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NUMERICAL OPTIMISATION OF GATING SYSTEM PARAMETERS FOR ALUMINUM METAL CASTING BY USING TAGUCHI'S ROBUST DESIGN TECHNIQUE

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ABSTRACT

An optimization technique for design of gating system parameters of a cylindrical aluminium casting based on the Taguchi method is proposed in this paper. The various gating systems for a casting model of aluminium are designed. Mould filling and solidification processes of the aluminum casting were simulated with the PROCAST 2009.1. The simulation results indicated that gating system parameters significantly affect the quality of the aluminum casting. In an effort to obtain the optimal process parameters of gating system, an orthogonal array, the signal-to- noise (S/N) ratio, and analysis of variance (ANOVA) were used to analyze the effect of various gating designs on cavity filling and casting quality using a weighting method.

KEYWORDS: Taguchi method, Computational simulation, Optimisation, Gating system, Aluminium casting.

INTRODUCTION

A large number of experimental investigations linking gating parameters with casting quality have been carried out by researchers and foundry engineers over the past few decades (Campbell, 2003; Yang et al., 2000). Since all liquid melt required filling up the casting cavity needs to be introduced through the gating system, it has been long recognized that gating system design plays one of the key elements in casting quality. Although there are general casting design guidelines and empirical equations for the gating ratio, pouring time, and gating system dimensions, the variations in casting parameters chosen by different researchers have led to significant variations in empirical guidelines (Runyoro et al., 1992; Campbell, 1998). This also forces foundries to carry out a number of trial and error runs and create guidelines based on their own experience. Traditionally, gating system design is performed by casting process engineers based on their individual knowledge and experience. In many cases, the gating system design is not optimal and often based on trial and error practice. This leads to not only a long casting development cycle but also a low reliability of casting design due to variation of individual knowledge and experience.

The use of a good gating system is even more important if a casting is produced by a gravity process (Ha et al., 2000). Compared with cast iron, aluminum metal is sensitive for receiving damage during the filling and has high susceptibility to oxidation and hydrogen absorption. Since oxide formation is instantaneous in aluminum, the design of gating system plays more important role on minimizing the entrance of oxides on the surface of the molten metal into the casting and also to prevent turbulence in the metal stream caused by excessive velocities of the molten metal, free-falling of the stream while passing from one level to another, vortices formed, or abrupt changes in the flow direction (Hu and Yu, 2002; Green and Campbell, 1994). Therefore, aluminum castings are vulnerable to certain defects such as porosity, oxide inclusions, which are known to be attributed to the faulty design of gating system with incorrect mould filling. In order to achieve a good gating system, it is necessary to start from fundamental hydraulic principles. In the past decades, some equations based on empirical relationships have been derived and used to design a gating system (Svoboda, 1995). After applying these relationships, a gating system of questionable quality is obtained. A lot of effort has been made to understand the influence of gating system design on mould filling using various techniques. A given design of gating system is usually validated by pouring and sectioning the test casting, or by observing the flow of molten metal in a sand mould using radiography, real time X-ray and video camera (Ha et al., 2000), or the flow of water in a transparent mould, or using contact wire sensing using computerized data acquisition (Schuhmann et al., 1994). Typically, modifying gating geometry by applying this trial-and-error approach, a better gating system can be achieved. However, this trial-and-error approach is time consuming and expensive.

The first research showing an effect to apply a numerical optimisation methodology to optimize a gating system is due to Bradley and Heinemann in 1993 (Bradley and Heinemann, 1993). They used simple hydraulic models to simulate the optimisation of gating during filling of moulds. In 1997, MacDavid and Dantzig used a mathematical development addressing the design sensitivity within two-dimensional mould geometry. By the end of the 1990s, the computer modeling enabled visualization of mould filling to be carried out cost-effectively in casting design and optimisation of gating system. Numerical simulators based on FDM and FEM methods provide powerful means of analyzing various phenomena occurring during the casting process (McDavid and Dantzig, 1998a,b). The trial-and error approach practices moved away from the real model to the virtual one. Numerical simulation program were able to simulate the behavior of molten metal close to reality, obtaining the better final design, but still not the optimum design (Kor et al., 2006).

Up to now, there is following optimisation method applying to the gating system design: the gradient search method, the FEM neural network method, and the Taguchi method (Lee and Lin, 2006; Esparza et al., 2006; Anastasion, 2002). Dr. Genichi Taguchi has introduced several new statistical tools and concepts of quality improvement that depend heavily on the statistical theory of experimental design (Taguchi, 1998; Byrne and Taguchi, 1987). Some applications of Taguchi's methods in the foundry industry have shown that the variation in casting quality caused by uncontrollable process variables can be minimized

(Johnston, 1989; Kumar and Gaindhar, 1995; Barua et al., 1997). The casting process has a large number of parameters that may affect the quality of castings. Some of these parameters are controllable while others are noise factors. Therefore, the optimisation of casting parameters using the Taguchi method is the better choice for rapid casting quality improvement.

