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Parameters in Injection Molding of Cooling Fan for Electronic Chips of Electric Vehicles

Jui-Hung Cheng,[1] Hsin-Hung Lin,[2,3*] and Jia-Hong Shen[1]

[1]Department of Mold and Die Engineering, National Kaohsiung University of Science and Technology,
415 Chien Kung Road, 807 Kaohsiung 80778, Taiwan
[2]Department of Creative Product Design, Asia University, 500, Lioufeng Road, Wufeng, Taichung 41354, Taiwan
[3]Department of Medical Research, China Medical University Hospital,
No. 2, Yude Rd., North Dist., Taichung 404327, Taiwan

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This research was carried out to determine the appropriate range of sensing temperature and pressure of the injection mold system of the cooling fan for electronic chips of an electric vehicle. The advanced product quality planning (APQP) method and the Taguchi method were adopted following the measurement system analysis (MSA) of the International Organization for Standardization's (ISO) technical specification (TS) (ISO/TS16949) and a production part approval process (PPAP) considering the chemical and mechanical properties of PBT-4130 as the material for the production of the cooling fan. In molding the cooling fan, time, temperature, and pressure are important factors. Thus, melt temperature, holding pressure, holding time, volume–pressure (V–P) point, melt injection, and cooling time in the injection mold process were investigated. Each factor was experimented with to find the optimal parameters at three different levels in the injection molding process. The result showed that the holding times of the melt at the holding pressures of 45, 55, and 65 MPa, melt temperature of 265 °C, and cooling time of 30 s were important for the production of the cooling fan. The precise and accurate sensing and control of temperatures and pressures were found to be critical for an injection mold system to manufacture high-quality products for machines or equipment. The results of this research provide important information and a basis for the appropriate use of sensors in designing an injection mold system for high-precision and high-quality plastic products such as cooling fans for electric vehicles.

1. Introduction

Cooling fans for electronic chips (integrated circuits) are widely used in information and computer technology devices. Recently, the demand for the cooling fan for chips has been rapidly increasing owing to the increasing number of electric vehicles, drones, virtual reality equipment, network servers, and other devices, all of which require high-performance electronic

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[*] Corresponding author: e-mail: hhlin@asia.edu.tw

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chips. Cooling fans for such electronic chips are different from those used in the past in terms of materials, specifications, and functions as the size, speed, and capacity of the chips have increased considerably. Therefore, new technologies are required for designing and manufacturing cooling fans for high-performance electronic chips for better performance. Nowadays, such advanced cooling fans are also demanded by the automotive industry. In the automotive market, electronic vehicles (EVs) are replacing conventional vehicles with combustion engines, with 5.4 million vehicles sold in 2022.(1) The quality requirements of the parts and components of EVs are considerably higher, especially for those related to heat dissipation and cooling, as EVs are vulnerable to fires due to their batteries. Therefore, in manufacturing EVs, it is strictly required to follow quality requirements and specifications such as ISO/TS 16949 and ISO 9001 combined with the technical manual of QS 9000.(2) ISO/TS 16949 specifies in detail the design, development, production, installation, and service of the parts of vehicles. The cooling fans for vehicles must also fulfill these specifications. Thus, manufacturers must introduce relevant technologies and methods to improve product quality and efficiency, reduce production costs, and ensure consistent quality of parts and components and waste reduction.(3) ISO/TS16949 can be applied to the development of cooling fans in the four main stages, namely, the engineering verification test (EVT) stage, design verification test (DVT) stage, production verification test (PVT) stage, and mass production verification (MVT) test stage (Fig. 1).

In developing cooling fans for the chips for EVs, it is critical to use an appropriate molding technology and define adequate parameters for weight reduction and quality of the final product. Such parameters include the mold temperature, injection rate, pressure, and holding time of the

