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OPTIMIZATION OF ALUMINIUM BLANK SAND CASTING PROCESS BY USING TAGUCHI'S ROBUST DESIGN METHOD

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Abstract: *In this paper, aluminium blank green sand (green) casting process was optimized by using Taguchi's robust design approach. An attempt was made to obtain optimal settings of two groups of aluminium blank sand casting processes. Single aluminium blank sand casting and double aluminium blanks sand casting for process robustness comparison. The casting process involves a number of parameters affecting various casting quality features of the product. In order to optimize the process seven control factors viz., grain size, clay content, moisture content, ramming, sprue size, riser size, and diameter to thickness (D/t) ratio of the blank were selected. Each factor was considered at three levels. For this study three uncontrollable (or noise) factors viz. metal flow rate, pouring temperature and humidity were identified. To capture the effect of noise factors casting yield, surface defects, and casting density for single and double castings were measured. An orthogonal array was constructed for the seven factors undertaken, and performing eighteen sets of experiments with their replicates generated the data. The signal-to-noise (S/N) ratios were calculated based on the design of experiments. The average values of S/N ratios for each factor at three levels were calculated and were plotted on the graph. Considering the maximum S/N ratios from the graph, the optimum levels of process factors for both single and double castings were obtained. A statistical analysis of variance (ANOVA) was performed to see which process parameters are statistically significant. A verification experiment was performed using the identified optimum conditions. The results have shown that single aluminium blank sand casting process is more robust than double aluminium blank sand casting process. This proved that single aluminium blank sand casting process had shown better insensitivity to noise factors. The experimental results confirmed the validity of used Taguchi robust design method for enhancing sand casting process and optimizing the sand casting parameters in aluminium blank casting process.*

Keywords: *Optimization, Sand casting process, Taguchi method, Aluminium-blank, Signal-to-noise ratio, Analysis of variance, Orthogonal array*

1. INTRODUCTION

In the present competitive environment, it is of paramount importance to maintain the quality of the castings and to aim at products with 'zero-defect' and 'right the first time'. Genichi Taguchi, a quality management expert from Japan laid foundation of a new method for quality improvement, in the 1950's and the early 1960's.

According to Taguchi the key element for achieving high quality and low cost is parameter design. Through parameter design optimal levels of process parameters (or control factors) are selected such that the influence of uncontrollable (or noise) factors causes minimum variation of system performance or response. These parameters should be controlled to improve the quality of both casting process and product. A number of problems of various types are associated with the casting process. These problems may be related to casting yield, defects, dimensional variations, surface texture and so on (Datta, 1998). If the casting process is not being managed properly, the problems may aggravate further resulting in defects which render the product weak and of low quality, thus, making them unfit for use.

In Taguchi's approach, quality is measured by the deviation of a quality characteristic from its target value. Uncontrollable factors, known as noise, cause such deviation and there-by lead to loss. Since the elimination of noise factors is impractical and often impossible, Taguchi method seeks to minimize the effects of noise and to determine the optimal level of the important controllable factors based on the concept of robustness (Mitra, 2001). Reddy et al. (1999) illustrates how to arrive at the optimum values of control factors which govern the quality of investment shell moulds. Barua et al. (1997) shows how to obtain an optimal setting of the process parameters of the V-process that may yield optimal mechanical properties to the Al-7% Si alloy castings.

Lin and Kackar (1985) show how a 36 run, orthogonal array design was used to improve a wave soldering process by studying 17 variables simultaneously. Pao et al. (1985) show how a parameter design experiment was used to optimize the response time of a computer operating system.

Phadke et al. (1983) illustrates how a parameter design experiment was used to improve the photolithographic process in integrated circuit fabrication. Prasad (1982) provide many examples of parameter design experiments.

In the context of product design, Taguchi (1976, 1977) recommends the use of orthogonal arrays for constructing design matrices. Orthogonal arrays are generalized Graeco-Latin Squares.

The general theory of orthogonal arrays was introduced by Rao (1947). Raghavarao (1971) proposed several methods for constructing orthogonal arrays. Kackar (1982) presented a catalog of important orthogonal array.

Taguchi and Wu (1979) recommends two methods for reducing interactions among design parameters transform data to reduce non-additivity and change the non-additive design parameters into variables that are additive. The change of variables can be accomplished by making the test settings of one design parameter depend on the test settings of another design parameter.

In parameter design experiments, three types of interactions are involved i.e., among design parameters, between design parameters and noise factors, and among noise factors.

Taguchi recognizes the presence of interactions among design parameters, but he down-plays their importance relative to the main effects in constructing the design matrix (Taguchi and Wu, 1979).

According to Taguchi, when there are limits on the number of test runs, it is better to include many design parameters in the design matrix (even until no degrees of freedom are left for estimating the residual error) than to include only a few design parameters and allow for estimating interactions.

The goal of a parameter design experiment is to identify optimal settings for all the design parameters, irrespective of their importance. Therefore, as far as possible, all design parameters should be studied simultaneously in a combined experiment.

A number of automotive suppliers have achieved quality and cost improvement through robust design. These applications include improvements in metal casting, injection moulding of plastic parts, wave soldering of electronic components, speedometer cable design, integrated circuit chip bonding, and picture tube lens coating (Phadke, 1989).