The purpose of this paper is to demonstrate how the application of numerical optimisation techniques can be used to develop an effective optimisation process for gating system design. An optimisation technique of gating system parameters based on aluminum metal casting using the Taguchi method with multiple performance characteristics is proposed. The analysis of variance is also investigated for the gating parameters with multiple characteristics. Mould filling and solidification processes of the castings were simulated with the *PROCAST 2009.1*. The simulation results indicated that gating system parameters significantly affect the casting quality. This virtual approach and optimisation technique can be applied to the foundry industry, which is evidently superior to typical trial-and-error approaches.

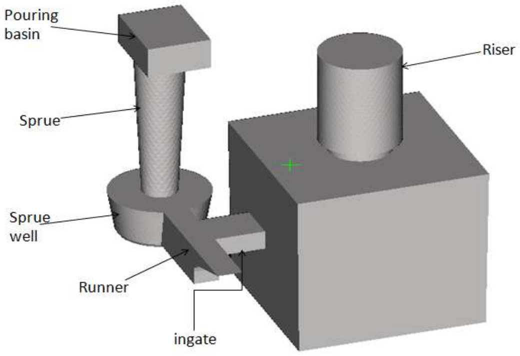

Fig.1 3-D CAD model of the test casting with gating system

(B.Ravi, 2009) Computer-aided casting design and simulation gives a much better and faster insight for optimising the feeder and gating design of castings. Key inputs, steps and results are discussed here. Casting simulation however, poses several challenges: technical as well as non-technical (resources) for industrial users. We highlight the best practices based on our experience with several casting simulation projects, and directions for further research in this area to make casting simulation more easy, accessible and economical for industrial users.

DESIGN OF EXPERIMENT BASED ON THE TAGUCHI METHOD

Gating System Parameters And Objectives Design

The objective of the parameter design is to optimize (D.C. Montgomery, 1991) the settings of the process parameter values for improving performance characteristics and to identify the product parameter values under the optimal process parameter values. In addition, it is expected that the optimal process parameter values obtained from the parameter design are insensitive to the variation of environmental conditions and other noise factors. Therefore, the parameter design is the key step in the Taguchi method to achieving high quality without increasing cost.

A cubical housing model was used as the test sand casting to demonstrate the numerical optimisation. The three-dimensional CAD model of the test casting is shown in Fig. 1 A cube of dimensions 100 mm × 100 mm × 100 mm and after adding allowances (shrinkage, machining & draft allowance) it dimensions becomes 107 mm × 105 mm × 104 mm. The casting material is defined pure Aluminium. The weight of casting is 3.171 kg. The process used for preparing mould cavity is sand casting. A pouring basin and tapered sprue were used and metal was introduced into the casting cavity through one runner and one ingate of rectangular cross-section. Single blind riser is used at top of the housing model of height 60 mm and diameter 45 mm. The gating system of housing is controlled by four independent parameters, namely ingate height, ingate width, runner height, runner width, as showed in Fig.2 Changing these parameters can modifying gating system geometry and cross section area separately.

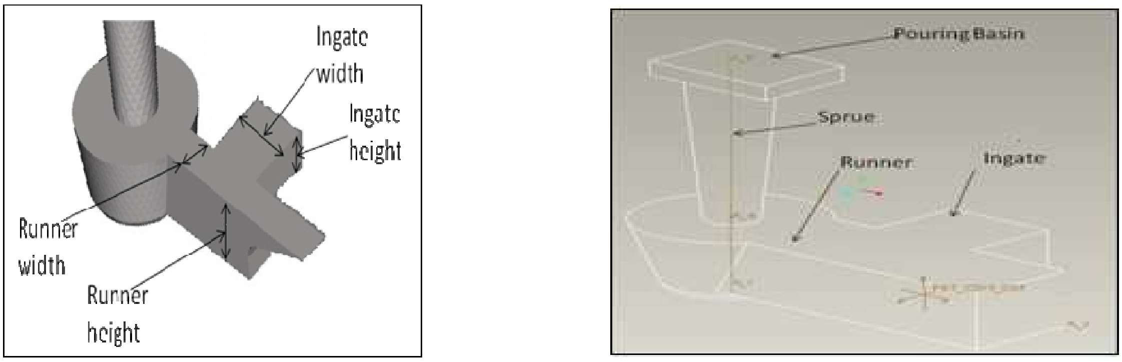

Fig.2 3-D model of gating system

Table 1. Gating System Parameters and their Level

Factor / Level	Ingate height A (mm)	Ingate width B (mm)	Runner height C (mm)	Runner width D (mm)
1	12	25	25	14
2	17	20	20	19
3	22	15	15	24

Since the lower and wide geometry help to reduce the metal velocity and get a smooth flow into mould, the parameter ranges of the design variables are given in the Table 1. In this work only four parameters ingate height, ingate width, runner height and runner width were changed. Remaining parameters kept constant for all the experiments. The theoretical calculation was done to design parameters values. In sprue , top diameter is 30 mm; bottom diameter is 20 mm and height of sprue is 98 mm.

