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Influence of Taguchi-Grey Relational Analysis of Gating System Design on Mechanical Properties of Casting

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Abstract

Throughout the casting process, mold filling plays a very significant role in the casting quality control. It is important to study the effect of gating system design on ingate velocity of the metal which affects the mechanical properties of casting. The effect of varying the design of four gating system elements namely pouring cup, sprue height, runner and ingate design on the multiple responses like tensile strength and percentage elongation is studied using a Taguchi's L9 OA. The Taguchi technique was coupled with a Grey Relational Analysis (GRA) to obtain a Grey Relational Grade (GRG) for evaluating multiple responses. ANOVA has been applied to identify the significance of different parameters and it was found that the pouring cup design and the runner cross-section along its length collectively contributed above 76% of the total GRG value. Finally, the confirmation tests were performed to validate the predicted optimized results and it established an improvement of 9.90% from the initial design.

Keywords: Mechanical properties, Gating system design, Aluminum alloy casting, Taguchi- grey relational analysis

1. Introduction

Foundry industries in developing nations suffer from poor quality and productivity due to involvement of number of process parameters in the casting. Throughout a casting operation, mold filling plays a significant role in casting a quality product. Proper and complete mold filling is the main objective of the sand casting process for ensuring high quality castings [1]. The gating system aims at providing a smooth, uniform, & complete filling of mold with pure molten metal. Smooth filling eliminates turbulence & uniform filling ensures complete mold filling [2]. The formation of various casting defects could be directly related to fluid flow phenomena in the stage of mold filling. Although there are general casting design guidelines and empirical

equations for gating ratio, pouring time, & gating dimensions. The variation in the casting parameters chosen by different researchers have led to significant variations in guidelines which not only leads to long lasting development cycle but also a low reliability of casting design [3]. In multiple-gate runner systems it is also essential that the liquid metal flows through each gate without entrapping detrimental oxide films & air bubbles in liquid metal. It is equally significant to have uniform distribution of molten metal through each gate. It is found in some studies that most of the molten metal enters the cavity through the gate farthest from the sprue which may be due to the use of runners with constant cross-sectional area throughout its length [4]. If poor gating techniques are used & if the molten metal is sensitive metal like aluminum & magnesium for receiving damage during flow through the gating system, the casting quality would be invariably

low [5]. Especially in gravity casting it relies upon the critical value of ingate velocity. Air entrainment during mold filling is a major source of oxide inclusion formation in the metal casting [6]. The formation of oxide film on the surface of aluminum melts i.e. Bifilms are detrimental as it has direct relationship with porosity & mechanical properties [7]. During the study it is found that the ultimate tensile strength (UTS) & elongation decreased with oxide addition as the section thickness increased [8]. Biggest part of the literature about the design of gating system focuses on inlets & runners. Few authors tried to reach the convenient shape of ingates using simulations. Height and width of ingates and runners were the factors, while few used offset pouring basins with a stopper along with pressurized gating system for reducing the volume of air entrained [9]. Some part of literature emphasized on pouring basin, sprue shape or alternatively used a L-shaped junction [10]. Foundry technologists use their own style of gating system designing as the theory of gating systems is not brought into general use sufficiently and therefore often not applied in practice [12-15].

Optimization of manufacturing process is always considered as one of important task to improve the performance of the process product [16]. The literature review indicates that the Taguchi method is the best option for DoE when number of process parameters are involved in the process [17]. Taguchi approach is suitable in experimental design for designing and developing a robust process [18]. Taguchi technique facilitates the evaluation of a single response variable. If more than one response has to be evaluated, the multi-objective optimization techniques are used [18]. In this paper, the combined approach of Taguchi's orthogonal array design with the Grey Relational Analysis (GRA) is used [19-22]. The GRA is a measurable procedure based on the grey system and transforms multiple qualitative characteristics into a single Grey Relational Grades (GRG) [23]. The objective of this paper is to study the influence of the gating system elements geometry on the mechanical properties of the casting such as tensile strength and its hardness value. In this effort a Taguchi's L9 orthogonal array is used with four control factors namely Pouring cup design, Sprue height, Runner cross-section after each ingate, and the Ingate shape to measure the responses with UTS and BHN. These multiple responses were converted into GRG's for every factor combinations using Grey Relational Analysis approach and were ranked from maximum GRG as 1 to the lowest GRG as 9. Thereafter, the most significant factors affecting the mechanical properties were identified using ANOVA. Finally, confirmation tests were conducted to verify the improvement of GRG, using the optimal levels of the design parameters.