2. DESIGN OF EXPERIMENTS

For finding the optimum settings of the control factors Taguchi's robust design methodology is applied. This method can be applied by using eight experimental steps that can be grouped into three major categories as follows (Phadke, 1989):

- Planning the experiment:
  (1) Identify the main function of casting process.
  (2) Identify the quality characteristic to be observed and the objective function to be optimized.
  (3) Identify the control factors and their alternate levels.
  (4) Identify noise factors and the testing conditions of the process.
  (5) Design the matrix experiment and define the data analysis procedure.
- Performing the experiment:
  (6) Conduct the matrix experiment.
- Analyzing and verifying the experimental results:
- (7) Analyzing the data, determining the optimum levels for the control factors, and predicting performance under these levels.
- (8) Conducting the verification (also called confirmation) experiment and planning future actions.

The procedure for applying the above steps in the present study is to improve the quality in terms of casting yield, surface defect, and casting density for single and double casting of aluminium blank sand casting process.

2.1 Aluminium blank sand casting process and its main function

The aluminium blank sand casting process was done using green sand mould. The process included the following steps.

- Preparing three groups of wooden patterns with three different thickness and same diameter for each group. Each consists of three patterns of the same size.
- Sieve the silica sand to grade the sand according to size.
- Preparing the mould green sand (a mixture of silica, clay, and moisture) as per the conditions of the experiments. Mould was prepared using a thick layer of 20-30mm moulding green sand around the pattern, backed by a heap of ordinary moulding sand.

The moulds were kept in open air for one whole day in order to partly dry them. Five moulding boxes were prepared at a time. For the casting process about eight kilograms aluminium alloy was melted. The molten aluminium alloy was poured into the prepared moulds to get the required aluminium blank sand casting.

The fluidity of the molten metal was tested at least three times during pouring of the molten metal into moulds. A rectangular strip 400×50×5mm was cast to have an idea of fluidity variation with time during pouring. The prepared aluminium blank sand castings are shown in Figure 1.

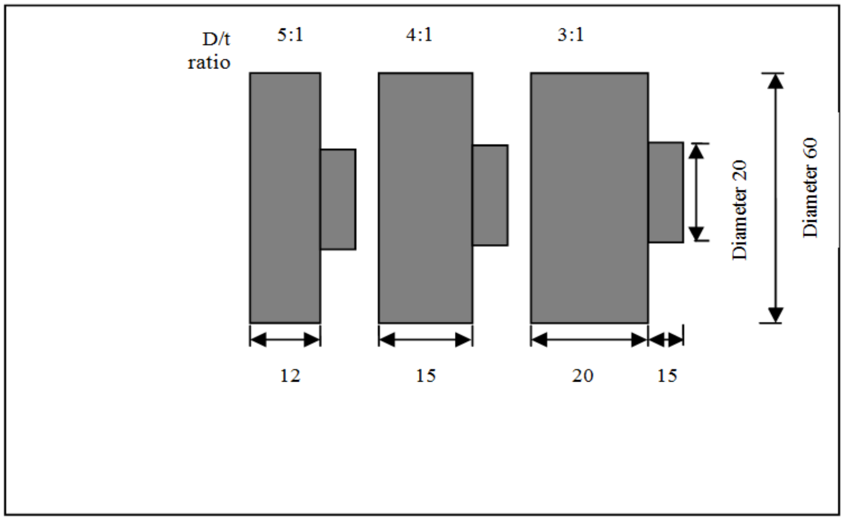


Fig. 1 Aluminium-blank casting produced by sand mould casting process

2.2 Quality characteristics and objective functions

Casting yield, surface defects, and casting density were selected as a quality characteristics. Casting yield can be defined as the ratio of the weight of casting to the total weight of casting with attachments (gates and risers etc.). The casting yield and casting density are 'larger-the-better' type of the quality characteristic (Taguchi, 1986; Phadke, 1989; Bagchi, 1993; Barua *et al.*, 1997). The objective function to be maximized is:

S/N ratio (η and η'')=-10log$_{10}$ (mean square reciprocal casting yield and casting density)

$$\text{S/N ratio } (\eta \text{ and } \eta'') = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \qquad (1)$$

Maximizing η and η'' results in minimizing sensitivity of the casting process to noise, hence, reduction in casting yield and casting density variation.

The surface defect is 'smaller-the-better' type of the quality characteristic (Taguchi, 1986; Phadke, 1989; Bagchi, 1993; Barua *et al.*, 1997).

The smaller the number of surface defects, better the casting quality, which implies better process performance. Here the objective function to be maximized is:

S/N ratio (η')=-10log$_{10}$ (mean square surface defects)

$$\text{S/N ratio } (\eta') = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \qquad (2)$$

Maximizing η' leads to minimization of quality loss due to surface defects. where S/N = ratio used for measuring sensitivity to noise factors, n is the number of experiments in the orthogonal array, and y_i the i^{th} value measured.

2.3 Control factors and their levels

In general, for a sand casting process, the following process parameters are important viz., type of the sand, sand grain shape, size and distribution, clay content, moisture content, permeability, ramming, metal composition, pouring temperature, pouring time, pouring height, metal fluidity, running and gating, risering or feeding, and design of castings.

A cause and effect diagram (Ishikawa diagram) (Ishikawa, 1990) is constructed to identify the control factors that may affect the aluminium sand casting process (Figure 2). On the basis of cause and effect diagram seven control factors were selected, and then their levels were defined as shown in Table 1.

