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Analysis of Injection Molding for Computer Cooling Fans by Taguchi Method and Grey Relational Analysis

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Abstract. Various factors affect the quality of a plastic product during the injection molding process. In this study, the quality engineering planning method, Taguchi Method, and grey relational analysis were used in this study to determine these factors and the Moldflow Plastics Insight (MPI) was used to conduct the moldflow analysis. By varying different types of operating conditions, the results obtained from the experiments were analyzed so as to verify the influence of each factor on the quality of the final product. The optimal processing parameters which can reduce the mold tryout time and the analysis cost were then determined. The plastic impeller of a computer cooling fan is selected as the case study and the goal is to resolve the warping problems. The deviations in the shear stress distribution as obtained by varying the S/N ratio of variance factors during the experiments are in agreement with the results of analyzing the grey information relational degrees. The most influential factor is the mold temperature, followed sequentially by the fill time, fill pressure, and melt temperature.

1. Introduction

With the advance in technologies, people have more requirements for a product and the trend is to have diversified products for now and in the future. The quality requirements for a material are getting stricter as well. As far as engineering material is concerned, conventional metal materials turn out to be insufficient to satisfy various types of requirements since they are affected easily by chemical corrosion or oxidation. For this reason, plastic materials are getting more popular due to its characteristics of easy processing, easy shaping, light weight, anti-corrosion and anti-rust properties. Moreover, different additives can be blended into a plastic material so as to enhance its performance. For example, composite materials such as glass fibers are added into plastics for the enhancement in the surface strength. Furthermore, with the improvement on plastic processing technologies, plastic materials are gradually replacing light metal materials or even alloy steels due to their superior specific strength. Among various processing methods for plastics, injection molding is the most promising one since it molds in one shot and is fast and convenient with a higher return on investment. Moreover, the high-pressure molding allows this manufacturing process to meet the precision requirements for most of the high-tech products.

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The Taguchi method [1] is a quality engineering planning approach, which was proposed by Dr. Taguchi Genichi based on the experimental design method initiated by Fisher [2]. In Taguchis opinion, Fishers statistical techniques can be simplified via the use of an orthogonal array, a signal to noise ratio (S/N), analysis of variance (ANOVA), and a response table or response graph for conducting analysis. He applied this method to industrial products and greatly simplified the required number of full-factor experiments. His method is now widely used for analyzing engineering designs and process optimizations, including the optimization for cutting processes [3] and the surface precision control in discharging processes [4].

As far as the effects of different processing parameters on quality are concerned, it is difficult to control the optimal molding processing parameters which might be further complicated when a designer is not able to master all of the relevant information. To this end, the so-called grey system theory was proposed by Deng [5, 6] so as to supply thoughts and solutions for any system problem with a limited amount of information. Similarly, other methods such as the grey relational model, grey information relation, grey model, and grey process were created and are now widely used in system analyses, forecasts, control applications, assessments, and decision-making scenarios. Laing [7] applied the grey relational theory to an energy program for hydropower scheduling. Similarly, Chang et al. [8] applied this approach to the optimization control during the process of plastic injection molding.

The *Moldflow MPI* software, which is within the integrated software of *I-deas Master Series 8*, was used in this study for conducting the analysis of mold flows and predicting the effects of processing parameters on the experimental results by computer simulation. After that, with the simulated results, the Taguchi method and grey relational theory were used to analyze and verify the effects of different engineering factors on product quality. Therefore, the optimal processing parameters can be determined so as to reduce the mold tryout time and the cost spent on analyses. The plastic impeller of a computer cooling fan is selected as the case study for investigating the warping problems that typically occur on a plastic part. The main factors which cause the warping problems were determined and the optimal processing conditions can be proposed by adjusting these factors. This way the quality of a plastic product can be enhanced and the production cost can be reduced.