2. Materials and Methods

2.1. Materials

The casting ingots material used in this study is Al-Si alloy commercially known as LM6 aluminum alloy. The chemical composition of the casting material in wt. percentage is given as shown in Table 1.

Table 1.

Chemical composition of the casting material in wt. percentage

Element	Si*	Fe*	Mn*	Cu	Mg	Ni	Pb	Zn
Wt. %	12	0.6	0.5	0.1	0.1	0.1	0.1	0.1

*--Principle alloying element

Commercial alloy LM6 is essentially a hypo-eutectic Al-Si alloy with lower copper content imparting an excellent corrosion resistance making it suitable for marine, chemical & dye industry castings. It has exceptional fluidity which enables it to be used for producing intricate castings of thick & thin sections. LM6 is also resistant to hot tearing when sand casted. Few of the applications of LM6 are marine on-deck castings, pump parts for paints & food industries, cast doors & panels chemical & dye industries. Also water-cooled inlet manifolds, motor housings, meter cases, & motor car fittings.

2.2. Methodology

The objective of this study is to investigate the effect of gating system geometry on casting quality & its mechanical properties like tensile strength & percentage elongation. In an effort to obtain an optimal gating system design, Taguchi methods can be used as an efficient problem solving tool to improve the casting quality by studying the effect of various gating system geometries on the mechanical properties of the castings. A rectangular plate casting of size 300*200*12 mm thick is casted with a commercial aluminum alloy LM6 using a multi-gate sand casting process. The gating system for this casting comprised of elements like Pouring basin, Tapered Sprue, Runner, & 3 equidistant Ingate as shown in Fig. 1. Three pouring cup designs, 3 heights of tapered sprue, 3 runner cross-sections along its length, & ingate geometries are considered as control parameters for the casting. To evaluate the casting soundness in the gating design, mechanical properties of the cast plate like Tensile strength & % elongation (UTS & % Elongation) is selected for multi-objective optimization. With the L9 (3⁴) OA of Taguchi method, four controllable factors at three levels per factor are as shown in Table 2..

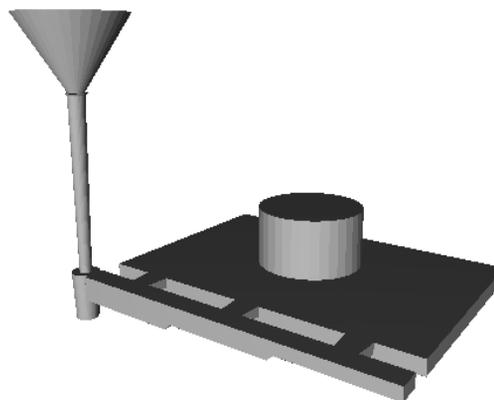


Fig. 1. Casting Assembly

Table 2.

Gating System Parameters and their Levels

Notation	Factor	Level 1	Level 2	Level 3
A	Sprue Height, mm	100	150	200
B	Ingate Design	Divergent	Rectangular	Convergent
C	Runner Cross-section	Tapered Reducing	Stepped Reducing	Rectangular
D	Pouring Cup Design	Offset Pouring Cup	Stepped-Offset Pouring Cup	Conical Cup

2.3. Specimens and Measurements

Evaluation of the mechanical properties of the Aluminum cast plate was performed by measuring its tensile strength (UTS) and percentage elongation (% Elongation). There were three samples prepared for each tests from all nine cast plates cut along the direction of flow of melt from ingate, in front of the three ingates of the plate. The standard tensile test samples (Fig. 2) were machined from the cast plate located in front of each ingate from all the nine samples and tensile test was performed on the Universal Testing Machine according to ASTM A370 standards and percentage elongation at the fracture was also noted along with.



Fig. 2. UTS Test Samples

2.4. Multi Response Optimization GRA

While Taguchi's OA experimental method is suitable to determine the optimum factor level combination for a single response characteristic. The factor levels are accessed in his study

are for two response variables namely UTS & % Elongation. Thus in the case of two or more responses with dissimilar quality characteristics, Grey Relational Analysis (GRA) is preferred as a multi-response optimization method. The influence of control factors on these response variables can be studied by retrieving the single weighted GRG. Thus the Grey Relational Grade can be treated as the overall evaluation of experimental data for the multi-response process. The multi-response optimization of mechanical properties of the casting is performed by following steps in GRA.