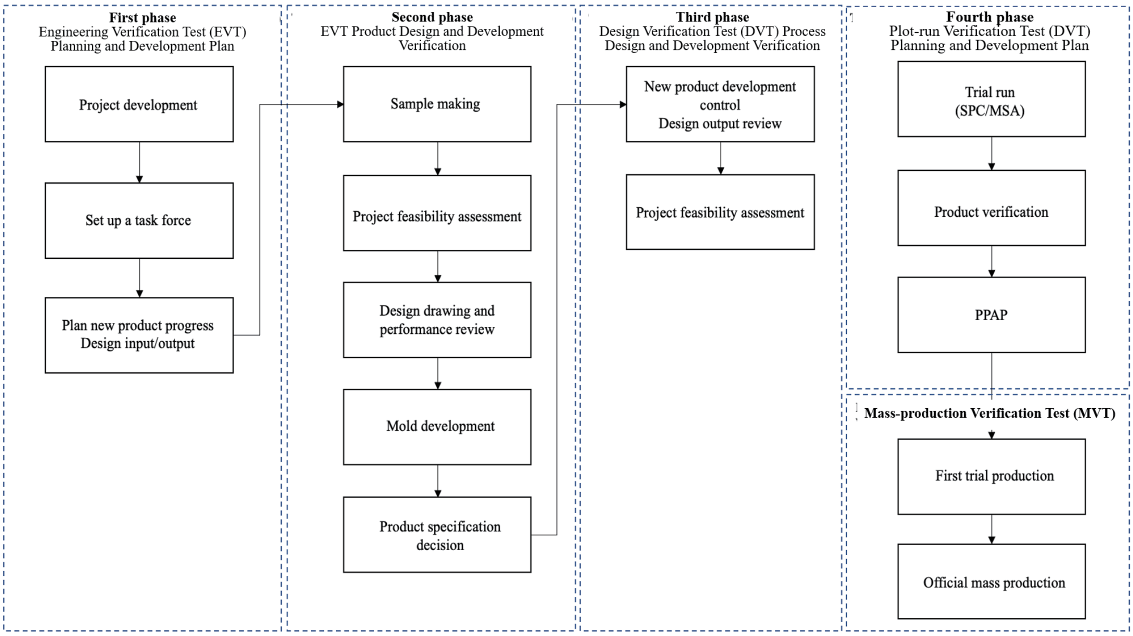


Fig. 1. Four phases in product development in ISO/TS16949.

melt in the injection mold. Controlling the parameters demands a comprehensive technology involving various sensor data and their processing and appropriate material.(4) Thus, such parameters are also important in the injection mold process of the cooling fans of the electronic chips for EVs as well as in finding and developing corresponding sensor technology for the process.

Therefore, we determined the optimal parameters for the injection molding of the cooling fans for electronic chips of EVs in this research. We used Taguchi's quality engineering analysis method (Taguchi method) with a simple orthogonal matrix with a relatively small number of factors to obtain information and optimize the parameters. The parameters were verified for the requirements of the final product through simulation.(5,6) The results of this research provide necessary information for developing sensor technology for the precision manufacturing of mold products for high-end machines and equipment. The determined optimal working range of sensors in the injection mold can be used to improve the performance of sensors.

2. Methods

2.1 Research procedure

We found the optimized parameters regarding time, temperature, and pressure in the injection mold of the cooling fan by verifying the theoretical results with simulation. The advanced product quality planning (APQP) method and the measurement system analysis (MSA) of ISO/TS16949 were considered in this research. The results of the simulation were validated with a production part approval process (PPAP) to propose the solution for the vibration caused by an unbalanced cooling fan and the warpage during injection molding. The overall research procedure is shown in Fig. 2.

2.2 Taguchi method

In the Taguchi method, the signal-to-noise ratio (SNR) is used as an indicator for judging the quality of product. The basic concept is to obtain products of better quality with a minimized deviation from the best quality.(7) The following equation is defined for η, which stands for SNR.

$$\eta = \log \text{(Useful Signal / Harmful Signal)} \tag{1}$$

The quality characteristics are divided into three types: 'the Larger The Better' (LTB), 'the Smaller The Better' (STB), and 'the Nominal The Best'.

2.2.1 LTB

Larger values are better when the target characteristic is not less than zero. An example is the lifetime of a product. The SNR of LTB is calculated as follows.