2. Literature Review

In polymer processing, fiber is usually added in order to increase product strength. Therefore, it is important to learn about the effects of the complex flow field on fiber movement, so as to strengthen the injection molding process. Fiber flows along with the fluid in the flow field, and because of the effect of fluid deformation, the fiber distribution direction will constantly vary in the movement process. The earliest method applied to describe fiber direction variation in the flow field was the model proposed by Jeffery [9]. Goldsmith and Mason [10] made use of Jefferys Model to simulate the movement of suspended particles in the stable and simple shear flow of Newtonian flow and the biaxial extensional flow, and studied the distribution conditions of suspended particles caused by the fountain flow effect in the forward flow front. Gandhi and Burns [11] analyzed the relationship between properties of polymer and fiber position in Dough molding compounds (DMC), and learned that the flow viscosity is related to the fiber array and fiber aspect ratio, and long fibers will increase the viscosity of polymer materials. Folkes [12] conducted experiments with different injection conditions combined with fibers of different lengths, and learned that with high-speed injection in the through- thickness of the plate cavity, the fiber array will be perpendicular to the flow direction, and with low-speed injection, they will be parallel to each other.

Blane et al. [13] has studied fiber array in injection molding strengthened thermoset plastics and found that with low injection flow, the fiber forms a quite thick core area in the cavity through-thickness (about 5-6% of half the cavity thickness). Bailey and Rzepka [14] have conducted disk and cavity experiments to study fiber structure in the surface/core layer of a cavity and found that low injection speed, high pressure, low mold temperature, and short fiber can result in quite a thin core area (about 5% of half the cavity thickness), and the fiber in the flow front is arrayed in a parabola because of the fountain flow effect.

Mahishi [15] used C-Mold moldflow analysis software to analyze the properties of a thin-shell disk, and found that the thin shell injection requires a higher flow rate and injection pressure. During the injection molding filling process, the following factors influence the fiber array:

1. Cavity thickness: Sanou et al. [16] studied the effects of cavity thickness on the fiber array. He studied fiber array direction on the central planes of cavities 127 mm long, 12.7 mm wide, 1.6 mm and 3.2 mm thick. Since these two cavities were close to the mold wall, the fiber array was parallel to the flow direction, due to the shear stress. For the thinner cavity (1.6 mm in thickness), the fiber array was in a single direction due to a larger shearing rate. In the thicker cavity (3.2 mm in thickness), the fiber array direction was obviously two-dimensional (parallel with and perpendicular to the flow direction).
2. Injection speed: Folkes [12] learned from experimenting that the injection speed may influence the fiber array structure. With a low injection speed, the small flow causes a lower flow rate, which results in a large temperature difference between the flow and mold wall, and thicker solidification forms. Then, as the fiber enters the cavity, the central fiber array will become parallel to the flow direction due to shear stress. With a high injection speed, the central fiber array is perpendicular to the flow direction.
3. Mold temperature: Based on experiments, Vincent et al. pointed out that mold temperature may influence fiber array. As the mold temperature rises, the fiber array in the surface layer is quite regular; with a lower mold temperature, the fiber array is rather chaotic. The study found that only when the mold temperature doubles will such differences happen, and this shows that the effects of mold temperature on fiber array is not significant.
4. Length of fiber: Bailey and Rzepka [14] stated that, based on research, the differences in fiber length may cause different effects of fiber rolling. Since a long fiber is confined on the coplanar, it needs a comparatively greater force to roll; however, the short fiber is easier to move and roll. Therefore, long fiber is difficult to process, although it has a better strengthening effect.

3. Mathematical Models of Plastic Flow

For the sake of simplification, some hypotheses were made as follows:

1. Very thin cavity
2. Neglect the effects of inertia and gravity
3. Neglect the through-thickness convection effect
4. Only consider the through-thickness heat conduction

With the above hypotheses, the whole solver governing equation is derived as:

- Equation of continuity:

$$\frac{\partial \rho}{\partial t} + \frac{(\partial \rho u)}{\partial x} + \frac{(\partial \rho v)}{\partial y} + \frac{(\partial \rho w)}{\partial z} = 0 \tag{1}$$

where, x and y stand for the plane coordinates, z stands for the through-thickness, u, v, and w stand for speeds in the respective x, y, z direction, t stands for time, and ρ stands for density.