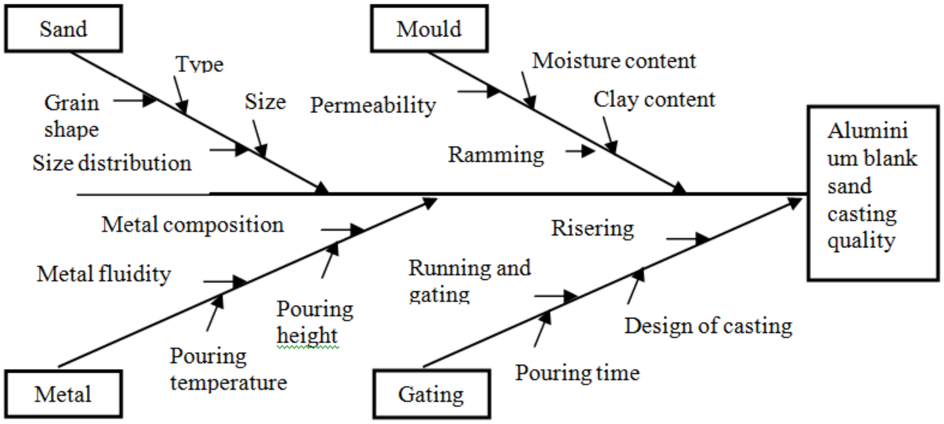


Fig. 2 Cause and effect diagram for quality characteristics

Table 1 Control factors and their levels

Control factors designation	Control factors	Levels*		
		1	2	3
A	Sand grain size	IS 10	IS 15	IS 25
B	Moisture content (%)	5.0	8.0	11.0
C	Clay content (%)	12.0	16.0	20.0
D	Ramming (Number of machine ramming)	2.0	4.0	6.0
E	Sprue size (Inch)	0.5	0.75	1.0
F	Riser size (Inch)	0.5	0.75	1.0
G	D/t ratio	5:1	4:1	3:1
* The starting level for each factor is identified by an underscore.				

2.4 Noise factors and testing conditions

In aluminium-blank sand casting process experiment, a number of noise factors affecting the casting process were identified. Some of these are variation of ambient temperature, humidity, pouring temperature, pouring speed and so forth. For our experiment the important noise factors considered were: metal flow rate-a factor which changes with time and pouring height, pouring temperature-varies from one group to the other group of castings, and humidity-produces gases which can be dissolved during melting and pouring. To capture the effects of variation (noise factors) of metal flow rate, pouring temperature, and humidity during the casting process, single and double moulds for castings were prepared.

2.5 Matrix experiment and data analysis plan

In robust design experiment, we vary the settings of control factors simultaneously in a few experimental runs. This efficient way of studying the effect of control factors can be achieved by planning matrix experiment using orthogonal arrays. An orthogonal array for a particular robust design can be constructed from the knowledge of the number of control factors, their levels, and the desire to study specific interactions. In aluminium-blank sand casting process study, there was no particular reason to study specific interactions and no unusual difficulty in changing the levels of any factor. In order to use a standard orthogonal array fitting our requirements the total degree of freedom (dof) for the present study is determined as shown in Table 2.

Therefore, in accordance to the dof count, at least fifteen experiments must be conducted to be able to estimate the desired seven main factor effects. Using Taguchi's standard methods of constructing orthogonal arrays (Taguchi, 1976; 1977), the standard array L_{18} was selected for this matrix experiment. The L_{18} orthogonal array has eight columns and eighteen rows as shown in Table 3.

Table 2 Count of dof

Source of dof	Required dof
Overall mean	1
A, B, C, D, E, F, G	Number of control factors (levels-overall mean)= 7(3-1)=14
Total	15

The eighteen rows of the L_{18} array represent the eighteen experiments to be conducted. However, to make it convenient for experimenting and to prevent translation error, the entire matrix (Table 3) should be translated using the level definitions (Table 1) to create control array (or experimenter's log sheet) as shown in Table 4.

Table 3 L18 (37) orthogonal array and factor assignment

Experiment Number	Column number and factor assignment*							
		A	B	C	D	E	F	G
	1	2	3	4	5	6	7	8
	e	Sand grain size	Moisture content (%)	Clay content (%)	Ramming (Number of machine ramming)	Sprue size (Inch)	Riser Size (Inch)	D/t* ratio
1	1	1	1	1	1	1	1	1
2	1	1	2	2	2	2	2	2
3	1	1	3	3	3	3	3	3
4	1	2	1	1	2	2	3	3
5	1	2	2	2	3	3	1	1
6	1	2	3	3	1	1	2	2
7	1	3	1	2	1	3	2	3
8	1	3	2	3	2	1	3	1
9	1	3	3	1	3	2	1	2
10	2	1	1	3	3	2	2	1
11	2	1	2	1	2	3	3	2
12	2	1	3	2	1	1	1	3
13	2	2	1	2	3	1	3	2
14	2	2	2	3	1	2	1	3
15	2	2	3	1	2	3	2	1
16	2	3	1	3	2	3	1	2
17	2	3	2	1	3	1	2	3
18	2	3	3	2	1	2	3	1

* Empty column is denoted by e.

2.6 Conducting the matrix experiment

Eighteen experiments were performed as specified by eighteen rows (Table 4). In each experiment, one single and one double casting were produced simultaneously.

The previously prepared five moulding boxes have enabled us to have fifteen castings (cast parts) at a time. Each experiment was replicated once. To determine the casting yield, each casting was weighted twice, i.e., before and after removing the gates and risers, etc. After machining of the cast, the weight and size were measured to determine its density.