In this study, in order to evaluate the sound casting comprehensively, the optimisation criteria for the housing casting sample were defined as: (1) casting quality, and (2) casting cost. The molten metal filling velocity and casting shrinkage porosity can demonstrate the casting quality; and the casting cost characteristic can be indicated by product yield. These three characteristics acting as multiple performance objectives for evaluating different gating system designs are defined as the Eqs. (1) – (3):

$$\text{Velocity}\ (v) = \sqrt{v_x^2 + v_y^2 + v_z^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

$$\text{Shrinkage Porosity}\ (\%) = \frac{V_{pores}}{Vol_{cast}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

$$\text{Casting Yield}\ (\%) = \frac{weight_{casting}}{weight_{casting} + weight_{gating+riser\ system}} \quad \ldots\ldots\ldots\ldots \quad (3)$$

Where v_x, v_y, v_z are three component of vector velocity. The product yield is defined by the weight of casting divided by total weight including sprue, gating and riser system. Porosity is defined by the ratio of the volume of all pores in the casting to the volume of whole cast.

A large number of experiments have to be carried out when the number of the process parameters increases. To solve this task, the Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with a small number of experiments only. A loss function is then defined to calculate the deviation between the experimental value and the desired value. Taguchi recommends the use of the loss function to measure the performance characteristic deviating from the desired value. The value of the loss function is further transformed into a signal-to-noise (S/N) ratio. Usually, there are three categories of the performance characteristic in the analysis of the S/N ratio, that is, the lower-the-better, the higher-the-better, and the nominal-the-better. The S/N ratio for each level of process parameters is computed based on the S/N analysis. Regardless of the category of the performance characteristic, the larger S/N ratio corresponds to the better performance characteristic. Therefore, the optimal level of the process parameters is the level with the highest S/N ratio. Furthermore, a statistical analysis of variance (ANOVA) is performed to see which process parameters are statistically significant. With the S/N and ANOVA analyses, the optimal combination of the process parameters can be predicted. Finally, a confirmation experiment is conducted to verify the optimal process parameters obtained from the parameter design. In this paper, the gating parameter design by the Taguchi method is adopted to obtain optimal gating system in aluminium casting.

Selection of Orthogonal Array for Design of Experiment

To select an appropriate orthogonal array for experiments, the total degrees of freedom need to be computed. The degrees of freedom are defined as the number of comparisons between process parameters that need to be made to determine which level is better and specifically how much better it is. For example, a three-level process parameter counts for two degrees of freedom. The degrees of freedom associated with interaction between two process parameters are given by the product of the degrees of freedom for the two process parameters. In the present study, the interaction between the gating parameters is neglected. Therefore, there are eight degrees of freedom owing to the four gating parameters in aluminium casting operations.

Once the degrees of freedom required are known, the next step is to select an appropriate orthogonal array to fit the specific task. Basically, the degrees of freedom for the orthogonal array should be greater than or at least equal to those for the process parameters. In this study, an L9 orthogonal array with four columns and nine rows was used. This array has eight degrees of freedom and it can handle three-level process parameters. Each gating parameter is assigned to a column and nine cutting parameter combinations are available. Therefore, only nine experiments are required to study the entire parameter space using the L9 orthogonal array. The experimental layout for the four gating parameters using the L9 orthogonal array is shown in Table 2.

Analysis Of The S/N Ratio With Multiple-Performance Characteristics

The Taguchi method uses signal-to-noise (S/N) ratio instead of the average value to interpret the trial results data into a value for the evaluation characteristic in the optimum setting analysis. This is because signal-to-noise ratio can reflect both the average and the variation of the quality characteristics. If the S/N ratio is expressed in dB units, it can be defined as Eq. (4) by a logarithmic function based on the Mean Square Deviation (MSD) around the target.

$$\eta = -10\log(\mathrm{MSD}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

where MSD is the mean-square deviation for the output characteristic. To obtain optimal casting cost, the higher-the-better quality characteristic for product yield must be taken. The MSD for the higher-the-better quality characteristic can be expressed as Eq. (5)

$$\mathrm{MSD} = \frac{1}{n}\sum_{i=1}^{n}\frac{1}{T_i^2} \quad \ldots\ldots (5)$$

where *n* is the total number of tests in a trial and T_i is the value of product yield at the ith test.