- Momentum equation:

$$0 = \frac{\partial}{\partial z}(\eta \frac{\partial u}{\partial z}) - \frac{\partial p}{\partial x} \tag{2}$$

$$0 = \frac{\partial}{\partial z}(\eta \frac{\partial v}{\partial z}) - \frac{\partial p}{\partial y} \tag{3}$$

- Energy equation:

$$\rho C_p\left(\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right) = \frac{\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)}{\partial z} + \eta\dot{\gamma}^2 \tag{4}$$

where, C_p stands for a specific heat, T stands for time, η stands for absolute viscosity, and $\dot{\gamma}$ stands for the shearing rate.

- Flow in Modified-Cross model:

(Viscosity is the function of shearing rate, temperature, and pressure)

$$\eta(\dot{\gamma}, T, p) = \frac{\eta_0(T, p)}{1 + [\frac{\eta_0\dot{\gamma}}{\tau^*}]^{1-n}} \tag{5}$$

$$\dot{\gamma} = \sqrt{\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2} \tag{6}$$

where, n is the material parameter, and τ^* stands for shear stress.

Its boundary conditions are:

$$\text{At z}= \pm b : u = v = 0; T = T_w \tag{7}$$

$$\text{At z=0:} \frac{\partial u}{\partial z} = \frac{\partial v}{\partial z} = 0 = \frac{\partial T}{\partial z} \tag{8}$$

where, T_w is the mold thickness. Since pressure is irrelevant to the Z direction, the momentum Equations (2) and (3) can be integrated as:

$$\eta\left(\frac{\partial u}{\partial z}\right) = \left(\frac{\partial p}{\partial x}\right)z \tag{9}$$

$$\eta\left(\frac{\partial v}{\partial z}\right) = \left(\frac{\partial p}{\partial y}\right)z \tag{10}$$

Based on the boundary conditions Equations (7) and (8):

$$v_x = \left(-\frac{\partial p}{\partial x}\right)\int_z^b \frac{z' dz'}{\eta} \tag{11}$$

$$v_y = \left(-\frac{\partial p}{\partial y}\right)\int_z^b \frac{z' dz'}{\eta} \tag{12}$$

Integrate the above Equations (11) and (12):

$$\bar{u} = \left(-\frac{\partial p}{\partial x}\right)\frac{s}{b} \tag{13}$$

$$\bar{v} = (-\frac{\partial p}{\partial y})\frac{s}{b} \tag{14}$$

$$S = \int_0^b \rho\frac{z^2dz}{\eta} \tag{15}$$

Introduce Equations (13) and (14) to acquire:

$$\frac{\partial}{\partial t}\int_0^h \rho dz - \frac{\partial}{\partial x}(s\frac{\partial p}{\partial x}) - \frac{\partial}{\partial y}(s\frac{\partial p}{\partial y}) = 0 \tag{16}$$

$$\rho = \rho(T, p) \tag{17}$$

$$\frac{\partial}{\partial t}\int_0^h \rho dz = G\frac{\partial p}{\partial t} + F \tag{18}$$

$$G = \int_0^x (\frac{\partial \rho t}{\partial \rho})_T dz + \int_x^h (\frac{\partial \rho_s}{\partial \rho})_T dz \tag{19}$$

$$F = \int_0^x (\frac{\partial \rho t}{\partial T})_P \frac{\partial T}{\partial t}dz + \int_x^h (\frac{\partial \rho_s}{\partial T})_p \frac{\partial T}{\partial t}dz + (\rho t - \rho_s)_z = x\frac{\partial x}{\partial t} \tag{20}$$

Boundary conditions in Equation (16) are:

P=0 at flow front (21)

$$P = P_e(x, y, t) \tag{22}$$

At the cavity entrance:

$$\frac{\partial p}{\partial n} = 0 \text{ on the mold wall} \tag{23}$$

- Fiber equation:

$$\frac{\partial \phi}{\partial t} = \frac{1}{2}[\frac{\partial w}{\partial x} - \frac{\partial u}{\partial z}] + \frac{r_p^2 - 1}{r_p^2 - 1} \bullet [\frac{1}{2}(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x})cos2\phi - \frac{1}{2}(\frac{\partial u}{\partial x} - \frac{\partial w}{\partial z})sin2\phi] \tag{24}$$

Here, ϕ stands for the included angle of the fiber and X axis; r_p stands for the fiber aspect ratio, $r_p = \frac{b}{a}$, and the starting angle of fiber at the entrance is set as a constant,

$$\phi_{moldinlet} = \psi_0 \tag{25}$$

Finally, finite elements are used to calculate the above equations.

