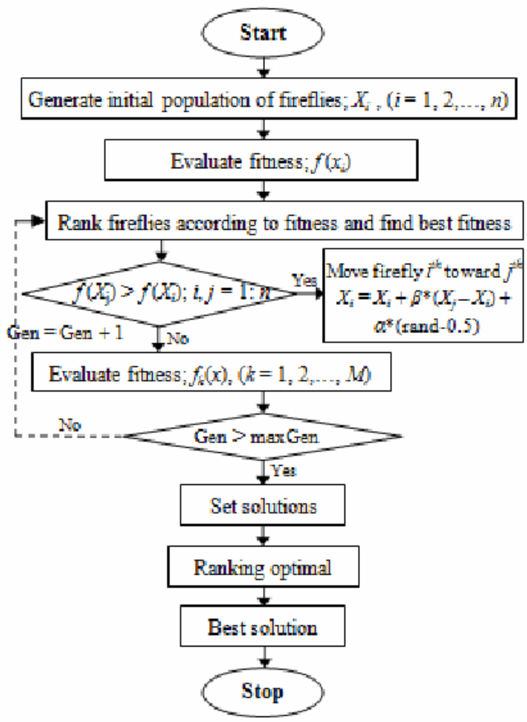

Fig. 4. Flow chart of firefly algorithm.

distance (r_{ij}) (distance between two fireflies). The attractiveness factor can be generated from Eq. (3).

$$\beta = \beta_0 e^{-\gamma r_{ij}^2}. \tag{3}$$

Given β_0 is the attractiveness at distance (r_0) = 0 and γ is a light absorption coefficient. The firefly algorithm can present the step by step as shown in Fig. 4.

3.5 Optimal injection process model

After verifying fitness function via RSM methodology then the objective model is employed to minimize warpage phenomenon as indicated in Eqs. (4) and (5), respectively.

Find X = [D, F, H] (4)

Minimize $Y(X)$ (5)

Subject to: $3 \le D \le 15$ s

$170 \le F \le 210$ °C

$20 \le H \le 60$ s.

All process parameters for an injection molding process following Toshiba IS80 Injection molding machine specification.

3.6 Annealing process for warpage reduction

After optimized process parameters, the annealing treatment process has a role to improve product quality of plastic parts. The annealing process is a secondary processing procedure that is employed during post-manufacturing. The certain temperature that should be below melting temperature points and around the glass transition temperature is used to be the annealing temperature. The purpose of annealing treatment depends on the various properties that need to be improved. For instance, improving dimensional stability and crack resistance especially warpage, volume shrinkage and residual stress problems. Plastic components can be classified to be crystalline and amorphous types, thus when amorphous areas become more crystalline under melting temperature, the dimensional accuracy can be shown as a better result. Also when annealing process is applied, the molecular orientation of plastic will adapt automatically and relieving residual stresses. Another advantage of heat treatment is the improvement of mechanical properties and heat resistance due to the annealing stage; an increase of crystallization will occur then density, tensile strength, flexural strength, glass transition temperature, and heat resistance will also be better [35]. Therefore, this research is concerned with using annealing treatment during post-manufacturing of plastic injection parts. Annealing temperature tests of 60 °C, 75 °C, 80 °C and 85 °C were used, and annealing time at 60 mins and 120 mins and cooling down in air over 12 hours, then the specimens are used to investigate the relationship of residual stress and warpage behavior. Next, use of photoelasticity to notice a behavior change of plastic injection parts.

3.6.1 Inspection of residual stress that directly affected warpage phenomenon on specimen via photoelasticity methodology

Presently, several techniques are used to investigate the residual stress on a specimen including stain gage measurement technique, X-ray technique, chemical probe testing technique, and so on. The useful technique is photoelasticity and this method can provide good practical results and it is not necessary to destruct a specimen which can be used to determine the stress distribution especially of a birefringent material. For instance, Realpe et al. [43, 44] had confirmed that they used the image processing techniques for photoelasticity methodology for particles concentration and characterization of shape, sizes of particles and shear stress. This testing methodology is used based on electromagnetic waves that pass through transparent materials. The dark-field polarization plan associated light waves and shows the stress distribution on a specimen [45] as shown in Fig. 5.