On the other hand, the lower-the-better quality characteristic for filling velocity and shrinkage porosity also is being taken for obtaining the optimal casting quality. The MSD for the lower-the-better quality characteristic can be expressed as Eq. (6):

$$\mathrm{MSD} = \frac{1}{n}\sum_{i=1}^{n} S_i^2 \quad \ldots\ldots (6)$$

where S_i is the value of filling velocity and shrinkage porosity at the ith test.

Table 2. L9 Orthogonal Arrays

Experiment	Ingate Height A	Ingate Width B	Runner Height C	Runner Width D
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

The proposition for the optimisation of a gating system with multiple performance characteristics (three objective) using a weighting method is defined as

$$X = Y \times Z \quad \ldots\ldots (7)$$

$$\text{where } X=\begin{bmatrix}\eta_{1C}\\ \eta_{2C}\\ \eta_{3C}\\ \eta_{4C}\\ \eta_{5C}\\ \eta_{6C}\\ \eta_{7C}\\ \eta_{8C}\\ \eta_{9C}\end{bmatrix};\quad Y=\begin{bmatrix}\eta_{11} & \eta_{12} & \eta_{13}\\ \eta_{21} & \eta_{22} & \eta_{23}\\ \eta_{31} & \eta_{32} & \eta_{33}\\ \eta_{41} & \eta_{42} & \eta_{43}\\ \eta_{51} & \eta_{52} & \eta_{53}\\ \eta_{61} & \eta_{62} & \eta_{63}\\ \eta_{71} & \eta_{72} & \eta_{73}\\ \eta_{81} & \eta_{82} & \eta_{83}\\ \eta_{91} & \eta_{92} & \eta_{93}\end{bmatrix};\quad Z=\begin{bmatrix}w_1\\ w_2\\ w_3\end{bmatrix} \quad \text{....................................(8)}$$

$$\& \sum_{i=1}^{3} w_i = 1 \quad \text{..(9)}$$

Assumption is using L9 orthogonal array. w1 is the factor of product yield; w2 is the factor of shrinkage porosity; w3 is the factor of filling velocity; jc is the multi-response S/N ratio in the jth test. ji is the ith single response S/N ratio for the jth test. wi is the weighting factor in the ith performance characteristics. The objective function was formulated according to the previous optimisation criteria:

$$\text{Maximize f(X)} = \eta_{\text{Yield}} w_1 + \eta_{\text{Porosity}} w_2 + \eta_{\text{Velocity}} w_3 \quad \text{...............................(10)}$$

Where w_1, w_2, w_3 are the weighting factors of S/N ratio for yield, porosity and velocity, respectively. The above objective function is presented in an analytical form as a function of input parameters since increased productivity, smooth cavity filling with minimized oxidation and reduced porosity play the important roles during casting manufacturing. However, in actual manufacturing process, for different components, the three characters should be considered as different critical roles by weighting factors. When defect elimination becomes critical, high weighting factors of porosity and velocity needs to be considered. However, for certain casting products, high yield factor may require due to lower cost demand. As an example, in this study, case 1 (523), case 2 (352) and case 3 (127) with three different combinations of weighting factors were selected for demonstrating various casting requirements.

Analysis Of Variance (Anova):

The purpose of the ANOVA is to investigate which of the process parameters significantly affect the performance characteristics. This is accomplished by separating the total variability of the multi-response S/N ratios, which is measured by the sum of the squared deviations from the total mean of the multi-response S/N ratio, into contributions by each of the process parameters and the error. The purpose of the analysis of variance is to investigate the gating system parameters (factors) with multiple characteristics that significantly affect the quality characteristic. The ANOVA was established on the sum of the square (SS), the degree of freedom (*D*), the variance (*V*), and the percentage of the contribution to the total variation (*P*). These five connective parameter symbols can be calculated as Eqs. (11) and (12)

$$SS_p = \sum_{i=1}^{m} \frac{(S\eta_{jc})^2}{t} - \frac{1}{m}\left[\sum_{i=1}^{m} \eta_{ic}\right]^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

$$SS_T = \sum_{i=1}^{m} \eta_{jc}^2 - \frac{1}{m}\left[\sum_{i=1}^{m} \eta_{ic}\right]^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

where m is the number of the tests (m= 9). p represents one of the tested parameters, j is the level number of this parameter p, t is the repetition of each level of the parameter p, and S jc is sum of the multi-response S/N ratio involving this parameter p and level j. The total degree of freedom is DT = m-1, for the tested parameter, Dp= t -1. As the following Eqs. (13) – (15) show, the variance (V) is defined as the sum of squares of each trial sum result involved the factor, divided by the degrees of freedom of the factor. The corrected sum of squares (SS'p) is defined as sum of squares of factors minus the error variance times the degree of freedom of each factor. The contribution (P) denotes the percentage of the total variance of each individual factor.