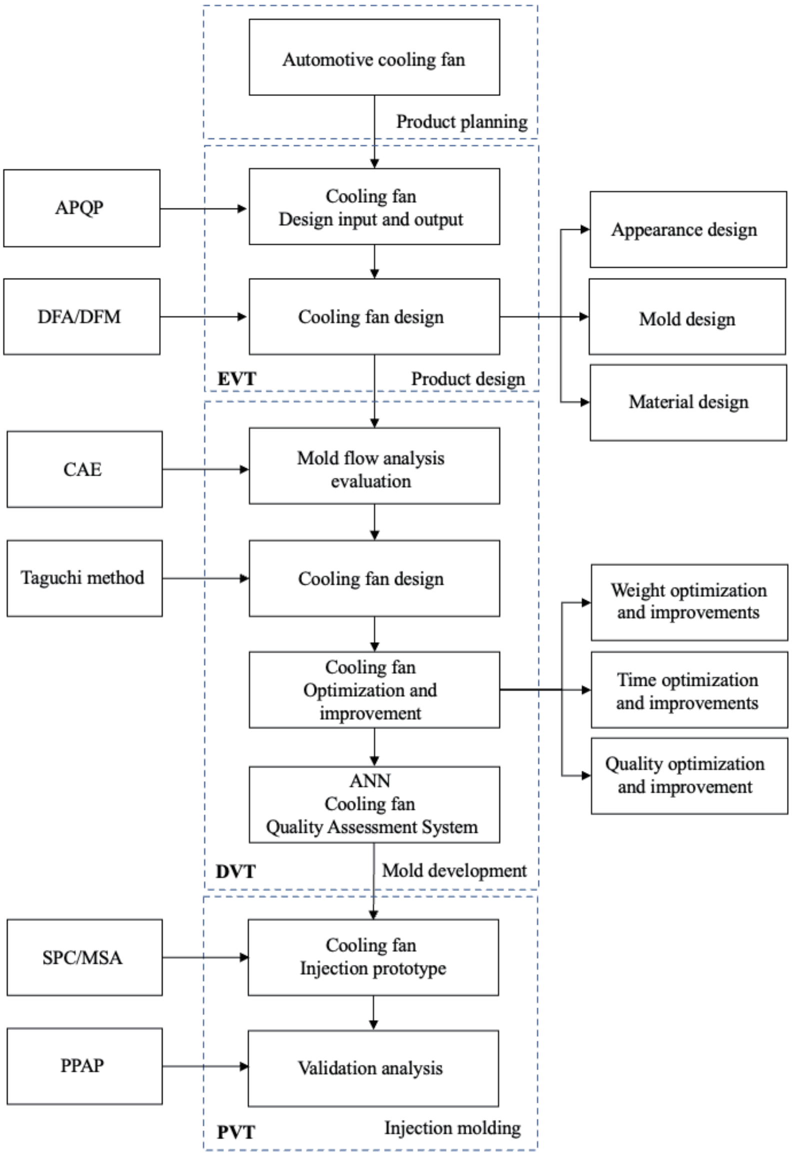


Fig. 2. Research procedure. (APQP: advanced product quality planning, DFA: design for assembly, DFM: design for manufacturing, CAE: computer-aided engineering, SPC: statistical process control, MSA: measurement system analysis, PPAP: production part approval process)

$$\eta = -10 \times \log\left[\frac{1}{n}\left(\frac{1}{y_1^2}+\frac{1}{y_2^2}+\frac{1}{y_3^2}+\ldots+\frac{1}{y_n^2}\right)\right] \tag{2}$$

Here, n is the number of Taguchi quality tests and y_n is the measured value of the nth Taguchi quality experiment.

2.2.2 STB

Smaller values are better when the target characteristic is not less than zero, for example, warpage in plastic product manufacturing. The SNR of STB is calculated as follows.

$$\eta = -10 \times \log\left(\frac{y_1^2 + y_2^2 + y_3^2 + \ldots + y_n^2}{n}\right) \tag{3}$$

2.2.3 Nominal The Best

When the target characteristic has a specific finite value, the SNR is calculated as follows.

$$\eta = -10 \times \log\left[\frac{1}{n-1}\sum_{i=1}^{n}\left(y_i - \overline{y}\right)^2\right] \tag{4}$$

3. Results and Discussion

3.1 Design parameters of injection mold of cooling fan

In designing the mold of the cooling fan, we considered two- and three-plate standard molds. The two-plate standard mold has more restrictions in the injection gate. When the cooling is completed, the mold is ejected from a runner through a gate. This method requires secondary processing to remove the gate and requires a hot runner to automatically separate the product from the runner. The overall mold cost is lower than that of the three-plate standard mold. The three-plate standard mold does not require the use of hot runners. The product is automatically separated from the flow channel during ejection, which requires the use of pinpoint gates. The advantage of the three-plate standard mold is that the melt in the runner cools down in the cavity, and the finished product is automatically separated from the gate after the process, which is appropriate for mass production with a simplified subsequent process.