The stress appearance depends merely on the recognition of color steamer and investigation of the order of stress values via a color steamer [46]. The stress distribution can be delivered by using stress-optic law. Firstly, there must be a consideration of a transparent model of polymer subjected to a plane state of stress. The relationships between stress and indices of refraction are as shown in Eq. (6) [47].

$$\begin{aligned} n_1 - n &= c_1\sigma_1 - c_2\sigma_2 \\ n_2 - n &= c_1\sigma_2 - c_2\sigma_1 \end{aligned} \tag{6}$$

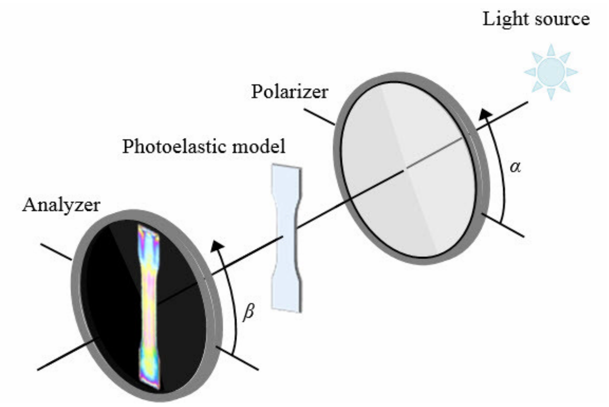

Fig. 5. The photoelasticity technique by the dark-field isochromatic of a specimen.

where σ_1 and σ_2 are the principle stresses that oriented with reference to a set of axes, n_1 and n_2 are the refractive indices that vibrate from polarizing axes whereas n is the refractive index in the unstressed condition. c_1 and c_2 are the direct stress-optic and the transverse stress optic coefficients. When this model is employed on a plane polarized light then the relative retardation (δ) can be provided as the refractive index function as show in Eq. (7):

$$\delta = \frac{2\pi h}{\lambda}(n_1 - n_2) \quad (7)$$

where λ is light wavelength, h is the thickness of a specimen.

Then combination of Eqs. (6) and (7) as shown in Eq. (8):

$$\delta = \frac{2\pi h}{\lambda}(c_1 - c_2)(\sigma_1 - \sigma_2)\,. \quad (8)$$

c_1 and c_2 can combine to be C as referred to as the optical activity coefficient or Brewster's constant as shown in Eq. (9):

$$\delta = \frac{2\pi h}{\lambda}C(\sigma_1 - \sigma_2)\,. \quad (9)$$

When there are concerns to relate fringe order (N), it can be rewritten as Eq. (10):

$$N = \frac{\delta}{2\pi} = h\frac{C}{\lambda}(\sigma_1 - \sigma_2)\,. \quad (10)$$

From Eq. (10) can be recast to be easier for defending residual stress as Eq. (11).

$$\sigma_1 - \sigma_2 = \frac{\delta}{2*h*C} = \frac{N*\lambda}{2*h*C}\,. \quad (11)$$

The constant C for polystyrene has a value if 5000 Brewster or equal to 5000×10^{-12} [48] and if there are uses of common geometry such as a thin-wall part or a flat sheet, the stress should be determined as Eq. (12).

$$\sigma = \frac{\delta}{h*C} = \frac{N*\lambda}{h*C}\,. \quad (12)$$

Before there is the determination of the residual stress on a specimen that affects warpage problem, there must be identification of fringe gradient direction via the relative retardation (δ) or defining fringe order (N) to implement into Eq. (12). Common methods use it to investigate the relative retardation (δ) and defining fringe order (N) is three fringe photoelasticity (TFP). The first step of this technique is creation of a color code in terms of R, G, B by a procedure of calibration according to ASTM-D4093-95. Then the total fringe order or the relative retardation in terms of R, G and B at a point on a specimen that is interested can be compared with the values of R, G, B in the calibration table. The error verification of values of R, G and B between the interested point and the calibration table can provide an error at Eq. (13) [47].

$$Error = \left(R_e - R_c\right)^2 + \left(G_e - G_c\right)^2 + \left(B_e - B_c\right)^2. \quad (13)$$

Given, values of the experiment points are subscript "*e*" and subscript "*c*" denotes the values in the calibration table. When a calculation of "*error*" should seek till the minimum of Error values, R, G, B outcome for Error equation is defined as the total fringe order and the relative retardation for employed Eq. (12). After it is able to seek residual stress on a specimen, this research will compare the results of warpage and residual stress of post-injection process parts and the parts that are annealed.

4. Results and analysis

The following section illustrates the results of screening process parameters, face centered composite design, optimized process parameters via Firefly algorithm, and minimized warpage through annealing treatment process.

4.1 Screening experiments step

After identifying machine factors based on an available adjustment of Toshiba IS80's machine parameters, simulation of warpage based on 2^{8-4} fractional factorial experiment design via Moldex3D was generated as shown in Table 2; next there is analysis of variance (ANOVA) of eight parameters. The significant terns of ANOVA that consider an effect are "*df*", "*Adj SS*", "*Adj Ms*", "*F-value*" and "*P-value*". "*df*" is a degree of freedom. "*Adj SS*" is adjusted sum of squares that is used to measure a variation of terms. "*Adj Ms*" is adjusted mean squares that is used to measure a variation of terms. "*F-value*" is a ratio of variation between sample means and variation within the samples. "*P-value*" is a probability of finding the observed results. Especially in this experiment, the factors that "*P*-value" is less than 0.05 are the most significant. Then the

Table 5. ANOVA table for screening factors of warpage phenomenon.