4. Calculation Steps and Process

The calculation steps for simultaneous solver equations for continuity, momentum, and energy are as follows:

1. Input the problematical geometrical form into the computer and use an auto partitioning program to partition it into many small element groups.
2. Select materials and processing conditions.
3. Solve the equations of continuity and momentum and acquire pressure and speed distribution. The state equation and nature equation are certainly included in the process, and the viscosity and density of each point inside the cavity can also be acquired.
4. Solve the energy equation with speed distribution and pressure distribution, and acquire the temperature distribution inside the cavity.
5. Repeat Steps 3 and 4 in order to acquire the pressure and temperature distribution of each time step. When the filling or pack time is up, end the program execution, and print out the simulation results, including temperature distribution, pressure distribution, shearing rate distribution, shear stress distribution, volume contraction distribution, and the filling state of fluid.
6. Use post-processing software and describe the distribution of simulation results with lines or shadow graphs. Judge whether the quality of the finished product is influenced by this and then modify the processing conditions or mold design.

5. Quality Engineering Planning Method, the Taguchi Method

There are many factors affecting plastic material injection, and such factors as filling speed, injection pressure, melt temperature, pack pressure, cooling tubes, and injection entrance will also influence the precision of finished products. As the injection is finished, the flow inside the cavity will result in unbalanced temperature and pressure, which then may cause residual stress and work piece deformation in the cooling process. The greatest difficulty is to locate the position of the split line and gate. The experimental case in this study is a fan, one of the most common 3C products. Since the product usually rotates at work, if one blades weight is different than the others, the center of fan gravity will miss the position of the central axis, which may cause high-frequency noise during rotation and shorten the life span of the product. This is a problem which the users do not accept, and nowadays, if any problem happens to traditional molds, the mold manufacturers usually add a gate at the position of the problem or modify the design to solve existing product problems. Therefore, with regard to parameter settings, the first priority is to reduce the parameters of warping and contraction. However, according to past literature reviews, the gate position and cooling water temperature are direct factors influencing the products cooling contraction, and exerts a certain degree of influence on the products warping in the cooling process. In the injection process, the different injection plastic materials and different fiber proportions included will also cause different flow states, and the injection time, injection pressure, and injection temperature are all parameters determining whether the plastic material filling can be completed. This study is confined to eight parameters, including material, glass fiber proportion, gate position, cooling water temperature, mold temperature, injection temperature, injection pressure, and injection time, to conduct moldflow analysis and study the parameters influences on product warping while analyzing and studying the development of a computer cooling fan.

The main steps of the quality engineering planning method, the Taguchi Method, include making use of an orthogonal array to plan related engineering factors to build experimental items, and analyze experimental results through signal to noise ratio (S/N), analysis of variance (ANOVA), and a response table or response graph. The structure of related process plans are listed as follows:

Step 1: Set the main factors influencing the problems in process as target quality and define the properties as the larger-the-better, the smaller-the-better, and the nominal-the-better.

Step 2: Set the variance factors according to each processing condition of the problems (the set target quality) they cause.

Step 3: Select standard values for variance factors; that is the setting of each related processing condition.

Step 4: Build the orthogonal array.
Step 5: Test each processing condition group in the orthogonal array.
Step 6: Transform the experimental data into S/N, where the equation for S/N is:

$$S/N = -10log(M.S.D.) \tag{26}$$

Here M.S.D stands for the mean square deviation of the results of target quality for each testing group.