Table 4 Control array (or Experimenter's log sheet) for aluminium-blank sand casting process

Experiment Number	Control factors						
	A	B	C	D	E	F	G
	Sand grain size	Moisture content (%)	Clay content (%)	Ramming (Number of machine ramming)	Sprue size (Inch)	Riser size (Inch)	D/t* ratio
1	IS 10	5	12	2	0.50	0.50	1
2	IS 10	8	16	4	0.75	0.75	2
3	IS 10	11	20	6	1.00	1.00	3
4	IS 15	5	12	4	0.75	1.00	3
5	IS 15	8	16	6	1.00	0.50	1
6	IS 15	11	20	2	0.50	0.75	2
7	IS 25	5	16	2	1.00	0.75	3
8	IS 25	8	20	4	0.50	1.00	1
9	IS 25	11	12	6	0.75	0.50	2
10	IS 10	5	20	6	0.75	0.75	1
11	IS 10	8	12	2	1.00	1.00	2
12	IS 10	11	16	4	0.50	0.50	3
13	IS 15	5	16	6	0.50	1.00	2
14	IS 15	8	20	2	0.75	0.50	3
15	IS 15	11	12	4	1.00	0.75	1
16	IS 25	5	20	4	1.00	0.50	2
17	IS 25	8	12	6	0.50	0.75	3
18	IS 25	11	16	2	0.75	1.00	1
*1, 2 and 3 are codes for ratios 5:1, 4:1 and 3:1 respectively.							

Weight of the casting was measured by a table physical balance and the yield was computed. The castings were carefully inspected visually for any surface defects. The observed data of concerning casting yield, surface defects, and after machining-density for single and double casting are listed in Table 5.

2.7 Analyzing the experimental results, determining the optimum levels for the control factors, and predicting performance under these levels

2.7.1 Analyzing the experimental results

For analysis of the results obtained from the experiment the S/N ratios were calculated (Phadke, 1989).

In our case we have two response values for each experimental condition for single and double castings (Table 5).

The S/N ratio for the casting yield (Table 5), given by Eq. (1), was computed as follows:

For a single casting yield, the S/N ratio is

$$\eta_s = -10\log_{10}\left[\frac{1}{2}\left(\frac{1}{0.657^2}+\frac{1}{0.601^2}\right)\right] =$$

-4.05dB

where η_s is S/N ratio for single casting yield.

Table 5 Experimental results of casting yield, surface defect, and casting density

Experim. Run	Casting yield (%)				Surface defects (defects/surface area)				Casting density (gm/cm^3)			
	Single casting		Double casting		Single casting		Double casting		Single casting		Double casting	
	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2
1	65.7	60.1	72.7	70.9	65	255	190	501	2.82	2.75	2.87	2.71
2	52.3	52.3	57.7	62.7	188	707	78	793	2.60	2.73	2.64	2.67
3	47.5	47.8	57.1	57.2	287	185	137	218	2.73	2.73	2.63	2.63
4	49.6	49.3	58.7	58.6	66	160	100	368	2.78	2.82	2.86	2.78
5	53.4	49.4	59.3	58.1	75	216	149	434	2.85	2.75	2.81	2.65
6	56.1	54.7	68.8	63.2	167	214	294	326	2.64	2.85	2.65	2.81
7	58.9	66.5	70.1	64.9	73	132	176	521	2.73	2.79	2.80	2.69
8	42.8	41.7	50.9	51.3	339	258	440	440	2.62	2.80	2.82	2.72
9	62.2	60.3	74.6	73.9	221	363	791	776	2.68	2.77	2.63	2.70
10	48.4	47.1	63.5	56.9	148	188	190	436	2.73	2.75	2.69	2.61
11	47.7	47.3	56.7	56.5	103	261	94	163	2.78	2.67	2.78	2.78
12	71.2	66.3	75.8	73.6	290	246	360	654	2.84	2.68	2.77	2.86
13	56.6	56.9	61.9	62.1	46	172	138	447	2.79	2.79	2.71	2.71
14	62.7	60.5	75.9	69.3	110	358	262	511	2.82	2.70	2.77	2.58
15	47.5	48.1	55.1	55.6	206	189	445	255	2.68	2.65	2.63	2.85
16	49.5	49.0	62.9	63.4	223	332	492	611	2.68	2.62	2.62	2.83
17	63.2	59.9	72.3	66.6	219	278	496	727	2.68	2.67	2.67	2.62
18	45.7	45.2	50.9	51.0	236	308	307	283	2.65	2.42	2.81	2.69

Table 6 Summary of S/N ratios for each experiment

Experim. Run	Experimental control factors levels matrix*								Casting yield η (dB)		Surface defects η' (dB)		Casting density η'' (dB)	
	e	A	B	C	D	E	F	G	Single casting	Double casting	Single casting	Double casting	Single casting	Double casting
1	1	1	1	1	1	1	1	1	-4.05	-2.88	-45.4	-51.6	8.89	8.90
2	1	1	2	2	2	2	2	2	-5.63	-4.43	-54.3	-55.0	8.51	8.48
3	1	1	3	3	3	3	3	3	-6.44	-4.86	-47.7	-45.2	8.72	8.39
4	1	2	1	1	2	2	3	3	-6.12	-4.63	-41.8	-48.6	8.94	9.00
5	1	2	2	2	3	3	1	1	-5.80	-4.63	-44.2	-50.2	8.94	8.71
6	1	2	3	3	1	1	2	2	-5.13	-3.63	-45.7	-49.8	8.61	8.71
7	1	3	1	2	1	3	2	3	-4.10	-3.43	-40.6	-51.8	8.82	8.77
8	1	3	2	3	2	1	3	1	-7.49	-5.83	-49.6	-52.9	8.65	8.85
9	1	3	3	1	3	2	1	2	-4.26	-2.59	-49.6	-57.9	8.70	8.51
10	2	1	1	3	3	2	2	1	-6.42	-4.45	-44.6	-50.5	8.75	8.46
11	2	1	2	1	1	3	3	2	-6.47	-4.94	-45.9	-42.5	8.70	8.88
12	2	1	3	2	2	1	1	3	-3.27	-2.54	-48.6	-54.5	8.81	8.99
13	2	2	1	2	3	1	3	2	-4.92	-4.15	-42.0	-50.4	8.91	8.66
14	2	2	2	3	1	2	1	3	-4.21	-2.81	-48.5	-51.2	8.81	8.53
15	2	2	3	1	2	3	2	1	-6.41	-5.14	-45.9	-51.2	8.51	8.73
16	2	3	1	3	2	3	1	2	-6.15	-3.99	-49.0	-54.9	8.46	8.69
17	2	3	2	1	3	1	2	3	-4.22	-3.19	-47.9	-55.9	8.55	8.45
18	2	3	3	2	1	2	3	1	-6.85	-5.86	-48.8	-49.4	8.05	8.78

