Weighted Sum Method for Multi-Objective Optimisation for Aluminium Metal Casting

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Abstract

An optimisation 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 Aluminium casting were simulated with the PROCAST, AUTOCAST, and MAGMASOFT etc. The simulation results indicated that gating system parameters significantly affect the quality of the Aluminium 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.

Index terms — Taguchi method, Computational simulation, Optimisation, Gating system, Aluminium casting.

1 Introduction

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; **??**ang 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 (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. Since oxide formation is instantaneous in Aluminium, the design of gating system plays more important role on minimising 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;. Therefore, Aluminium 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. Computer-aided casting design and simulation gives a much better and faster insight for optimising the feeder and gating design of castings (B. Ravi, 2009).

The first research showing an effect to apply a numerical optimisation methodology to optimise 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).

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. 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. Mould filling and solidification processes of the castings can be simulated with the PROCAST, AUTOCAST, MAGMASOFT etc. 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.

2 II.

Design of experiment based on the Taguchi method

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. 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. The experimental layout for the four gating parameters used L9 orthogonal array. III.

3 Gating system parameters and objectives design

The objective of the parameter design is to optimise (D.C. **??**ontgomery, 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. A cubical housing model was used as the test sand casting to understand the numerical optimisation. The three-dimensional CAD model of the test casting is shown in Fig. 1. The casting material is defined Aluminium. 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.

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. In this work gating parameters like runner height, runner width, ingate height and ingate width were changed. Remaining parameters kept constant for all the experiments. 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 IV.

4 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 signalto-noise ratio can reflect both the average and the variation of the quality characteristics. S/N ratio can be defined as Eq. (**??**) (4) Where MSD is the mean-square deviation for the output characteristic. The MSD for the higher-thebetter quality characteristic can be expressed as Eq. (**??**) (5) 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) Where n is the total number of tests in a trial and Ti is the value of product yield and Si is the value of filling velocity and shrinkage porosity at the ith test.

The proposition for the optimisation of a gating system with multiple performance characteristics (three objective) using a weighting method is defined as(7) (8)**(9)**

Assumption is using L9 orthogonal array. w 1 is the factor of product yield; w 2 is the factor of shrinkage porosity; w 3 is the factor of filling velocity; ? jc is the multi-response S/N ratio in the j th test. ? ji is the ith single response S/N ratio for the j th test. w i is the weighting factor in the i th performance characteristics. The objective function was formulated according to the previous optimisation criteria: (10) Where w 1 , w 2 , w 3 are the weighting factors of S/N ratio for yield, porosity and velocity, respectively.

V.

5 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 five connective parameter symbols can be calculated as Eqs. (**??**1) and (**??**2)(11) (12) (13) (14) (15)

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 multiresponse S/N ratio involving this parameter p and level j. The total degree of freedom is D T = m-1, for the tested parameter, D p = t -1, V p is the variance, SS' p is the corrected sum of squares and P is the contribution of reach individual factor.

6 VI.

7 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. & ? ? ? 3 1 i i 1 w Maximize f(X) = 3 Velocity 2 Porosity 1 Yield w ? w ? w ? ? ? 2 m 1 i ic m 1 i 2 jc p ? m 1 t) (S ? SS ? ? ? ? ? ? ? ? ? ? ? ? 2 m 1 i ic m 1 i 2 jc T ? m 1 ? SS ? ? ? ? ? ? ? ? ? ? ? ?

8 Result and Discussion

Based on simulation result the value of shrinkage porosity & filling velocity are for different 9 sets of gating system. Casting yield is calculated with eq. (**??**). Now S/N ratio is calculated for all values of the three performance characteristics with at the help of Eq. (**??**)-(**??**). The three combination of weighting factor were selected in this study of multi-response S/N ratio calculated with the help of Eq. (**??**)-(9). 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.

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 multiresponse S/N ratio for case 1-3, respectively. The multiresponse S/N ratio for each level of the gating system parameter is calculated based on Eqs. (**??**) -(9). 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.

9 VIII.

10 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 SST from the total mean of the multi- ear 2012 Y response S/N ratio ? jc can be calculated by Eq. (**??**1) -(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.

11 IX.

12 Validation experiment

The Validation experiment is the final step in verifying the conclusions from the previous round of experimentation. The estimated S/N ratio ? opt using the optimal level of gating parameters can be calculated as Eq.16 (16) Where ? tm is total mean of the multi-response S/N ratio, ? 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. In confirmation experiment, it is found that 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%.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 X.

13 Conclusion

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; the multiple performance characteristics such as product yield, shrinkage porosity, and filling velocity can be simultaneously considered and improved through this optimisation technique. For case 1 and case 2 and case 3, the A3B1C1D1 is the optimum level with the maximum multi-response S/N ratio. 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. The optimal parameters for the gating system may be same with different weighting factors from case inside

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Figure 1: Fig. 1 :?

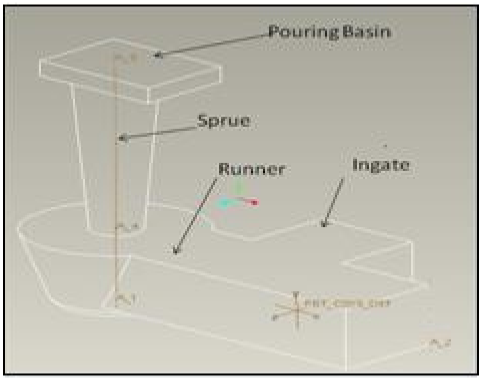

Figure 2:

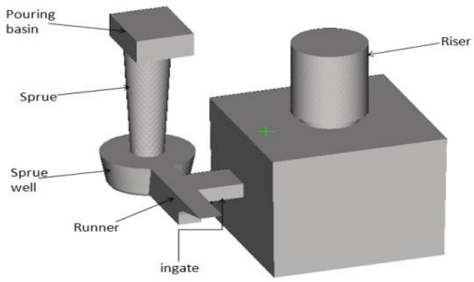

Figure 3:

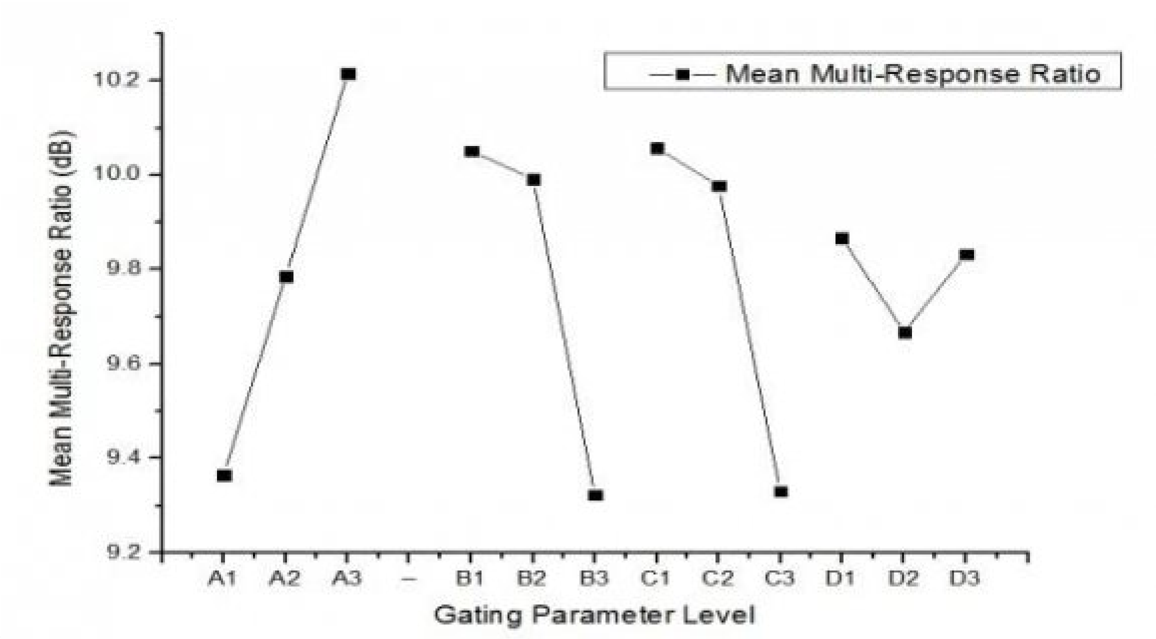

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Figure 4: Fig. 2 :Fig. 3 :

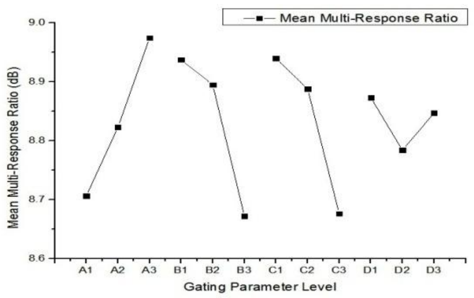

Figure 5: Weighted

[Bradley and Heinemann ()] 'A hydraulicsbased optimisation methodology for gating design'. F Bradley , S Heinemann . *Appl. Math. Model* 1993. 17 p. .

[Ravi et al. (2009)] *Computer-aided Casting Design and Simulation*, B Ravi , V N I T Sttp , Nagpur . 2009. July 21.

[Montgomery ()] *Design and Analysis of Experiments*, D C Montgomery . 1999. Singapore: Wiley.

[Lee and Lin ()] 'Design of the runner and gating system parameters for a multi-cavity injection mould using FEM and neural network'. K S Lee , J C Lin . *International Journal of Advance Manufacturing Technology* 2006. 27 p. .

[Mcdavid and Dantzig ()] 'Design sensitivity and finite element analysis of free surface flows with application to optimal design of casting rigging system'. R M Mcdavid , J A Dantzig . *International Journal of Numerical Methods Fluids* 1998a. 28.

[Mcdavid and Dantzig ()] 'Experimental and numerical investigation of mould filling'. R M Mcdavid , J A Dantzig . *Modeling of Casting, Welding and Advanced Solidification Processes (MCWASP VIII)*, (Chicago, USA) 1998b. p. .

[Green and Campbell ()] 'Influence of oxide film filling defects on the strength of Al-7Si-Mg alloy castings'. N R Green , J Campbell . *AFS Trans* 1994. 102 p. .

[Green and Campbell ()] 'Influence of oxide film filling defects on the strength of Al-7Si-Mg alloy castings'. N R Green , J Campbell . *AFS Trans* 1994. 102 p. .

[Taguchi ()] *Introduction to Quality Engineering*, G Taguchi . 1998. New York: McGraw-Hill.

[Hu and Yu ()] 'Numerical simulation of squeeze cast magnesium alloy AZ91D'. H Hu , A Yu . *Modeling. Simulation of. Material Science. Eng* 2002. 10 p. .

[Anastasion ()] 'Optimisation of the aluminium die casting process based on the Taguchi method'. K S Anastasion . *Journal of Engineering and Manufacturing* 2002. 216 p. .

[Byrne and Taguchi ()] 'The Taguchi approach to parameter design'. D M Byrne , S Taguchi . *Qual. Progr* 1987. p. .

[Campbell ()] 'The ten castings rules guidelines for the reliable production of reliable castings: a draft process specification'. J Campbell . *Materials Solutions Conference on Aluminium Casting Technology* 1998. p. .