Source	*df*	*Adj SS*	*Adj MS*	*F-value*	*P-value*
Main effects	8	0.240302	0.030038	7.80	0.007
A	1	0.001949	0.001949	0.51	0.500
B	1	0.000022	0.000022	0.10	0.942
C	1	0.000074	0.000074	0.02	0.894
D	1	0.134176	0.134176	34.86	0.001
E	1	0.002357	0.002357	0.61	0.460
F	1	0.075598	0.075598	19.64	0.003
G	1	0.001163	0.001163	0.30	0.600
H	1	0.024964	0.024964	6.49	0.038
Error	7	0.026943	0.003849	-	-

Addition: S = 0.0620408, R-Sq = 89.92 %, R-Sq (adjust) = 78.40 %, R-Sq (prediction) = 47.33 %.

Table 6. ANOVA table for warpage (after backward elimination).

Source	*df*	*Adj SS*	*Adj MS*	*F-value*	*P-value*
Model	7	0.314192	0.044885	332.47	< 0.001
Linear	3	0.165577	0.055192	408.83	< 0.001
D	1	0.069896	0.069896	517.74	< 0.001
F	1	0.019151	0.019151	141.86	< 0.001
H	1	0.000202	0.000202	1.50	0.246
Square	2	0.062784	0.031392	232.53	< 0.001
*D*D*	1	0.037613	0.037613	278.61	< 0.001
*H*H*	1	0.001202	0.001202	8.90	0.012
2-way interaction	2	0.004125	0.002063	15.28	0.001
*D*H*	1	0.003374	0.003374	24.99	< 0.001
*F*H*	1	0.000751	0.000751	5.56	0.038
Error	11	0.001485	0.000135	-	-
Lack-of-fit	7	0.001485	0.000212	-	-
Pure error	4	0	0	-	-

Addition: S = 0.011619, R-Sq = 99.55 %, R-Sq (adjust) = 99.23 %, R-Sq (prediction) = 97.02 %.

eight factors were presented in Table 5, it shows that the significant factors that should be used in central composite design stage are packing time (*D*), melt temperature (*F*) and cooling time (*H*) as noticed as the coefficient of determination "*R-Sq*" at 89.92 %, "*P-value*" at less than 0.05 of three factors.

4.2 Creating modelling through face centered composite design step

Gaining packing time (*D*), melt temperature (*F*) and cooling time (*H*) being the main effects from initial screening step, meant that the face centered composite design (FCC) was simulated to provide warpage results as shown in Table 4. Analysis of variance (ANOVA) is used to validate and expertly seek the predicted warpage models through a backward elimination stage as shown in Table 6. In Table 6, the coefficient of predicted determination (R-Sq (prediction)) was more than 99 %, which means high reliability of the warpage model. Therefore, this table indicates a backward elimination situation that packing time (*D*), melt temperature (*F*) and cooling time (*H*) mainly affected warpage phenomenon. There were also square actions and interaction impacts of both *D* and *H* factors that affected the warpage problem. Following response surface methodology can produce a polynomial warpage equation of the main three factors as established as in Eq. (14).

$$\begin{aligned} \text{Warpage } (W) &= 0.072196 - 0.083144D + 0.00536F \\ &- 0.002926H + 0.003090D*D \\ &+ 0.00005H*H + 0.000171D*H \\ &- 0.000024F*H. \end{aligned} \tag{14}$$

Then the confirmable model was validated by using random tests of 8 test simulations compared between warpage results of Moldex3D results and calculated model as illustrated in Table 7. The deviated percentage of warpage results between model calculation and Moldex3D simulation were a range of 1.08 and -2.28 that means that the warpage polynomial equation is reliable to be employed in the firefly algorithm step for

Table 7. Comparison of predicted vs. actual run based on Moldex3D software and empirical test.

No.	*D* (sec)	*F* (° C)	*H* (sec)	Moldex3D simulation	Predicted models	% model deviation based on Moldex3D
				W (mm)	*W* (mm)	*W* (%)
1	4	175	38	0.5513	0.5545	0.58
2	5	185	40	0.5528	0.5449	-1.45
3	7	188	60	0.4499	0.4548	1.08
4	9	180	55	0.3850	0.3764	-2.28
5	10	195	44	0.4314	0.4323	0.21
6	14	200	48	0.4446	0.4451	0.11
7	8	205	52	0.5114	0.5019	-1.89
8	15	179	39	0.3792	0.3742	-1.34

% deviation based on Moldex3D was calculated using the equation: [(predicted value – simulated value)/predicted value] × 100

Table 8. Warpage values before and after optimization methods.