$$V_P = \frac{SS_P}{D_P} \times 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (13)$$

$$SS'_P = SS_p - D_p V_e \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (14)$$

$$P_p = \frac{SS'_P}{SS_T} \times 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (15)$$

COMPUTATIONAL EXPERIMENT

Simulation of the mould filling and solidification process required geometrical information for the casting, the gating system and the sand mould. Solid CAD models were created using the Pro-E wildfire 4.0 software of PTC (Parametric Technology Corporation) and converted into PARASOLID (.x_t) file. Then the PARASOLID (.x_t) file directly imported to ProCAST 2009.1 for simulation. Once the meshed geometry is established, the casting process design parameters, then the initial boundary conditions are defined according to the actual experimental condition for doing simulation. Table 2 show the boundary condition defined for all simulation experiments. With the ViewCast module the fluid flow in the cavity and solidification during the casting process were analyzed and potential defects were predicted.

The View Cast can only view the fluid flow and temperature field patterns in the cavity during the casting process and predict the potential defects graphically. in order to generate the corresponding simulation result data file according to the specific 3D coordinate in the casting model based on FEM model node number VisualCast module (ProCAST 2009.1) was employed to study to predict the filling velocity and shrinkage porosity numerically.

Table 2. Initial boundary conditions

1	Material definition (Initial temperature) (°C)	Pure Aluminium	700°C
2	Boundary Definition (heat transfer coefficient) (W/m^2 K)	Casting-mould	1000
3	Filling definition (pouring time) (sec)	Mesh cast	15

The numerical simulation results of shrinkage porosity and filling velocity with 9 sets of gating parameters are give in Table 3, including the 9 sets of product yield calculated by Eq.(3).

Table 3: Numerical simulation result for product, shrinkage porosity and filling velocity

Experiment Number	Product yield (%)	Shrinkage Porosity (%)	Filling velocity (cm/s)
1	88.4174	0.921	40.65
2	88.4568	0.924	45.87
3	88.6274	0.922	71.66
4	87.8393	0.921	35.49
5	88.7043	0.924	46.57
6	88.1813	0.923	48.7
7	88.1005	0.921	41.25
8	87.5024	0.918	29.71
9	88.5408	0.923	39.71

RESULTS AND DISCUSSIONS

Multi-Response S/N Ratio with Different combination of weighting Factors

Based on simulation result the value of shrinkage porosity & filling velocity are shown in Table 3 for different 9 sets of gating system. Casting yield is calculated with eq. (2). Now S/N ratio is calculated for all values of the three performance characteristics with at the help of Eq. (4)-(6) which are shown in Table 4.

Table 4: S/N Ratio of objectives

Experimental number	The S/N ratio (yield)	The S/N ratio (porosity)	The S/N ratio (velocity)
1	38.9308	0.8192	-32.1818
2	38.9346	0.6866	-33.2311
3	38.9514	0.7054	-37.1059
4	38.8738	0.7148	-31.002
5	38.9589	0.6866	-33.3624
6	38.9075	0.696	-33.7502
7	38.8996	0.7148	-32.3087
8	38.8404	0.7431	-29.4589
9	38.9429	0.696	-31.9789

The three combination of weighting factor were selected in this study of multi-response S/N ratio calculated with the help of Eq. (7)-(9). The value of different combination are shown in Table (5)

Table 5. Multi-Response S/N ratio with three weighting factor

Multi- Response S/N Ratio		
Case 1 (w_1= 0.5, w_2=0.2,w_3=0.3)	Case 2 (w_1= 0.3, w_2=0.5,w_3=0.2)	Case 3 (w_1= 0.1, w_2=0.2,w_3=0.7)
9.9538	5.6003	-18.4913
9.6353	5.3775	-19.231
8.485	4.6169	-21.9379
10.2793	5.8191	-17.671
9.608	5.3585	-19.3205
9.4679	5.2702	-19.5952
9.9001	5.5655	-18.5832
10.7312	6.1319	-16.5886
10.017	5.6351	-18.3517

Now to calculate the response of each factor to its individual level was calculated by averaging the S/N ratios of all experiments at each for each factor. With three combination of weighting factors, the factors mean multi-response ratio for each level are summarized in Table 6.6(A, B, C) for all three different cases.