Step 7: Calculate the analysis of variance with S/N, acquire the S/N response table or response graph, and check the contribution rate of each variance. That is, find the adjustment factors. The contribution rate of each variance factor is the influence degree of each variance on the target quality and provides the designers with a reference for comparatively adjusting more significant variance factors in order to improve the target quality and provide them with a basis for comparatively modifying more insignificant variance factors in order to reduce costs.

6. Grey Relational Theory

Take one grey information relationship space as:

$$\{Q(X), R\} \tag{27}$$

where, Q(X) is the class of grey information relationship factors and R is the interaction coefficient. Take factor subclass X_i

$$X_i = [X_i(1), X_i(2), ...X_i(k)], i \in I, k \in N \tag{28}$$

where, $X_0(k)$ is the reference array, $X_i(k)$, i0 is the comparison array, and the relational coefficient of the grey information relationship between $X_i(k)$ and $X_0(k)$ is defined as:

$$r_i(k) = r[X_0(k), X_i(k)] \tag{29}$$

The relational degree of the grey information relationship between X_i and X_0 is:

$$r(X_0, X_i) = \frac{1}{n}\sum_{k=1}^{n} r[X_0(k), X_i(k)] = \frac{1}{n}\sum_{k=1}^{n} r_i(k) \tag{30}$$

The quantification model of the relational coefficient of the grey information relationship between $X_i(k)$ and $X_0(k)$ is defined as [7, 8]:

$$r_i(k) = r[X_0(k), X_i(k)] = \frac{\Delta min + \zeta\Delta max}{\Delta_{0,j}(k) + \zeta\Delta max} \tag{31}$$

where $\Delta_{0,j} = |X_0(k) - X_i(k)|$ stands for the absolute difference of two comparison arrays, $\Delta min = \underset{j\in 1}{min}\underset{k}{min}|X_0(k) - X_i(k)|$ stands for the minimum absolute difference of all comparison arrays, $\Delta max = \underset{j\in 1}{max}\underset{k}{min}|X_0(k) - X_i(k)|$ stands for the maximum absolute difference of all comparison arrays; and ζ stands for the identification coefficient, whose value will be adjusted based on the actual needs of the system, which is usually set as 0.5 [5, 6] between 0 and 1.

From the analysis above, four major grey relational formulas and the quantification model of the relational degree are used to build the grey information relationship analyzing model: Step 1: Initialize original arrays.

Step 2: Solve the difference sequence $\Delta_{0,j} = |X_0(k) - X_i(k)|$.

Step 3: Solve Δmin and Δmax of the comparison arrays.

Step 4: Calculate the relational coefficient $r_i(k)$. Set the identification coefficient as 0.5, and introduce the difference sequence, the minimum and maximum values of the absolute differences into the quantification model of the relational degree of the grey information relationship, and acquire the grey relational coefficient.

Step 5: Calculate the relational degree $r(X_0, X_i)$ of the grey information relationship between X_i and X_0.

Step 6: Array the relational degrees of the main factors in the grey system with other factors.

7. Case Study

7.1. Objective of the case study

This study adopted the computer cooling fan as the case for discussion. Figure 1 is the 3D modeling stereogram of the computer cooling fan with a diameter of 85 mm and a height of 27 mm made of ABS engineering plastic. In order to obtain the runner design optimization and reduce product molding, the 3D plastic product model, runner, and cooling water channel are shown in Figure 2. This product requires very strict attention to specification stability, planeness and warping in the production process, and product design and appearance in order to promote the competitive strength of traditional molds. In this study, Mold-Flow/Pack/Cool/Warp is used before mold opening, to simulate mold modification on the computer for processes including injection molding filling/packing/cooling/warping. In the injection molding filling process, the lower shear stress distribution must be maintained, and good flow is also necessary to obtain a more comparatively even volume contraction rate in order to avoid the warping problem in the molding process and keep the warping value within acceptable tolerance limits after the mold opening. Therefore, the warping problem of a computer cooling fan in the molding process is dealt with via existing injection molding machines, and by utilizing the process optimizing treatments mentioned, to quickly identity and create the best processing conditions and adjustable factors to improve quality and reduce costs.