	Recommended condition method		FA method	
Objectives	*Moldex3D simulation*	*Experiments*	*Moldex3D simulation*	*Experiments*
Maximum warpage (mm)	0.43	0.49	0.33	0.38

seeking suitable process parameters.

4.3 Optimal step

Substituting Eq. (14) added into Eq. (5) to be a fitness equation, packing time, melt temperature, and cooling time were optimized suitable values as shown in Fig. 4. Firefly parameters are set-up as the number of iterations equal to 200, the size of population equal to 50, the absorption coefficient equal to 0.5, the maximum attractiveness equal to 0.5, and the random perturbation rate equal to 0.2 according to researches of Sudsawat et al. [27] and Lobato et al. [49]. Then the optimal results suggest as shown in Fig. 6 and Table 8, the measurement of a deflection used 5 positions, a long dog bone length compared to warpage results between Moldex3D simulation and empirical experiment via Toshiba IS80 injection molding. The highest maximum of warpage was at P5 position as shown in Fig. 6, and Table 8 presents the maximum warpage equal to 0.43 and 0.49 mm that was simulated via Moldex3D software and actual experiments respectively for recommended condition (9 s packing time, 190 °C melt temperature, and 40 s cooling time). Meanwhile the maximum warpage that was generated from Firefly algorithm provides 0.33 and 0.38 mm that were simulated through Moldex3D software and actual experiments respectively at 12 s packing time, 170 °C melt temperature, and 50 s cooling time.

All the results were based on Moldex3D and actual experiments provide the percentage of averaged error deviation at 13.95 % and 15.15 % of warpage measurement from a ratio of recommended condition and Firefly algorithm method.

The Firefly algorithm performance can provide the better warpage reduction than recommended condition results as

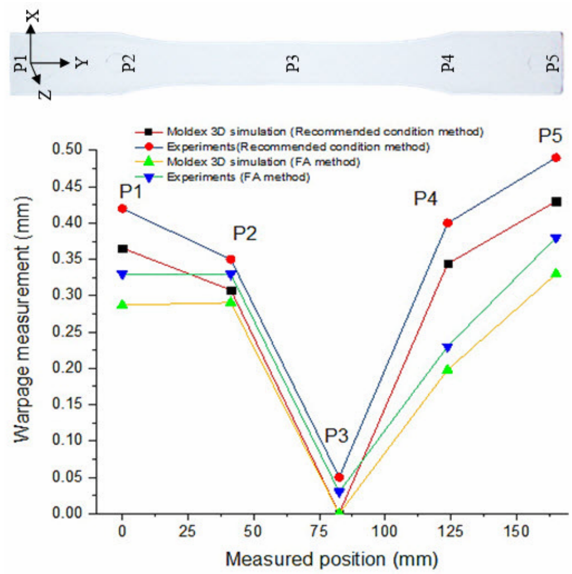

Fig. 6. Measurement of warpage on specimens at each point compared between experiments and Moldex3D simulations.

23.26 % and 22.45 % by Moldex3D simulation tests and empirical tests respectively.

4.4 Annealing treatment step

In this step, heat treatment process is used to reduce warpage phenomenon by using an electronic laboratory oven. Heat provided the effective result of rearranging the amorphous structure to become the crystalline structure [35] that directly affected the mitigation of residual stress on a specimen. After annealing treatment process, there is use of pho-