Table 6. The factor's mean multi-response S/N ratio for each level with three weighting factor

A	**Multi-Response S/N Ratio for CASE 1 (w_1= 0.5, w_2=0.2,w_3=0.3)**			
Level	Ingate Height	Ingate width	Runner Height	Runner width
1	9.358	10.0444	10.0509	9.8596
2	9.7851	9.9915	9.9772	9.6678
3	10.2161	9.3233	9.3311	9.8318
B	**Multi-Response S/N Ratio for CASE 2 (w_1= 0.3, w_2=0.5,w_3=0.2)**			
Level	Ingate Height	Ingate width	Runner Height	Runner width
1	5.1982	5.6616	5.6675	5.5313
2	5.4826	5.6226	5.6106	5.4044
3	5.7775	5.1741	5.1803	5.5227
C	**Multi-Response S/N Ratio for CASE 3 (w_1= 0.1, w_2=0.2,w_3=0.7)**			
Level	Ingate Height	Ingate width	Runner Height	Runner width
1	-19.8867	-18.2485	-18.225	-18.7212
2	-18.8622	-18.38	-18.4179	-19.1364

The Optimal Gating System For The Different Combination of Weighting Factor

For case 1, the order of the performance characteristics is the product yield (w_1= 0.5), the shrinkage porosity (w_2= 0.2), and the filling velocity (w_3= 0.3). For case 2, the order of the performance characteristics is the product yield (w_1= 0.3), the shrinkage porosity (w_2= 0.5), and the filling velocity (w_3= 0.2).Finally, for case 3, the order of the performance characteristics is the product yield (w_1= 0.1), the shrinkage porosity (w_2= 0.2), and the filling velocity (w_3= 0.7). Figs. 6.1–6.3 show the multi-response S/N ratio for case 1–3, respectively. The multi-response S/N ratio for each level of the gating system parameter is calculated based on Eqs. (7) – (9).

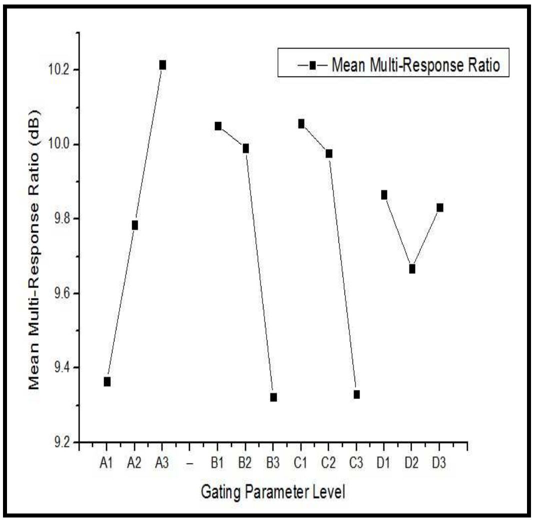

Fig.4: Multi-response S/N ratio graph for

for case 1 (w_1= 0.5, w_2=0.2, w_3=0.3)

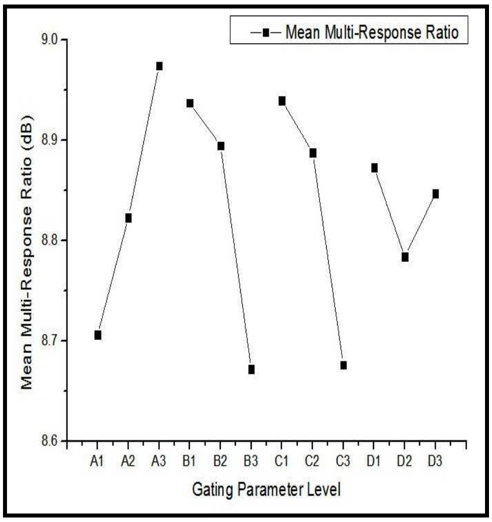

Fig. 3- Multi-response S/N ratio graph

four case 2 (w_1= 0.3, w_2=0.5, w_3=0.2)

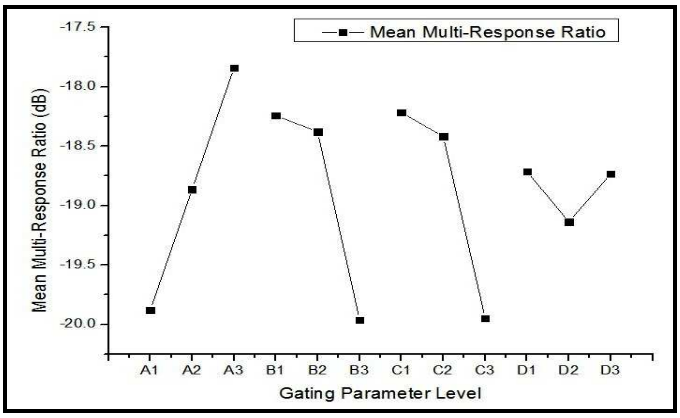

Fig. 5: Multi-response S/N ratio graph for case 3 (w_1= 0.1, w_2=0.2, w_3=0.7)

As shown in previous equations, regardless of the lower-the-better or the higher-the-better performance characteristics, the larger the multi-response S/N ratio the smaller is the variance of performance around the objective value. For case 1, case 2 and case 3 the A3B1C1D1 is the maximum multi-response S/N ratio. The larger ingate height will help to lower the ingate filling velocity characteristic which has largest weighting factor for performance characteristics of all three cases. However, the relative important factor among the gating parameters for the multiple performance characteristics still need to be investigated by using the analysis of variance (ANOVA) method which can conduct the factor contribution more accurately.