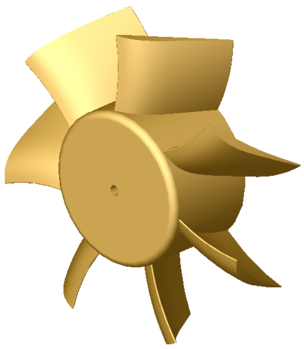

Figure 1: Computer cooling fan

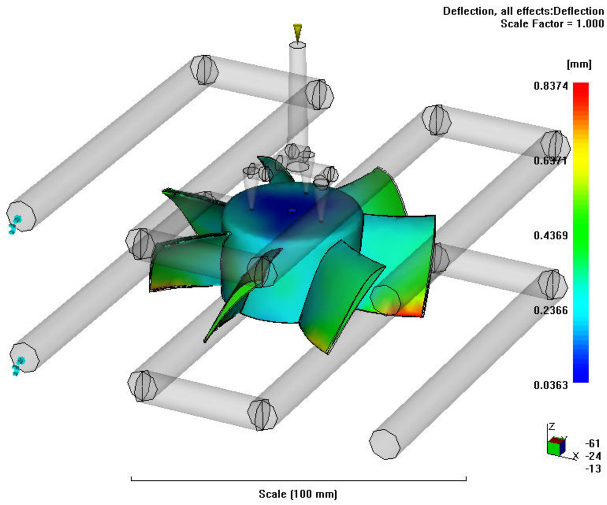

Figure 2: 3D model, runner, and cooling water channel

7.2. Steps based upon the process planning mentioned above are:

Step 1: Possible causes for warping problem are:

1. Molding process: inappropriate settings of processing conditions, such as injection pressure, injection speed, packing time, and mold temperatures;
2. Mold: variations in plastics specifications and surface thicknesses or bad mold composition; and
3. Material: high contraction rate.

In order to avoid the warping problem in the molding process, lower shear stress distribution must be maintained in the injection molding and filling processes, so that the plastics may contract evenly in order to reduce deformation after opening the mold. Therefore, the shear stress is set as the target quality and its property is defined as the smaller-the-better.

Step 2: The variance factors are set, based upon four processing conditions, including mold temperature, melt temperature, fill pressure, and fill time.

Step 3: When setting standard values for variance factors, processing conditions advised by PBT for other materials may be taken as references to set the standard table for mold temperature, melt temperature, fill pressure, and fill time, as shown in Table 1.

Table 1: Standard table of processing condition factors

Symbol	Processing condition factor	Unit	Standard 1	Standard 2	Standard 3
A	Mold temperature	°C	200	215	230
B	Melt temperature	°C	40	45	50
C	Fill pressure	MPa	200	210	220
D	Fill time	Sec	0.71sec	0.81sec	0.91sec

Step 4: Based on the Taguchi Method, use the L_9 orthogonal array to allocate four processing conditions, as shown in Table 2.

Table 2: L_9 orthogonal array allocation

Group	A	B	C	D
	Mold temperature	Melt temperature	Fill pressure	Fill time
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Step 5: Conduct tests on each processing condition group in the orthogonal array, shown in Table 3, and start the *Moldflow MPI* moldflow analysis software to analyze shear stress distribution.

Step 6: Convert the data obtained from the moldflow analysis into S/N. As the smaller-the-better is set for the property of the target quality, the calculation is:

$$S/N = -10log(\frac{\sum_{i=1}^{n} y_i^2}{n}) \tag{32}$$

where y_i is the value obtained from the experiment, and n is the number of experiments done.

Step 7: There are standard values of four different variance factors in Table 4, based on which the optimal group is A3, B1, C1, and D1 and the worst condition group is A1, B2, C2, and D3. The S/N response graph is also acquired, shown in Figure 3. In Figure 3, the slope represents the influence degree of the variance factor upon the target quality. The bigger the slope, the more influential it will be. In order to prevent the appearance of burr, the variance factors are arrayed in the following, according to their degree of influence: mold temperature, fill time, fill pressure, and melt temperature. Also, according to the ANOVA of S/N ratio for all variance factors affecting molding pressure in Table 5, it can be seen from the contribution rates that significant variance factors include mold temperature and fill time, which can serve as references for promoting quality, Insignificant variance factors are fill pressure and melt temperature, which can serve as a basis for cost reduction.