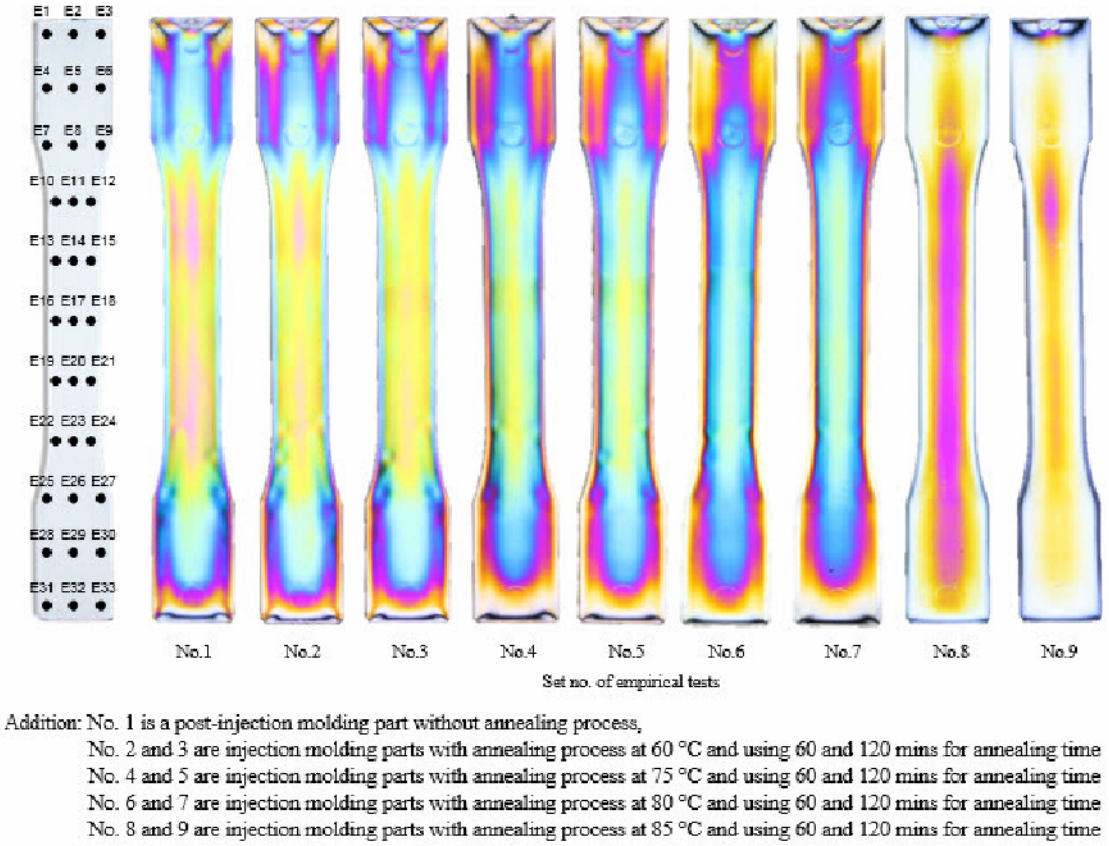

Fig. 7. Photoelasticity measurement of specimens before and after annealing treatment process.

toelasticity technique along with warpage measurements to investigate whether residual stress affected warpage phenomenon. Fig. 7 presents a set of 10 variable photoelasticity tests at each annealing temperature and time. Residual stress reflection via the pattern of the fringes show that no. 1 provides various colors more than others especially if there are comparisons of no. 1, no. 8 and 9, it was the most difference of colors. The colors that show on a specimen used to verify a retardation of light wave and fringe order according to three fringe photoelasticity (TFP) methodology [47] by specifying 33 measured positions (E1 to E33 points) are as shown in Fig. 7. The residual stress results that generated a retardation and fringe order by TFP methodology and added into Eq. (12) are illustrated in Fig. 8. When looking at no. 1, maximum and minimum residual stress outcomes that were calculated from TFP methodology are 0.101 and 0.017 MPa while the specimens which passed annealing process of no. 8 and 9 provided 0.064, 0.017, 0.058 and 0.017 respectively. These results present that annealing process at a suitable temperature can be a good choice to reduce the residual stress of plastic parts.

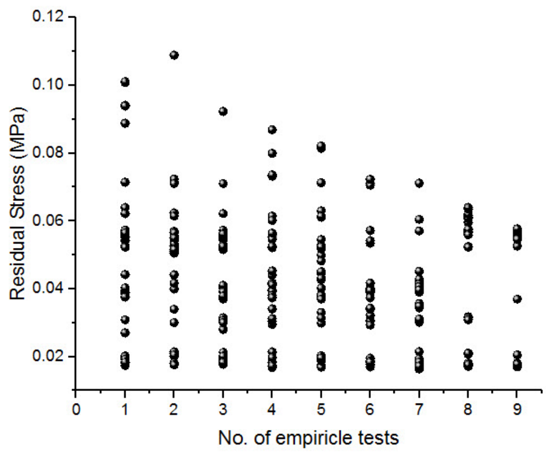

Fig. 8. Measurement of residual stress on specimens before and after annealing treatment process.

4.5 Comparisons of warpage reduction and residual stress on specimens

Warpage measurement at 5 positions (P1 to P5) as shown in Fig. 9 can provide good performance. This measurement suggests that the maximum warpage reflection occurs at the end of a specimen (P5). If there is a comparison of warpage occurrence between a specimen without annealing treatment and a specimen through annealing process, it can be summarized that more annealing temperature and time can provide a good solution for warpage reduction. The specimens that through annealing process at 85 °C and 120 mins can reduce warpage at 76.32 % compared with an optimized specimen before an-

Table 9. Warpage and residual stress values before and after annealing treatment process.