The factor contribution with different combination of weighting factors:

The purpose of the ANOVA is to investigate which of the process parameters significantly affect the performance characteristics. This is accomplished by separating the total variability of the multi-response S/N ratios, which is measured by the sum of the squared deviations from the total mean of the multi-response S/N ratio, into contributions by each of the process parameters and the error. First, the total sum of the squared deviations SS_T from the total mean of the multi-response S/N ratio $\square_{jc}$ can be calculated by Eq. (11) – (15). Table (6.7) - (6.9) shows the results of ANOVA for case 1 to case 3. It can be found that the contribution of Ingate height and Ingate width is more than other Runner factors. The sequence of the four factors affecting the casting quality is the Ingate height, the Ingate width, the Runner height, and the Runner width. For case 1, Case 2 and case 3, the contribution of two Ingate parameters is more than 66% .This shows that ingate parameter make a significant effect on the three case quality objective

Table 7: Result of the ANOVA for case 1 (w_1= 0.5, w_2=0.2, w_3=0.3)

Symbol	**Gating Parameters**	**Degree of Freedom (D)**	**Sum of Squares (SS_p)**	**Variance (V_p)**	**Corrected Sum of Squares ($SS_p{}'$)**	**Contribution (P_p) (%)**	**Rank**
A	Ingate hgt.	2	1.1044	0.5522	1.1044	35.8649	1
B	Ingate wid.	2	0.9693	0.48465	0.9693	31.4773	2
C	Runner hgt.	2	0.9412	0.47059	0.9412	30.5643	3
D	Runner wid.	2	0.0645	0.03223	0.0645	2.0934	4
Error			0	0		0	
Total		8	3.0793			100	

Table 8: Result of the ANOVA for case 2 (w_1= 0.3, w_2=0.5, w_3=0.2)

Symbol	Gating Parameters	Degree of Freedom (D)	Sum of Squares (SS_p)	Variance (V_p)	Corrected Sum of Squares (SS_p')	Contribution (P_p) (%)	Rank
A	Ingate hgt.	2	0.5034	0.2517	0.5034	35.9665	1
B	Ingate wid.	2	0.4404	0.2202	0.4404	31.4673	2
C	Runner hgt.	2	0.4257	0.2128	0.4257	30.4119	3
D	Runner wid.	2	0.0302	0.0151	0.0302	2.1542	4
Error			0	0		0	
Total		8	1.3997			100	

Table 9: Result of the ANOVA for case 3 (w_1= 0.1, w_2=0.2, w_3=0.7)

Symbol	Gating Parameters	Degree of Freedom (D)	Sum of Squares (SS_p)	Variance (V_p)	Corrected Sum of Squares (SS_p')	Contribution (P_p) (%)	Rank
A	Ingate hgt.	2	6.2764	3.1382	6.2764	36.0558	1
B	Ingate wid.	2	5.4535	2.7267	5.4535	31.3283	2
C	Runner hgt.	2	5.3419	2.6709	5.3419	30.6872	3
D	Runner wid.	2	0.3357	0.1679	0.3357	1.9286	4
Error			0	0		0	
Total		8	17.4075			100	

VALIDATION EXPERIMENT

The Confirmation experiment is the final step in verifying the conclusions from the previous round of experimentation. The estimated S/N ratio η_{opt} using the optimal level of gating parameters can be calculated as Eq.16

$$\eta_{opt} = \eta_{tm} + \sum_{j=1}^{n} (\eta_{om} - \eta_{tm}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (16)$$

Where η_{tm} is total mean of the multi-response S/N ratio, η_{om} is mean of the multi-response S/N ratio at the optimal level, and *n* is the number of the main design parameters that affect the quality characteristics. Tables 10–12 show the confirmation experiments using the optimal gating parameters of case 1 to case 3. As Table 10 shown the increase in multi-response S/N ratio from the initial gating parameters to the optimal gating parameter is 0.52864 dB. As product Yield has decrease 0.55%, the shrinkage porosity is decreased by 1.19% and filling velocity is decreased by19.14%;

Table 10: Results of the conformation experiment for case1 (w_1= 0.5, w_2=0.2, w_3=0.3)