2.5. Data Preprocessing

Data preprocessing is performed to normalize the original reference sequences to a comparable sequence within the range of 0 to 1. This normalization approach, into a group of sequences, is also called grey relational generation. The transformed sequence is grouped into 3 characteristics namely higher-the-better (HTB), lower-the-better (LTB), nominal-the-better (NTB). For higher-the-better characteristics, the sequence can be normalized by equation (1):

$$X_i(k) = \frac{y_i(k) - \min y_i(k)}{\max y_i(k) - \min y_i(k)} \quad (1)$$

where:

$X_i(k)$ is the value after grey relational generation,

$\min y_i(k)$ is the smallest value of $y_i(k)$ for k^{th} response, and \max

$y_i(k)$ is the largest value of $y_i(k)$ for the k^{th} response.

2.6. Calculating Grey Relational Coefficient (GRC) and Grey Relational Grade (GRG)

The deviation sequence is the next step in GRA, after normalization, which is computed using the equation (2):

$$\Delta_{oi}(k) = \|X_0(k) - X_i(k)\| \quad (2)$$

To determine the relationship between optimal and normalized results, the GRC is calculated using equation (3):

$$\xi_i(k) = \frac{\Delta_{min} + \psi \Delta_{max}}{\Delta_{oi}(k) + \psi \Delta_{max}} \quad (3)$$

where:

$\Delta_{oi}(k)$ is the deviation sequence of the reference sequence & ψ is the distinguishing coefficient (0 to 1), is generally set as 0.5 to maintain equal weightage.

Based on GRC, a composite Grey Relational Grade GRG is then computed by averaging the GRC of each response variable using equation (4):

$$GRD, y_i = \frac{1}{n} \sum_{i=D}^n \xi_i(k) \quad (4)$$

The next step is prediction & verification of quality characteristics using optimal level of design parameters. The predicted GRG is calculated using equation (5):

$$Y_{predicted} = \gamma_m + \sum_{i=1}^q \gamma_0 - \gamma_m \quad (5)$$

where:

γ_0 is max. average GRG at optimal levels of factors,
 γ_m is mean GRG, and q is number of factors affecting response values.

2.7. Analysis of Variance (ANOVA)

ANOVA is a statistical approach to analyze the influence of selected parameters on the output response and distributed variability of the response variables among the factors. This is accomplished by separating the total variability of GRG's, which is measured by the sum of squared deviations from the total mean of GRG, into contributions of each parameter. The inferences derived from the ANOVA table are used to identify which input parameters are responsible for changes, in the process performance ie. Response, so that the process can be improved by controlling these significant factors.

3. Result and Discussion

3.1. Multi objective optimization by Grey Relational Analysis

In the present study, the multiple performance characteristics have been investigated with grey relational approach. In this method, the multiple performance characteristics can be converted into single relational grade. After performing the experiments as per Taguchi's L₉ Orthogonal Array and recording the response data of UTS and BHN for all nine experiments with three repetitions each as shown in Table 3. Data pre-processing by grey relational generation was performed on the experimental data of the responses from Table 3, namely UTS & BHN. After normalizing the data in the range of 0 to 1 using equation 1, subsequently the deviation sequence is obtained by equation 2. The next step after deviation sequence was of calculating Grey Relational Coefficient (GRC) for each value of responses using equation 3. Finally, Grey Relational Grade's (GRG) were determined after averaging the GRC's using equation 4. As listed in Table 3 GRG's and their corresponding ranks ascertained are as given as Rank 1 to the maximum GRG to Rank 9 to the lowest GRG. The response table 4 was calculated from the mean GRG's for the factor at that level. The grades in the response table serves

as a measure of the correlation between the reference sequence and comparability sequence of GRA. Higher values of GRG's indicate a strong correlation. Therefore, it is possible to arrive at the combination of optimal parameters which maximize the overall response, from the response table for GRG. Table 4 indicates that the maximum GRG exists at A1, B2, C3, &D1.

Table 3.