	Maximum warpage (mm)			Maximum residual stress (MPa)		
Methods	*Before annealing process*	*Annealing process* (60 mins)	*Annealing process* (120 mins)	*Before annealing process*	*Annealing process* (60 mins)	*Annealing process* (120 mins)
Post-injection process	0.38	-	-	0.101	-	-
Annealing at 60 °C	-	0.38	0.37	-	0.109	0.092
Annealing at 75 °C	-	0.30	0.29	-	0.087	0.082
Annealing at 80 °C	-	0.28	0.25	-	0.072	0.071
Annealing at 85 °C	-	0.16	0.09	-	0.064	0.058

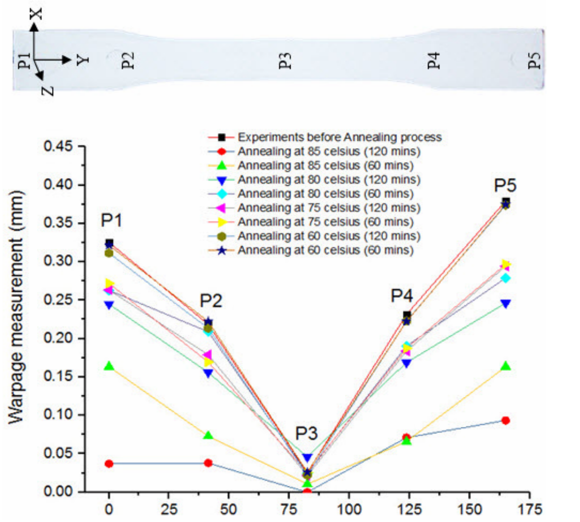

Fig. 9. Measurement of warpage on specimens at each point compared between experiments before and after annealing treatment.

nealing process. Therefore, it can be clarified as shown in Fig. 9 that if there is use of annealing treatment that sets the consumption of more temperature and time for solving warpage phenomenon, the warpage will reduce dramatically. Also, Table 9 can indicate when enhanced annealing temperature and time are from 60 °C to 85 °C and 60 mins to 120 mins respectively, warpage phenomenon will successively decline. Likewise, for residual stress, when it is given more annealing temperature and time, the residual stress can be relieved continually at 42.57 % compared between a specimen without annealing treatment and using annealing process at 85 °C and 120 mins. Therefore, the warpage can be mitigated dramatically by using Firefly algorithm to optimize process parameter during PIM process and also if relieving of more warpage phenomenon is required, annealing treatment is the best choice to reduce obvious warpage phenomenon from 0.38 mm to 0.09 mm. Also annealing treatment can relieve the residual stress from 0.101 MPa to 0.058 MPa which affected the reduction of the warpage problem and crack resistance problems [35].

5. Conclusions

In this research, an efficient optimization methodology using firefly algorithm (FA) and response surface methodology (RSM) and heat treatment are employed to minimize warpage of thin PIM parts according to ASTM-D638 Type1. The results of this study are illustrated as follows:

(1) According empirical experiment, packing time, cooling time, and melt temperature are the most significant factors influencing warpage reduction.

(2) According to response surface methodology and Firefly algorithm optimization, it can seek suitable packing time, cooling time, and melt temperature that provide a warpage mitigation less than recommended factor setting at 23.26 % and 22.45 % by Moldex3D simulation tests and empirical tests respectively.

(3) In annealing treatment process, warpage phenomenon reduced more from optimization stage at 76.32 % by using annealing process at 85 °C and 120 mins.

(4) In photoelasticity technique, which is a practical, low cost technique, it can notice residual stresses for injection molding polystyrene parts. The residual stresses decreased considerably with high temperature annealing at 42.57 % compared with a specimen without annealing process and contrasted with warpage occurrence.

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References

[1] B. Ozcelik and T. Erzurumlu, Comparison of the warpage optimization in plastic injection molding using ANOVA, neural network model and genetic algorithm, *J. Matprotec.*, 171 (2006) 437-445.

[2] N. R. Subramanian, L. Tingyu and Y. A. Seng, Optimizing warpage analysis for an optical housing, *J. Mechatronics*, 15 (2005) 111-127.

[3] H. Kutaran and T. Erzurumlu, Efficient warpage optimization of thin shell plastic parts using response surface methodology and genetic algorithm, *Int. J. Adv. Manuf. Technol.*, 27 (2006) 468-472.

[4] T. Erzurumlu and B. Ozcelik, Minimization of warpage and sink index in injection-molded thermoplastic parts using Taguchi optimization method, *J. Matdes*., 27 (2006) 853-861.