	Initial gating parameter	Prediction	Experiment
Level	A1B1C1D1	A3B1C1D1	A3B1C1D1
Product yield (%)	88.42		87.9314
Shrinkage porosity (%)	0.921		0.91
Filling velocity (cm/sec)	40.64		32.86
S/N ratio (dB)	9.975	10.71	10.50364
Improved multi-response S/N ratio (dB)			0.52864

Table 11: Results of the confirmation experiment for case 2 (w_1= 0.3, w_2=0.5, w_3=0.2)

	Initial gating parameter	Prediction	Experiment
Level	A1B1C1D1	A3B1C1D1	A3B1C1D1
Product yield (%)	88.42		87.9314
Shrinkage porosity (%)	0.921		0.91
Filling velocity (cm/sec)	40.64		32.86
S/N ratio (dB)	5.2518	5.9613	6.0068
Improved multi-response S/N ratio (dB)			0.75498

For the case 2, the increase of the multi-response S/N ratio from the initial gating parameters to the optimal gating parameters is 0.75498 dB as Table 11 shown;

Table 12: Results of the confirmation experiment for case 3(w_1= 0.1, w_2=0.2, w_3=0.7)

	Initial gating parameter	Prediction	Experiment
Level	A1B1C1D1	A3B1C1D1	A3B1C1D1
Product yield (%)	88.42		87.9314
Shrinkage porosity (%)	0.921		0.91
Filling velocity (cm/sec)	40.64		32.86
S/N ratio (dB)	-18.1493	-16.4217	-17.182
Improved multi-response S/N ratio (dB)			0.96734

For the case 3, the increase of the multi-response S/N ratio from the initial gating parameters to the optimal gating parameters is 0.96734 dB as Table 12.

CONCLUSIONS

The Taguchi method with multiple performance characteristics has been demonstrated for obtaining a set of optimal gating system parameters based on the defined objectives. The conclusions may be stated as follows:

1. The multiple performance characteristics such as product yield, shrinkage porosity, and filling velocity can be simultaneously considered and improved through this optimisation technique.
2. For case 1 and case 2 and case 3, the A3B1C1D1 is the optimum level with the maximum multi-response S/N ratio.
3. Regardless of the case 1 to case 3, the sequence of the four factors affecting the casting quality is the, the ingate height, the ingate width runner height and the runner width. The ingate height is the most significant factor which influences the casting quality
4. The optimal parameters for the gating system may be same with different weighting factors from case inside
5. The increase of the multi-response S/N ratio from the initial gating parameters to the optimal gating parameters for case 1, 2 and 3 is 0.52864, 0.75498 and 0.96734 dB.\

REFERENCES

1. Anastasion, K.S., 2002. “Optimization of the aluminium die casting process based on the Taguchi method,” Journal of Engineering and Manufacturing, 216, 969–977.
2. Bradley, F., Heinemann, S., 1993. “A hydraulics-based optimization methodology for gating design”, Appl. Math. Model. 17,406–414.
3. B. Ravi, 2009 “Computer-aided Casting Design and Simulation”, STTP, V.N.I.T. Nagpur, July 21,
4. Byrne, D.M., Taguchi, S., 1987. The Taguchi approach to parameter design. Qual. Progr., 19–26
5. Campbell, J., 1998. “The ten castings rules guidelines for the reliable production of reliable castings: a draft process specification”. In: Materials Solutions Conference on Aluminum Casting Technology, Chicago, pp. 3–19.
6. D.C. Montgomery, Design and Analysis of Experiments, Wiley,Singapore, 199
7. Green, N.R., Campbell, J., 1994. Influence of oxide film filling defects on the strength of Al–7Si–Mg alloy castings. AFS Trans.102, 341–347.
8. Green, N.R., Campbell, J., 1994 “ Influence of oxide film filling defects on the strength of Al–7Si–Mg alloy castings”, AFS Trans.102, 341–347.
9. Hu, H., Yu, A., 2002, “Numerical simulation of squeeze cast magnesium alloy AZ91D”, Modeling. Simulation of. Material Science. Eng. 10, 1–11.

10. Lee, K.S., Lin, J.C., 2006. "Design of the runner and gating system parameters for a multi-cavity injection mould using FEM and neural network", International Journal of Advance Manufacturing Technology, 27, 1089–1096.
11. McDavid, R.M., Dantzig, J.A., 1998a. Design sensitivity and finite element analysis of free surface flows with application to optimal design of casting rigging system. International Journal of Numerical Methods Fluids 28.
12. McDavid, R.M., Dantzig, J.A., 1998b. "Experimental and numerical investigation of mold filling.", Modeling of Casting, Welding and Advanced Solidification Processes (MCWASP VIII), Chicago, USA, pp. 59–66.
13. ProCAST 2009.1, Release Notes and Manual.
14. Taguchi, G., 1998. "Introduction to Quality Engineering". McGraw-Hill, New York.