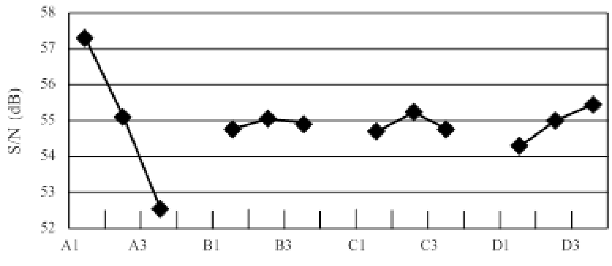

Figure 3: S/N response graph of each variance factor affecting shear stress distribution deviation

Table 3: Orthogonal array allocation of processing conditions

Group	Mold temperature (°C)	Melt temperature (°C)	Fill pressure (MPa)	Fill time (Sec)
1	200	40	200	0.71
2	200	45	210	0.81
3	200	50	220	0.91
4	215	40	210	0.91
5	215	45	220	0.71
6	215	50	200	0.81
7	230	40	220	0.81
8	230	45	200	0.91
9	230	50	210	0.71

Table 4: S/N ratio of standard values of variance factors affecting shear stress

Processing condition factor	Standard		S/N (dB)
Mold temperature (°C)	A1	200	-57.249
	A2	215	-55.089
	A3	230	-52.498
Melt temperature (°C)	B1	40	-54.841
	B2	45	-55.063
	B3	50	-54.932
Fill pressure (MPa)	C1	200	-54.703
	C2	210	-55.256
	C3	220	-54.877
Fill time (Sec)	D1	0.71	-54.331
	D2	0.81	-55.097
	D3	0.91	-55.409

Table 5: ANOVA of S/N of all variance factors affecting shear stress

Factor	Mobility	Variation	Variant	Simple variation	Contribution rate
	f	SS	V	SS	ρ
Mold temperature	2	33.95549	16.97774	22.6783	92.64%
Melt temperature	2	0.075144	0.037572		
Fill pressure	2	0.479242	0.239621		
Fill time	2	1.844955	0.922477	1.567762	4.31%
Pooled error	4	0.554386	0.138596	1.1108772	3.05%
Total		36.35483		36.35483	100%

7.3. The steps for building a grey information relation analyzing model are in the following sequence:

Step 1: Initialize experimental data arrays, including mean shear stress distribution deviation, resulting from processing condition simulations in Table 6, shown in Table 7.

Table 6: Allocation table for the mean shear stress resulting from processing condition group tests

Group	1	2	3	4	5	6	7	8	9
Mean shear stress deviation	652.26	778.8	761.3	613.62	532.36	561.38	420.54	438.4	406.48
Mold temperature	200	200	200	215	215	215	230	230	230
Melt temperature	40	45	50	40	50	45	40	45	50
Fill pressure	200	210	220	210	220	200	220	200	210
Fill time	0.71	0.81	0.91	0.91	0.71	0.81	0.81	0.91	0.71

Table 7: Allocation table for the mean shear stress resulting from processing condition group tests

Group		1	2	3	4	5	6	7	8	9
Mean shear stress deviation	X_0	0.1263	0.1508	0.1474	0.1188	0.1031	0.1087	0.0814	0.0849	0.0787
Mold temperature	X_1	0.1034	0.1034	0.1034	0.1111	0.1111	0.1111	0.1189	0.1189	0.1189
Melt temperature	X_2	0.0988	0.1111	0.1235	0.0988	0.1235	0.1111	0.0988	0.1111	0.1235
Fill pressure	X_3	0.1058	0.1111	0.1164	0.1111	0.1164	0.1058	0.1164	0.1058	0.1111
Fill time	X_4	0.0974	0.1111	0.1248	0.1248	0.0974	0.1111	0.1111	0.1248	0.0974

Step 2: Solve the difference sequence $\Delta_{0,j} = |X_0(k) - X_i(k)|$, shown in Table 8.