* Empty column is denoted by e.

The same method of calculation was applied to double casting yield too.

The S/N ratio for surface defects (Table 5), given by Eq. (2), was computed as follows:

For a single casting surface defect, the S/N ratio is

$$\eta_s^{'} = -10 \log_{10}\left[\frac{1}{2}(65^2 + 255^2)\right] = \text{-45.4 dB}$$

where $\eta_s^{'}$ is S/N ratio for single casting's surface defect. The same method of calculation was applied to double casting surface defects too.

The S/N ratio for casting density (Table 5), given by Eq. (1), was computed as follows:

For single casting density, the S/N ratio is

$$\eta_s^{''} = -10\left[\frac{1}{2}\left(\frac{1}{2.82^2} + \frac{1}{2.75^2}\right)\right] = \text{8.89dB}$$

where $\eta_s^{''}$ is S/N ratio for single casting density.

The same method of calculation was applied to double casting density too.

The S/N ratios for each experiment were determined by using Eqs. (1) and (2) and have been shown in Table 6 for single and double castings.

Analysis of variance (ANOVA): The main aim of ANOVA is to investigate the design parameters and to indicate which parameters are significantly affecting the output parameters. In the analysis, ANOVA was performed (Tables 7, 8, and 9) by computing the following steps (Phadke, 1989):

(i) Calculation of average S/N ratio (η) for quality characteristics by factor level: For control factor A level 1 (or A_1) single casting yield.

m_{A1}= 1/6(η_1+η_2+η_3+η_{10}+η_{11}+η_{12})

m_{A1}= 1/6(-4.05-5.63-6.44-6.42-6.47-3.27)=-5.38dB

where m_{A1} is the average S/N ratio of factor A at level 1.

The average S/N ratio for levels A_2 and A_3 of sand grain size, as well as those for various levels of the other factors, can be computed in a similar way.

(ii) Calculation of dof for each factor: Since factor A has three levels, it has two degrees of freedom for single casting yield. In general, the dof associated with a factor is one less than the number of levels.

(iii) Calculation of the total sum of squares:

$$\text{Total sum of squares} = \sum_{i=1}^{n}(\eta_i - m)^2 \quad (3)$$

where m is the overall mean of average S/N ratio by factor level and η_i is the response of i^{th} experimental run.Total sum of squares for single casting yield:

$$= (-4.05 + 5.44)^2 + (-5.63 + 5.44)^2 + \ldots$$
$$+ (-6.85 + 5.44)^2 = 24.48\ (dB)^2$$

The total sum of squares for double casting yield, as well as for the remaining two quality characteristics is obtained in a similar way.

(iv) Calculation of sum of squares due to various factors: Sum of squares due to factor A for single casting yield:

$$= 6(m_{A1} - m)^2 + 6(m_{A2} - m)^2 + 6(m_{A3} - m)^2$$

(4)

$$= 6(-5.38 + 5.44)^2 + 6(-5.43 + 5.44)^2$$
$$+ 6(-5.51 - 5.44)^2$$

= 0.0516$(dB)^2$

Because there are six experiments each at levels A_1, A_2, A_3 consequently each square due to each level should have multiplier equal to the number of experiments for that specific case. The sum of squares due to various factors for double casting yield, as well as for the remaining two quality characteristics is obtained in a similar way.

(v) Calculation of sum of squares due to error: The orthogonality of the matrix experiment implies the following relationship among various sums of squares.

For single casting yield:

The sum of squares due to error=(Total sum of squares)-(Total of sums of squares due to various factors) (5)

=24.48(0.0516+0.39+2.57+1.61+3.48+9.42+6.22)=0.738$(dB)^2$

The sum of squares due to error for double casting yield, as well as for the remaining two quality characteristics is obtained in a similar way.

(vi) Calculation of mean square: Using previously calculated values of sum of squares and dof of each factor, mean square values for each factor can be determined.

Consequently, Mean square=Sum of square ÷ dof (6)

Thus, mean square of factor A for single casting yield=0.0516 ÷ 2=0.0258$(dB)^2$

The mean square for double casting yield, as well as for the remaining two quality characteristics is obtained in a similar way.

(vii) Calculation of pooled error sum of squares: In the interest of gaining the most information from a matrix experiment, all or most of the columns should be used to study process or product parameters. As a result, no dof may be left to estimate error variance. However, an approximate estimate of the error variance can be obtained by pooling the sum of squares corresponding to the factors having the lowest mean squares. As a rule of thumb, the sum of squares corresponding to the bottom half of the factors (as defined by lower mean square) corresponding to about half of the degrees of freedom be used to estimate the error mean square or error variance.