In designing runners and gates, it is necessary to use six standard deviations and the concept of design for manufacture and assembly (DFMA) and to consider gates and mold bases for the choice of runners. Usually, in the two-plate standard mold, a large nozzle is chosen to find the optimal pouring point. This design considerably reduces the complexity of the mold and the cost of the mold base construction, as it is relatively simple. In this research, a two-plate standard mold with a Dashuikou design was adopted to produce the cooling fan to which the runner and gate were attached. However, as the melt flow through the large gate sometimes causes an imbalance of the cooling fan, the pouring design of the small nozzle of the three-plate standard mold was adopted to separate the mold and the product. In this way, the time and cost of subsequent processing were significantly reduced (Table 1). By using a runner with one mold, two cavities, and two-point pouring, the warpage problem could be improved significantly, which increased production capacity.

Table 1
Comparison of different gate runner designs.

	Two-plate standard mold	Three-plate standard mold
Gate design	Large gate (direct gate)	Small gate design (pin gate)
Product ejection condition	The product is ejected together with the gate.	The product is separated from the gate and ejected.
Follow-up processing	The injected product needs to be removed from the runner.	As the injected product is removed from the runner automatically, the appearance of the product is inspected.
Product balance	The cooling fan for vehicles has a problem with balance.	The cooling fan has a better balance.
Mold cost	Low	High
Mold complexity	Low	High

Table 2
Shrinkage rate, recommended runner design, and recommended gate design of PBT-4130.

<table>
<tr><th colspan="7">Shrinkage</th></tr>
<tr><th>Test Conditions</th><th>Vertical</th><th>Horizontal</th><th>Vertical</th><th>Horizontal</th><th>Vertical</th><th>Horizontal</th></tr>
<tr><td>Room temperature for 24 h (%)</td><td>0.36</td><td>1.6</td><td>0.22</td><td>1.24</td><td>0.19</td><td>1.09</td></tr>
<tr><td>190°C for 3 h (%)</td><td>0.46</td><td>1.71</td><td>0.42</td><td>1.67</td><td>0.41</td><td>1.62</td></tr>
<tr><td>120°C for 24 h (%)</td><td>0.49</td><td>1.71</td><td>0.44</td><td>1.67</td><td>0.44</td><td>1.62</td></tr>
<tr><th colspan="7">Recommended runner design</th></tr>
<tr><th>Part Thickness (mm)</th><th colspan="3">Runner length (mm)</th><th colspan="3">Runner diameter (mm)</th></tr>
<tr><td>0.5–1.5</td><td colspan="3">51</td><td colspan="3">1.6–3.2</td></tr>
<tr><td>1.5–3.8</td><td colspan="3">102</td><td colspan="3">3.2–4.8</td></tr>
<tr><th colspan="7">Recommended gate design</th></tr>
<tr><th>Type</th><th>Thickness (mm)</th><th colspan="2">Depth (mm)</th><th>Width (mm)</th><th colspan="2">Section length (mm)</th></tr>
<tr><td rowspan="2">Pinpoint</td><td><3.2</td><td colspan="2">0.7–1.3</td><td>—</td><td colspan="2">1</td></tr>
<tr><td>3.2–6.4</td><td colspan="2">1.0–3.0</td><td>—</td><td colspan="2">1</td></tr>
<tr><td rowspan="4">Rectangle</td><td><0.7</td><td colspan="2"><0.5</td><td><1</td><td colspan="2">1</td></tr>
<tr><td>0.7–2.3</td><td colspan="2">0.5–1.5</td><td>0.7–2.3</td><td colspan="2">1</td></tr>
<tr><td>2.3–3.2</td><td colspan="2">1.5–2.2</td><td>2.3–3.3</td><td colspan="2">1</td></tr>
<tr><td>3.2–6.4</td><td colspan="2">2.2–4.2</td><td>3.3–6.4</td><td colspan="2">1</td></tr>
</table>

On the basis of these results, we designed a cooling fan mold and its product using PBT-4130 for injection molding. The molding material included 30 wt.% of flame-retardant glass fiber. The shrinkage rate, the recommended runner design, and the recommended gate design are presented in Table 2.(8)

For the configuration of the runner and gate of the mold, Eq. (5) was used to calculate the pin-point gate diameter.

$$d = n \times c \times A \tag{5}$$

Here, c is the thickness, d is the gate diameter, n is the number of gates, and A is the surface area of the product.