Table 8: Difference sequence $\Delta_{0,j} = |X_0(k) - X_i(k)|$

Group		1	2	3	4	5	6	7	8	9
Mold temperature	X_1	0.0229	0.0474	0.0440	0.0077	0.0080	0.0024	0.0374	0.0340	0.0402
Melt temperature	X_2	0.0275	0.0397	0.0239	0.0200	0.0204	0.0024	0.0173	0.0262	0.0448
Fill pressure	X_3	0.0205	0.0397	0.0310	0.0077	0.0133	0.0029	0.0350	0.0209	0.0324
Fill time	X_4	0.0289	0.0397	0.0266	0.0060	0.0057	0.0024	0.0297	0.0400	0.0187

Step 3: Acquire $\Delta min = \Delta_{0,6}(1) = 0.0024$ and $\Delta max = \Delta_{0,1}(1) = 0.474$ from Table 8.

Step 4: Set the identification coefficient as 0.5 in the calculation of a grey relational coefficient, and acquire grey relational coefficients for all variance factors, as shown in Table 9.

Table 9: Relational degree coefficients $r_i(k)$

Group		1	2	3	4	5	6	7	8	9
Mold temperature	X_1	0.5605	0.3674	0.3858	0.8323	0.8231	1.0000	0.4274	0.4530	0.4092
Melt temperature	X_2	0.5102	0.4124	0.5485	0.5974	0.5926	1.0000	0.6366	0.5233	0.3817
Fill pressure	X_3	0.5917	0.4124	0.4778	0.8323	0.7055	0.9834	0.4453	0.5853	0.4657
Fill time	X_4	0.4969	0.4124	0.5648	0.8788	0.8894	1.0000	0.4894	0.4105	0.6163

Step 5: Calculate the relational degree $r(X_0, X_1)$ between variance factors X_i and the mean shear stress distribution deviation X_0, as shown in Table 10.

Table 10: Relational degree $r(X_0, X_1)$ of grey information relationship

Factors	Relational Degree
Mold temperature	1.2565
Melt temperature	0.5781
Fill pressure	0.6110
Fill time	0.6398

Step 6: While arraying the relational degrees of the main factors in the grey system with other ones, the main factor is the mean shear stress distribution deviation X_0, and other factors are variance factors for X_i.

Based on the relational degree $r(X_0, X_1)$, from the burr-proof case, it can be seen that the relational degree of the mold temperature factor on the mean shear stress distribution deviation is the largest (relational degree: 1.2565), followed in sequence by fill time, fill pressure, and melt temperature; and all three are very close to each other- nearly half of the relational degree of the mold temperature. This result is identical to the variance conditions of S/N ratio of variance factors in Table 7. The most significant variance factor is mold temperature with a contribution rate as high as 92.64% leaving the factor of fill time with only 4.31%.

8. Conclusion

Quality engineering planning methods including the Taguchi method and the grey relational theories were used in this study to resolve the warping problem of a computer cooling fan. The results indicated that the S/N ratios of variance factors which lead to the deviation in the shear stress distribution corresponded to the results of the analysis of grey information relational degrees. The most influential factor is the mold temperature, followed by the fill time, fill pressure, and melt temperature. Moreover, the analysis by the relational degrees, which represent a factors contribution rate, indicated that the most significant variance factor is the mold temperature, followed by the fill time. These results serve as a good reference for enhancing the quality of a plastic product. The factors including the fill pressure and the melt temperature are those with less significant variance, which can be further adjusted so as to achieve the goal of cost reduction. Based on the results, it is clear that the proposed approach can ensure the success of a process, reduce the number of mold tryouts, and save the cost and time that otherwise might potentially be wasted. This way a process can be optimized in a scientific and rational way so as to achieve the goal of producing a small amount of products with a higher degree of diversity. As a result, a product that is manufactured by this optimized process not only meets design requirements but also have a higher level of competitiveness due to the cost reduction effects.

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