Here also, the lowest sum of squares are noted and then summed. Consequently, pooled error sum of squares for single casting yield $=0.0516+0.39+0.738=1.18(\mathrm{dB})^2$

Error of variance computed in this way is indicated by parentheses, and the computation is called pooling. By the traditional statistical assumption, pooling gives a biased estimate of error variance. To obtain a better estimate of error variance, a significantly larger number of experiments would be needed, the cost of which is usually not justifiable compared to the added benefit. The pooled error sum of squares for double casting yield, as well as for the remaining two quality characteristics is obtained in a similar way.

(viii) Calculation of F value: We can calculate this value using previously obtained values of mean square and pooled error mean square. Consequently,

F=Mean square of each factor ÷ Pooled error mean square (7)

Thus, F for factor C for a single casting yield:

Mean square of factor C ÷ Pooled error mean square=1.29 ÷ 0.169=7.63

The F value for double casting yield, as well as for the remaining two quality characteristics is obtained in a similar way.

Usually, when the F value is less than 1, the experiment error out weights the control factor. When the F value is approximately equal to 2, the control factor has only a moderate effect compared with the experiment error. When the F value is greater than 4, this means that a change in the process parameter has a significant effect on the quality characteristics (Fowlkes and Creveling, 1995).

The control factor effects for casting yield (η), surface defects (η') and casting density (η''), and their respective ANOVA are given in Tables 7, 8, and 9 for single and double castings respectively.

Table 7 ANOVA for the S/N ratio for casting yield (%)

Single casting							Double casting						
Control factors													
Average η_s by factor level (dB)			dof	Sum of square	Mean Square	F value	Average η_d by factor level (dB)			dof	Sum of square	Mean Square	F value
1	2	3					1	2	3				
A. Sand grain size													
-5.38	-5.43	-5.51	2	0.0516*	0.0258	-	-4.02	-4.17	-4.15	2	0.0924*	0.0462	-
B. Moisture content (%)													
-5.29	-5.64	-5.39	2	0.39*	0.195	-	-3.92	-4.30	-4.10	2	0.45	0.225	3.88
C. Clay content (%)													
-5.26	-5.10	-5.97	2	2.57	1.29	7.63	-3.89	-4.17	-4.26	2	0.47	0.235	4.05
D. Ramming (Number of machine ramming)													
-5.14	-5.85	-5.34	2	1.61	0.805	4.76	-3.93	-4.43	-3.98	2	0.92	0.460	7.93
E. Sprue size (Inch)													
-4.85	-5.58	-5.90	2	3.48	1.74	10.29	-3.70	-4.13	-4.50	2	1.94	0.970	16.72
F. Riser size (Inch)													
-4.62	-5.32	-6.38	2	9.42	4.71	27.87	-3.24	-4.05	-5.05	2	9.88	4.94	85.17
G. D/t ratio													
-6.17	-5.43	-4.73	2	6.22	3.11	18.40	-4.00	-3.96	-3.58	2	4.69	2.345	40.43
Error			3	0.738*	0.246					3	0.198*	0.066	
Total			17	24.48	1.44					17	18.64	1.096	
(Error)			(7)	(1.18)	(0.169)					(5)	(0.290)	0.058	
Overall mean													
-5.44							-4.14						
*Indicates the sum of squares added together to form the pooled error sum of squares shown in parentheses.													

Table 8 ANOVA for the S/N ratio for surface defect (defects/surface area)

Single casting							Double casting						
Control factors													
Average $\eta_s^{'}$ by factor level (dB)			dof	Sum of square	Mean Square	F value	Average $\eta_d^{'}$ by factor level (dB)			dof	Sum of square	Mean Square	F value
1	2	3					1	2	3				
A. Sand grain size													
-47.7	-44.7	-47.6	2	34.85	17.42	3.32	-49.88	-50.24	-53.78	2	55.74	27.87	9.92
B. Moisture content (%)													
-43.9	-48.4	-47.7	2	70.37	35.18	6.71	-51.29	-51.27	-51.33	2	0.012*	0.006	-
C. Clay content (%)													
-46.1	-46.4	-47.5	2	6.53*	3.26	-	-51.27	-51.61	-50.75	2	2.37*	1.18	-
D. Ramming (Number of machine ramming)													
-45.8	-48.2	-46.0	2	21.29	10.64	2.03	-49.38	-52.84	-51.68	2	24.62	12.31	4.38
E. Sprue size (Inch)													
-46.5	-47.9	-45.5	2	17.45	8.72	1.66	-52.50	-52.10	-49.29	2	36.72	18.36	6.53
F. Riser size (Inch)													
-47.5	-46.5	-45.9	2	7.85*	3.92	-	-53.36	-52.38	-48.16	2	91.62	45.81	16.30
G. D/t ratio													
-46.4	-47.7	-45.8	2	11.33	5.66	1.08	-50.96	-51.75	-51.19	2	1.98*	0.992	-
Error			3	22.3*	7.44					3	20.97*	6.99	
Total			17	191.94	11.29					17	234.03	13.77	
(Error)			(7)	(36.68)	(5.24)					(9)	(25.33)	(2.81)	
Overall mean													
-46.65							-51.29						
*Indicates the sum of squares added together to form the pooled error sum of squares shown in parentheses.													