[5] K. T. Chiang and F. P. Chang, Analysis of shrinkage and warpage in an injection-molded part with a thin shell feature using the response surface methodology, *Int. J. Adv. Manuf. Technol*., 35 (2007) 468-479.

[6] Y. Gao and X. Wang, An effective warpage optimization method in injection molding based on the Kriging model, *Int. J. Adv. Manuf. Technol*., 37 (2008) 953-960.

[7] Y. Gao and X. Wang, Surrogate-based process optimization for reducing warpage in injection molding, *J. Matprotec*, 209 (2009) 1302-1309.

[8] B. Ozcelik and I. Sonat, Warpage and structural analysis of thin shell plastic in the plastic injection molding, *J. Matdes*., 30 (2009) 367-375.

[9] E. Hakimian and A. B. Sulong, Analysis of warpage and shrinkage properties of injection-molded micro gears polymer composites using numerical simulations assisted by the Taguchi method, *J. Matdes*., 42 (2012) 62-71.

[10] G. Zheng, W. Guo, Q. Wang and X. Guo, Influence of processing parameters on warpage according to the Taguchi experiment, *J. Mech. Sci. Technol*., 29 (2015) 4153-4158.

[11] B. Farshi, S. Gheshmi and E. Miandoabchi, Optimization of injection molding process parameters using sequential simplex algorithm, *J. Matdes*., 32 (2011) 414-423.

[12] S. Kitayama, R. Onuki and K. Yamazaki, Warpage reduction with variable pressure profile in plastic injection molding via sequential approximate optimization, *Int. J. Adv. Manuf. Technol*., 72 (2014) 827-838.

[13] F. Yin, H. Mao, L. Hua, W. Guo and M. Shu, Back propagation neural network modeling for warpage prediction and optimization of plastic products during injection molding, *J. Matdes*., 32 (2011) 1844-1850.

[14] H. Shi, S. Suming and X. Wang, A warpage optimization method for injection molding using artificial neural network with parametric sampling evaluation strategy, *Int. J. Adv. Manuf. Technol*., 65 (2013) 343-353.

[15] W. C. Chen and D. Kurniawan, Process parameters optimization for multiple quality characteristics in plastic injection molding using Taguchi method, BPNN, GA, and hybrid PSO-GA, *Int. J. Precis. Eng. Manuf*, 15 (2014) 1583-1593.

[16] Y. C. Chiang, H. C. Cheng, C. F. Huang, J. L. Lee, Y. Lin and Y. K. Shen, Warpage phenomenon of thin-wall injection molding, *Int. J. Adv. Manuf. Technol*., 55 (2011) 517-526.

[17] P. Larpsuriyakul and H. G. Fritz, Warpage and countermeasure for injection-molded in-mold labeling parts, *J. Polymer Engineering and Science*., 51 (2011) 411-418.

[18] R. Sánchez, J. Aisa, A. Martinez and D. Mercado, On the relationship between cooling setup and warpage in injection molding, *J. Mesurement*., 45 (2012) 1051-1056.

[19] X. Wang, G. Zhao and G. Wang, Research on the reduction of sink mark and warpage of the molded part in rapid heat cycle molding process, *J. Matdes*., 47 (2013) 779-792.

[20] C. Wang, M. Huang, C. Shen and Z. Zhao, Warpage prediction of the injection-molded strip-like plastic parts, *J. Cjche*., 24 (2016) 665-670.

[21] W. Guo, L. Hua, H. Mao and Z. Meng, Prediction of warpage in plastic injection molding based on design of experiments, *J. Mech. Sci. Technol*., 26 (2012) 1133-1139.

[22] G. J. Kang, C. H. Park and D. H. Choi, Metamodel-based design optimization of injection molding process variables and gates of an automotive glove box for enhancing its quality, *J. Mech. Sci. Technol*., 30 (2016) 1723-1732.

[23] X. S. Yang, Firefly algorithms for multimodal optimization, *J. Ajams*., 5792 (2009) 169-178.

[24] E. Osaba, X. S. Yang, F. Diaz, E. Onieva, A. D. Masegosa and A. Perallos, A discrete firefly algorithm to solve a rich vehicle routing problem modelling a newspaper distribution system with recycling policy, *J. Soft Computing*, 20 (2016) 1-14.

[25] R. Shukla and D. Singh, Selection of parameters for advanced machining process using firefly algorithm, *J. Estch*., 20 (2017) 212-221.

[26] A. Belloufi, M. Assas and I. Rezgui, Intelligent selection of machining parameters in multipass turning using firefly algorithm, *Int. J. Model. Simu.*, 2014 (2014) 1-6.