Equation (6) was used for calculating the area of the fan blade and the wheel valley of the cooling fan.

$$A = 7 \times A_{wing} + A_{housing} \tag{6}$$

In reference to the thickness presented in Table 2, the optimum needle gate diameter was calculated as 0.495 mm, but in the mold, it was adjusted to 0.5 mm.

Other than the area and gate, the optimal waterway configuration ratio (pipe diameter: distance between the water pipe and finished product: waterway distance) was calculated as 1:3:5. By the finite element method, the optimal pipe diameter was determined to be 6 mm, the distance between the water pipe and the finished product was 18 mm, and the distance between the water channels was 30 mm.

3.2 Design result

We used computer-aided design (CAD) software to draw the design of the injection mold for the cooling fan. The DFMA design was used with the pin gate design equation for an easy repair of a single part and replacement of the mold core. Considering the equations given, we reduced the possibility of design errors. To confirm the feasibility of the mold, determine possible defects, and reflect necessary changes before mold processing, the Moldflow® simulation was carried out. In these processes, the mold development and design input and output were determined. Figure 3 shows the final design of the cooling fan mold.

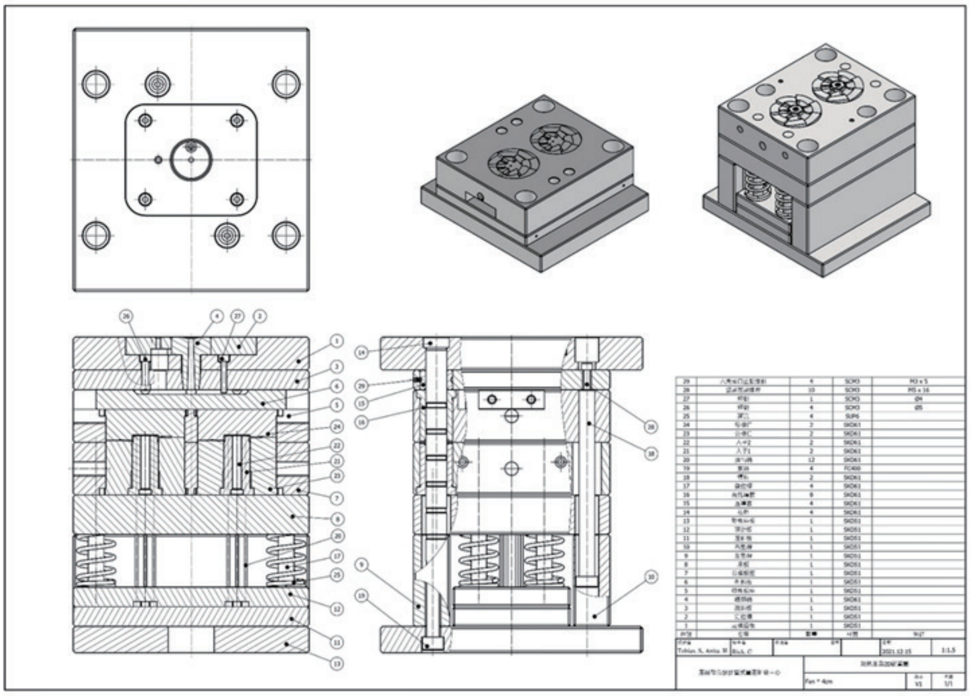


Fig. 3. Design of the cooling fan mold for cooling fans of electronic chips of vehicles.

3.3 Validation of design parameters

After the mold design was completed, simulations were conducted to adjust the design parameters to obtain the best result.

3.3.1 Mold filling time

In the simulation, the optimal mold filling time was obtained to fill the mold cavity and eject the product smoothly. The result is shown in Fig. 4.

3.3.2 Injection pressure

The results of the CAE analysis of the injection pressure showed that the injection pressure was gradually increased from 50 to 150 MPa within 5 s (Fig. 5). This result was important in injection molding using PBT-4130 for any product.

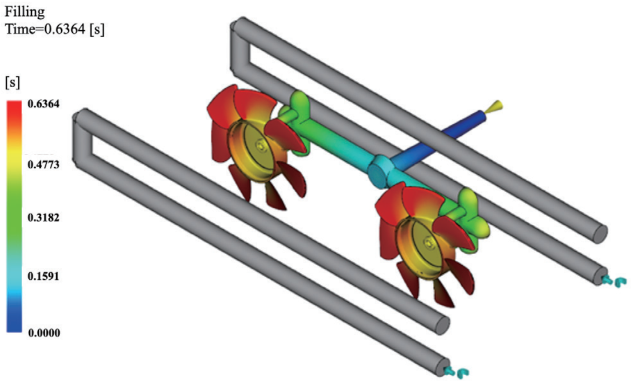


Fig. 4. (Color online) Optimal mold filling time in injection molding of cooling fan.