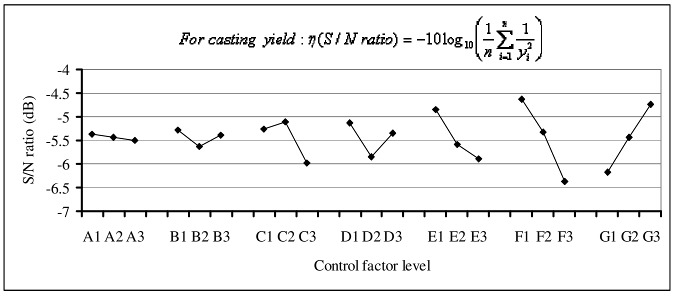
Table 9 ANOVA for the S/N ratio for casting density (gm/cm^3)

Single casting							Double casting						
Control factors													
Average $\eta_s^{''}$ by factor level (dB)			dof	Sum of square	Mean Square	F value	Average $\eta_d^{''}$ by factor level (dB)			dof	Sum of square	Mean Square	F value
1	2	3					1	2	3				
A. Sand grain size													
8.73	8.79	8.54	2	0.2046	0.1023	3.41	8.68	8.72	8.68	2	0.0066	0.0033	-
B. Moisture content (%)													
8.80	8.69	8.57	2	0.159	0.0795	2.65	8.75	8.65	8.69	2	0.0312*	0.0156	-
C. Clay content (%)													
8.72	8.67	8.67	2	0.0102*	0.0051	-	8.75	8.73	8.61	2	0.0696	0.0348	1.90
D. Ramming (Number of machine ramming)													
8.65	8.65	8.76	2	0.0486*	0.0243	-	8.76	8.79	8.53	2	0.243	0.1215	6.64
E. Sprue size (Inch)													
8.74	8.63	8.69	2	0.0366*	0.0183	-	8.76	8.63	8.70	2	0.0516	0.0258	1.41
F. Riser size (Inch)													
8.77	8.63	8.66	2	0.0654	0.0327	1.09	8.72	8.60	8.76	2	0.0834	0.0417	2.28
G. D/t ratio													
8.63	8.65	8.78	2	0.0798	0.0399	1.33	8.74	8.66	8.69	2	0.0204*	0.0102	-
Error			3	0.1745*	0.058					3	0.1065*	0.0355	
Total			17	0.7787	0.046					17	0.6123	0.0360	
(Error)			(9)	(0.2699)	(0.03)					(9)	0.1647	0.0183	
Overall mean													
8.69							8.69						
*Indicates the sum of squares added together to form the pooled error sum of squares shown in parentheses.													

A summary of the control factor effects is tabulated in Table 10, and the control factor effects are displayed graphically in Figures 3 (a) and (b) for single and double castings respectively, which makes it easy to visualize the relative effects of the various factors on all three characteristics (i.e., casting yield, surface defect, and casting density).

Table 10 Summary of control factors effects

Control factor level	Casting yield				Surface defect				Casting density			
	Single		Double		Single		Double		Single		Double	
	η_s dB	F value	η_d dB	F value	$\eta_s^{'}$ dB	F value	$\eta_d^{'}$ dB	F value	$\eta_s^{''}$ dB	F value	$\eta_d^{''}$ dB	F value
A. Sand grain size												
A_1: IS 10	-5.38	-	-4.02	-	-47.7	3.32	-49.88	9.92	8.73	3.41	8.68	-
A_2: IS 15	-5.43		-4.17		-44.7		-50.24		8.79		8.72	
A_3: IS 25	-5.51		-4.15		-47.6		-53.78		8.54		8.68	
B. Moisture content (%)												
B_1: 5%	-5.29	-	-3.92	3.88	-43.9	6.17	-51.29	-	8.80	-	8.75	-
B_2: 8%	-5.64		-4.30		-48.4		-51.27		8.69		8.65	
B_3: 11%	-5.39		-4.10		-47.7		-51.33		8.57		8.69	
C. Clay content (%)												
C_1: 12%	-5.26	7.63	-3.89	4.05	-46.1	-	-51.27	-	8.72	-	8.75	1.90
C_2: 16%	-5.10		-4.17		-46.4		-51.61		8.67		8.73	
C_3: 20%	-5.97		-4.26		-47.5		-50.75		8.67		8.61	
D. Ramming* (Number of machine ramming)												
D_1: 2	-5.14	4.76	-3.93	7.93	-45.8	2.03	-49.38	4.38	8.65	-	8.76	6.64
D_2: 4	-5.85		-4.43		-48.2		-52.84		8.65		8.79	
D_3: 6	-5.34		-3.98		-46.0		-51.68		8.76		8.53	
E. Sprue size (Inch)												
E_1: 0.5	-4.85	10.29	-3.70	16.72	-46.5	1.66	-52.50	6.53	8.74	-	8.76	1.41
E_2: 0.75	-5.58		-4.13		-47.9		-52.10		8.63		8.63	
E_3: 1	-5.90		-4.50		-45.5		-49.29		8.69		8.70	
F. Riser size (Inch)												
F_1: 0.5	-4.62	27.87	-3.24	85.17	-47.5	-	-53.36	16.30	8.77	1.09	8.72	2.28
F_2: 0.75	-5.32		-4.05		-46.5		-52.38		8.63		8.60	
F_3: 1	-6.38		-5.05		-45.9		-48.16		8.66		8.76	
G. D/t ratio**												
G_1: 1	-6.17	18.40	-4.80	40.43	-46.4	1.08	-50.96	-	8.63	1.33	8.74	-
G_2: 2	-5.43		-3.96		-47.7		-51.75		8.65		8.66	
G_3: 3	-4.73		-3.58		-45.8		-51.19		8.78		8.69	
Overall mean	-5.44		-4.14		-46.65		-51.29	8.69	8.69		8.69	
* 2, 4, and 6 are number of rammings; ** 1, 2, 3 are codes for ratios 5:1, 4:1, 3:1, respectively.												