[27] S. Sudsawat and W. Sriseubsai, Optimized plastic injection molding process and minimized the warpage and volume shrinkage by response surface methodology with genetic algorithm and firefly algorithm techniques, *India J. Eng. Mater. S.*, 24 (2017) 228-238.

[28] X. Chen, Y. C. Lam and D. Li, Analysis of thermal residual stress in plastic injection molding, *J. Jmatprotec*., 101 (2000) 275-280.

[29] S. H. Tang, Y. M. Kong, S. M. Supaun, R. Samin and S. Sulaiman, Design and thermal analysis of plastic injection mould, *J. Jmatprotec*., 171 (2006) 259-267.

[30] M. T. Acevedo-Morantes, M. Brieva-Sarmiento and A. Realpe-Jimenes, Effect of the molding temperature and cooling time on the residual stress of crystal polystyrene, *J. Dyna*., 81 (2014) 73-80.

[31] B. Kim and J. Min, Residual stress distribution and their influence on post-manufacturing deformation of injection-molded plastic parts, *J. Jmatprotec*., 245 (2017) 215-226.

[32] A. Guevara-Morales and U. Figueroa-Lopez, Residual stresses in injection molded products, *J. Meter. Sci.*, 49 (2014) 4399-4415.

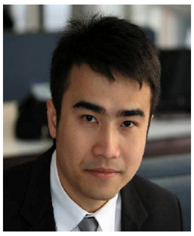
[33] Y. B. Lee and T. H. Kwon, Modeling and numerical simulation of residual stresses and birefringence in injection molded center-gated disks, *J. Jmatprotec*., 111 (2001) 214-218.

[34] C. Weng, W. B. Lee, S. To and B. Y. Jiang, Numerical simulation of residual stress and birefringence in the precision injection molding of plastic microlens arrays, *J. Icheatmasstransfer*., 36 (2009) 213-219.

[35] A. A. Aly, Heat treatment of polymers: A review, *Int. J. Materials Chemistry and Physics*, 1 (2015) 132-140.

[36] K. Prashantha, J. Soulestin, E. Lafranche, P. Krawczak, G. Dupin and M. Claes, Taguchi analysis of shrinkage and war-

page of injection-moulded polypropylene/multiwall carbon nanotubes nanocomposites, *Epresspolymlett*, 3 (2009) 630-638.
[37] K. Ramesh and S. S. Deshmukh, Automation of white light photoelasticity by phase-shifting technique using colour image processing hardware, *J. Optlaseng*, 28 (1997) 47-60.
[38] K. Ramesh and S. K. Mangal, Data acquisition techniques in digital photoelasticity: A review, *J. Optlaseng*, 30 (1998) 53-75.
[39] K.-M. Tsai, C.-Y. Hsieh and W.-C. Lo, A study of process parameters for injection molding on surface quality of optical lenses, *J. Matprotec*., 209 (2009) 3469-3477.
[40] D. Mathivanan, M. Nouby and R. Vidhya, Minimization of sink mark defects in injection molding process – Taguchi approach, *Int. J. Ijest*, 2 (2010) 13-22.
[41] Z. Zhang and B. Jiang, Optimal process design of shrinkage and sink marks in injection molding, *J. Wuhan Univ. Technol*., 22 (2007) 404-407.
[42] D. Montgomery, *Design and analysis of experiments*, John Wiley and Sons, New York, NY (2005).
[43] A. Realpe and C. Velazquez, Growth kinetics and mechanism of wet granulation in a laboratory-scale high shear mixer: Effect of initial polydispersity of particle size, *Chemical Engineering Science*, 63 (2008) 1602-1611.
[44] A. Realpe and C. Velazquez, Pattern recognition for characterization of pharmaceutical powders, *Powder Technology*, 169 (2) (2006) 108-113.
[45] M. Frocht, *Photoelasticity*, John Wiley & Sons, 1 (1941) 100-108.
[46] C. W. Chang, H. S. Lien and J. H. Lin, Determination of reflection photoelasticity fringes analysis with digital image-discrete processing, *Measurement*, 41 (2008) 861-8.
[47] K. Ramesh, *Digital photoelasticity: Advanced techniques and applications*, Springer-Verlag Berlin Heidelberg (2000) ISBN-13:978-3-642-64099-5.
[48] J. Des Cloizeaux and G. Jannink, *Polymers in solution: Their modelling and structure*, New York: Ed., Oxford University Press, 1 (2010).
[49] F.-S. Lobato and J.-V. Steffen, Multi-objective optimization firefly algorithm applied to (Bio) chemical engineering system design, *J. Ajams*., 1 (2013) 110-116.



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