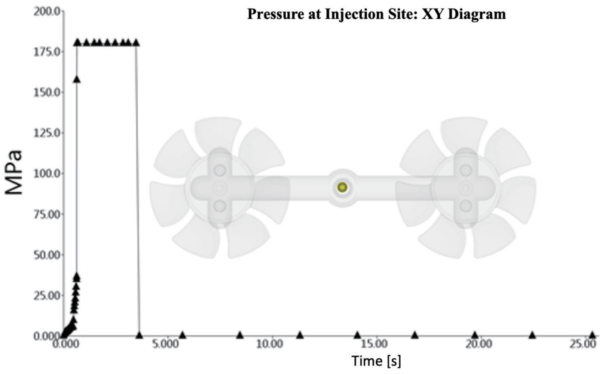


Fig. 5. Injection pressure analysis result in injection molding of cooling fan.

3.3.3 Pressure loss

We explored the relationship between the thickness of the cooling fan and the material and the runner design using pressure loss. Although the runner with a large diameter reduced the pressure loss when the melt flowed through, the entire molding cycle took a longer time, thereby reducing production capacity. In contrast, the runner with a small diameter caused significant pressure loss in the melt flow but it made the entire molding cycle shorter and the temperature of the melt after passing through the runner more uniform. With the given gate parameter, the analysis of the pressure loss of the mold is shown in Fig. 6.

3.3.4 Warpage analysis

Warpage analysis was the most important, as the warpage of the cooling fan blades affected the balance and noise when using the cooling fan. Therefore, the Taguchi method was used to find the best molding parameters and minimize the warpage. The results were obtained through CAE analysis and are shown in Fig. 7.

3.4. Simulation result

The Taguchi method was applied to investigate the relationships of control factors such as time, temperature, and pressure and the interactions between them in injection molding the cooling fan. The results help to improve the manufacturing process. In the method, the most important factor for the minimum amount of warpage was found with the most efficient production cycle for mass production, the shortest production time, and an optimized production cost. The CAE simulation was used for the Taguchi method. Each factor was varied according to the recommended value of PBT-4130 and the related analysis results. Each control factor was simulated at three levels as follows: melt temperatures of 250, 265, and 280 °C; holding pressures of 45, 55, and 65 MPa in the injection mold; cooling times of 20, 25, and 30 s for the molded product; mold temperatures of 70, 80, and 90 °C; V–P points of 95, 97, and 99 %; injection times of 0.4, 0.5, and 0.6 s; and holding times of 3, 5, and 7 s (Table 3).

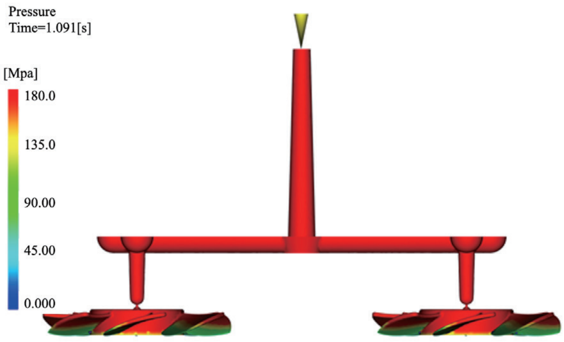
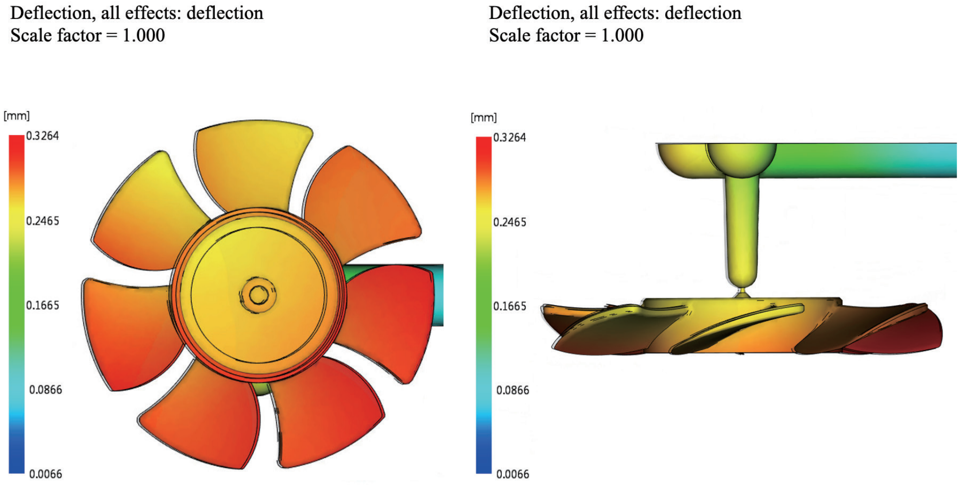