Taguchi's L₉ OA Results and Grey Relational Analysis Results

Trial No.	Response Values		Grey Relational Coef. (GRC)		Grey Relational Grade (GRG)	Rank
	UTS	% Elongation	GRC UTS	GRC %Elong.		
E1	104.333	1.667	0.772	1.000	0.8861	2
E2	97.183	1.593	0.545	0.855	0.6998	3
E3	88.137	1.067	0.397	0.419	0.4082	7
E4	81.780	0.800	0.333	0.333	0.3333	9
E5	96.820	1.300	0.537	0.542	0.5391	4
E6	108.237	1.600	1.000	0.866	0.9331	1
E7	94.590	1.173	0.492	0.468	0.4799	5
E8	90.693	1.067	0.430	0.419	0.4247	6
E9	83.350	0.987	0.347	0.389	0.3682	8

3.2. ANOVA for Grey Relational Grade

An ANOVA was performed on the GRG data in order to investigate the significance and percentage contribution of each factor on the multiple performance characteristics of mechanical properties of the casting plate at 95% confidence level. Table 5 for ANOVA of GRG value, shows that the Pouring Cup Design has the highest influence on the GRG value with 38.50%, followed by the Runner cross section along length influenced GRG value with 38.15% contribution. These two factors contributed for above 76% on the GRG value. The remaining two factors being Sprue height and the Ingate type contributed 23.25% and 0.10% respectively. Stepped off-set Pouring cup implies turbulence free & smooth filling of molten metal while Tapered runner signifies the importance of controlling the critical ingate velocity while maintaining the flowrate equal through all ingates in a multi-gate system. The Sprue height of 100mm suggests the minimum head requirement in order to control the velocity of melt, while the Ingate shape was found to be of least importance in affecting on the mechanical properties as a result. Therefore, it is possible to arrive at the combination of optimal parameters which maximize the overall response, from the response table for GRG. Table 4 indicates that the maximum GRG exists at A1, B3, C1, &D2.

Table 4.

Response Table for GRG

LEVEL	SPRUE Ht.	INGATE	RUNNER C/S	POURING CUP
1	0.6647*	0.5664	0.7479*	0.5978
2	0.6018	0.5545	0.4671	0.7042*
3	0.4242	0.5698*	0.4757	0.3887
Delta	0.2404	0.0153	0.2808	0.3155
Rank	3	4	2	1

*-Indicates Maximum Value.

3.3. Confirmation Test

The final step of Grey Relational Analysis is to predict and verify the performance improvement of the responses after identifying the optimal settings. The predicted GRG was computed using equation 5 and was found to be 0.9956. Confirmation tests were conducted to validate the outcomes of the analysis and the average GRG was calculated. For the optimized conditions, the GRG of 0.8661 for the initial design to 0.9518 for the confirmation experiment with optimal parameters setting of A1, B3, C1, and D2. Further it can be inferred from the Table 6 that the results of the confirmation experiment are in good agreement with the predicted values. Additionally, an improvement of 9.90% in GRG is also obtained from the initial design.

Table 5.

ANOVA for GRG

	DoF	S S	M S	P (%)
SPRUE Ht.	2	0.093295	0.046648	23.25
INGATE	2	0.000387	0.000193	0.10
RUNNER C/S	2	0.153040	0.076520	38.15
POURING CUP	2	0.154591	0.077295	38.50
TOTAL	8	0.401313		

Table 6.

Results for Confirmation Experiment

Initial Design Parameters	Optimal Design Parameters	
	Prediction	Experiment
Setting Level	A1, B1, C1, D1	A1, B3, C1, D2
Grey Relational Grade	0.8861	0.9956
Improvement in GRG		14.95%
		9.90%

4. Conclusion

An approach to integrate Taguchi method and GRA is proposed in this study to identify the optimal designs of the gating system elements of sand casting to meet the multiple quality objectives of aluminum castings like UTS and % elongation. From the response table of GRG, the optimal set of gating elements design for enhanced mechanical properties for a commercial aluminum alloy LM6 were identified to be a stepped offset pouring cup with a tapered sprue height of 100 mm and a tapered reducing runner cross section attached to the convergent ingates. ANOVA table for GRG indicated that the Pouring Cup design and the Runner cross section along its length were the major contributors summing to 76%. The % contribution of sprue height was found to be 23.25%, while the contribution of Ingate Type was mere 0.10% on the GRG value. Finally, to validate the optimization confirmation test was conducted and found an improvement of 9.90% in GRG, from GRG of 0.8661 for the initial design to 0.9518 for the confirmation experiment with optimal parameters setting.

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