Fig. 6. (Color online) Result of pressure loss analysis in injection molding of cooling fan.



(a) (b)

Fig. 7. (Color online) Warpage analysis of cooling fan. (a) Top view of warpage analysis and (b) front view of warpage analysis.

Table 3
Control factors and their levels in Taguchi method in this research.

Control factors	Level (code)		
Melt temperature (°C)	250 (A1)	265 (A2)	280 (A3)
Holding pressure (MPa)	45 (B1)	55 (B2)	65 (B3)
Cooling time (s)	20 (C1)	25 (C2)	30 (C3)
Mold temperature (°C)	70 (D1)	80 (D2)	90 (D3)
V–P points (%)	95 (E1)	97 (E2)	99 (E3)
Injection time (s)	0.4 (F1)	0.5 (F2)	0.6 (F3)
Holding time (s)	3 (G1)	5 (G2)	7 (G3)

The degree of freedom (DOF) in the simulation was calculated as

$$DOF = m \times (n - 1). \tag{7}$$

Here, m is the number of factors and n is the level number.

DOF was calculated as 20, so the number of the calculations must be at least 20.

3.5. Results of Taguchi method

The control factors and their levels were input into the CAE analysis. In the results, the parameters were investigated and recorded in the Taguchi table, and SNR was calculated as shown in Fig. 8.

The results of the Taguchi method showed that holding time was the most important factor affecting the overall quality of the finished product. In the injection molding of the cooling fan, the adjustment of holding time at the holding pressures of 45, 55, and 65 MPa was critical to

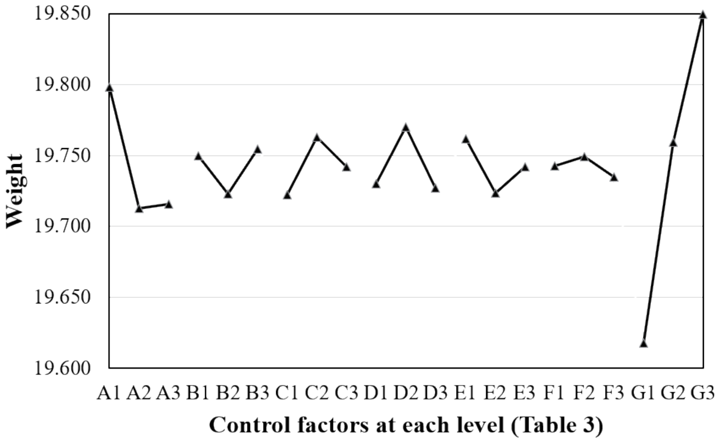
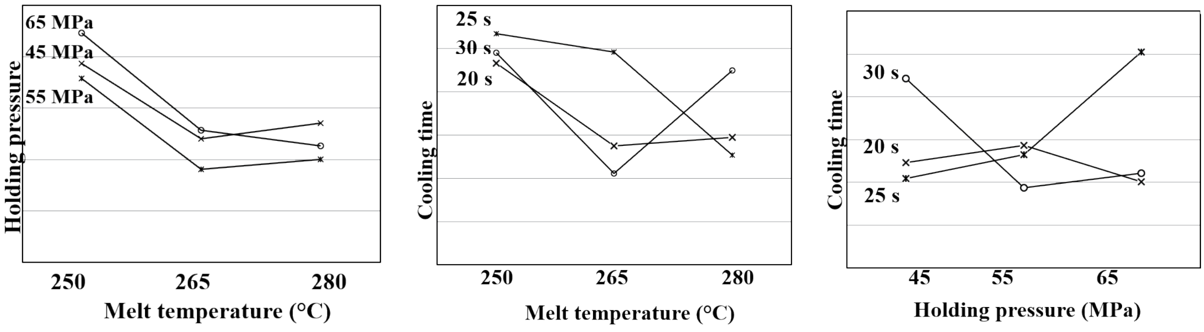


Fig. 8. Weight–factor response plot of SNR of the Taguchi method of control factors at each level of the injection mold of cooling fan.

Table 4
Optimal parameters for injection molding of cooling fan.

Control factors	Level
Melt temperature (°C)	265 (A2)
Holding pressure (MPa)	55 (B2)
Cooling time (s)	20 (C1)
Mold temperature (°C)	90 (D3)
V–P points (%)	97 (E2)
Injection time (s)	0.6 (F3)
Holding time (s)	3 (G1)



(a) (b) (c)

Fig. 9. Interaction of control factors. (a) Melt temperature and holding pressure, (b) melt temperature and cooling time, and (c) holding pressure and cooling time.

producing a cooling fan of optimum quality. In the simulation, the difference between the maximum and minimum weights was 0.155 g, which was 13 times higher than the average difference. The optimum combination of the factors was determined as listed in Table 4.

The interaction between melt temperature, holding pressure, and cooling time is shown in Fig. 9. Strong interactions were found at a melt temperature of 265 °C and cooling time of 30 s

Table 5
Optimal factors for injection molding of cooling fan considering interactions.

Control factors	Level
Melt temperature (°C)	265 (A2)
Holding pressure (MPa)	55 (B2)
Cooling time (s)	30 (C3)
Mold temperature (°C)	90 (D3)
V–P points (%)	97 (E2)
Injection time (s)	0.6 (F3)
Holding time (s)	3 (G1)

[Fig. 9(b)], and a holding pressure of 65 MPa and a cooling time of 25 s [Fig. 9(c)]. A significant interaction was not observed between melt temperature and holding pressure [Fig. 9(a)]. The optimal combination of the control factors became different from that predicted with the weight calculated by the Taguchi method due to interactions (Table 5).

4. Conclusions

The optimized parameters for the injection molding of cooling fans of the electronic chips of EVs were determined by the Taguchi method with the finite element method. To obtain the parameters, the APQP method, MSA of ISO/TS16949, and a PPAP were considered as they are important references for product quality management. PBT-4130 was considered as the material for manufacturing the cooling fan. Time, temperature, and pressure were selected as important factors to optimize the parameters for the most efficient production method. Melt temperature, holding pressure in the mold, cooling time of the product, mold temperature, V–P point in the injection mold, melt injection time into the injection mold, and holding time in the injection mold were defined as the control factors in the Taguchi method. Each factor was simulated at three different levels that were defined using the CAE analysis and considering the properties of PBT-4130. The result of the Taguchi method showed that the most important factor affecting the injection molding of the cooling fan using PBT-4130 was the adjusted holding time of the melt in the injection mold at the holding pressures of 45, 55, and 65 MPa. However, the interaction of the control factors affected the selection of the parameters. In the simulation, a melt temperature of 265 °C and a cooling time of 30 s were selected for the optimized production of a cooling fan manufactured with injection molding.

The results of this research are important in the design of the injection mold for any plastic product of high precision and quality. As the importance of time, pressure, and temperature has been confirmed for injection mold production, it is necessary to use advanced sensor technology to control them in the manufacturing process. The determined holding time, holding pressure, melt temperature, and cooling time can be used as the basic information to develop relevant sensors in the corresponding working range in the injection molding process. The results of this research also provide a reference to design and develop an injection mold system to manufacture high-quality products.

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About the Authors

Jui-Hung Cheng is a professor at the Department of Mold and Die Engineering at National Kaohsiung University of Science and Technology, Kaohsiung, Taiwan. His major research interests include product-integrated design, creative design methods, STEAM education, and problem/project-based learning. (rick.cheng@nkust.edu.tw)

Hsin-Hung Lin is a professor at the Department of Creative Product Design at Asia University, Taichung, Taiwan. His major research interests include the application of fuzzy set theory in product design, concurrent engineering in product design, computer-aided design, the application of neural networks and gray theory in product design, color planning for product design, heat transfer analysis, and the application of reverse engineering in product design. (hhlin@asia.edu.tw)

Jia-Hong Shen is a graduate of the Department of Mold and Die Engineering at National Kaohsiung University of Science and Technology in Taiwan. Throughout his studies, he developed a strong interest in mold design, mold engineering, and product design, which he continues to pursue in his professional career. (F110147123@nkust.edu.tw)