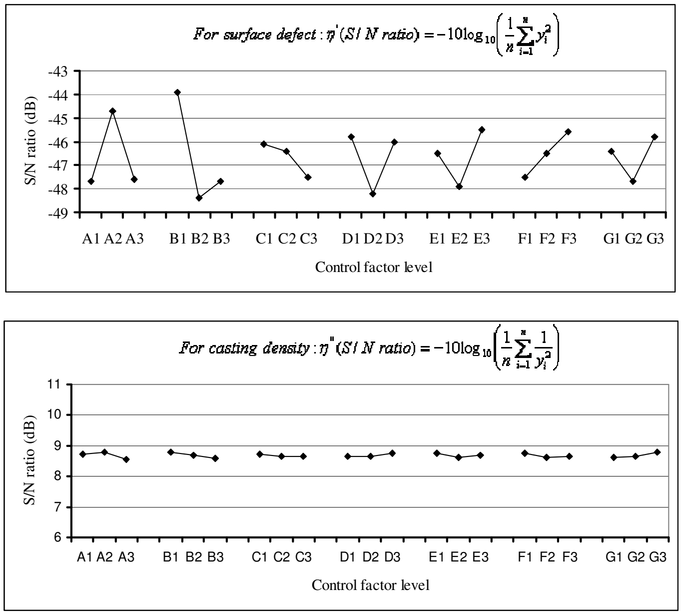


Fig. 3 (a) Plots of control factors effects for single casting (A_3, B_2, C_2, D_2, E_2, F_2, and G_1 indicates starting level)

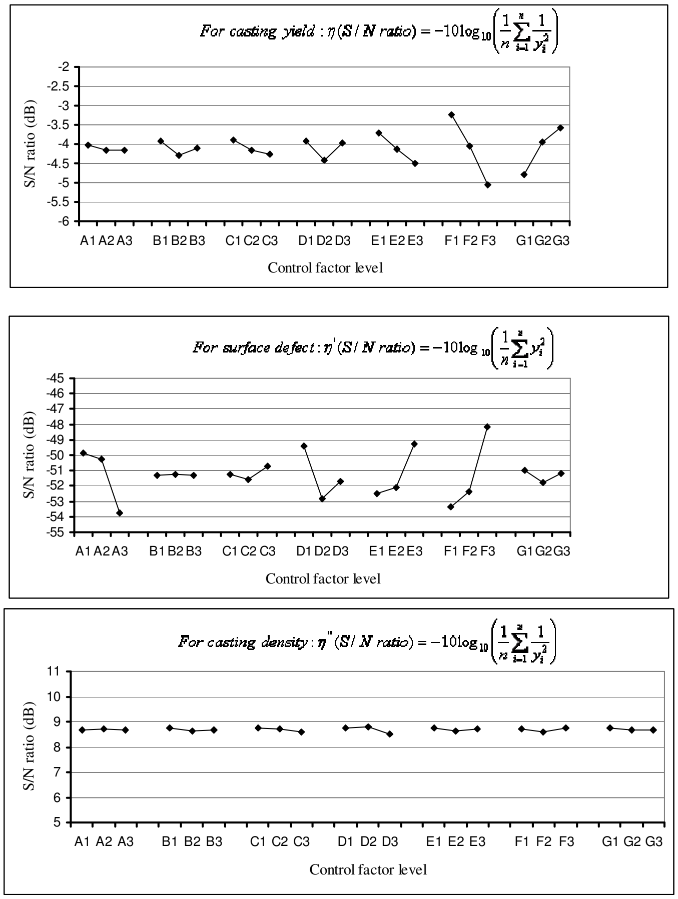


Fig. 3 (b) Plots of control factors effects for double casting (A_3, B_2, C_2, D_2, E_2, F_2, and G_1 indicates starting level)

For ease of the interpretation of the control factor effects plotted in Figures 3 (a) and (b), we note the following relationship between the decibel scale and the natural scale for the three characteristics (Besterfield, 2001):

- An increase in 11 by 6dB is equivalent to reduction in the casting yield variability by a factor of 4. An increase in η by 10dB is equivalent to a reduction in the casting yield variability by a factor of 10.
- The above statements are valid if we substitute $\eta^{'}$, or $\eta^{''}$ for η, and surface defect or casting density variability for casting yield variability.

2.7.2 Determining the optimum levels for the control factors

Referring to Figures 3 (a) and (b), and Table 10, the following observations can be made about the optimum settings for single and double casting cases:

(i) Sand grain size (Factor A): It has negligible effect on casting yield of both single and double castings. It has large effect on surface defects of both single and double castings; also large effect on single casting and negligible effect on double casting density are observed. The optimum levels for single and double casting yield and surface defect for double casting is IS10; and IS15 for surface defect of single casting and density for both castings. Changing the sand grain size from the initial settings to their respective optimum settings of both single and double castings has shown improvement of $\eta_s^{'}$ and $\eta_d^{'}$ by 2.9dB and 3.9dB respectively. These results for surface defects show that use of finer sand gives better product (i.e. with low number of defects). This is because finer sand moulds resist metal penetration and produce smooth casting surfaces. But sand fineness and mould permeability are in conflict with each other and hence must be balanced for optimum results.

(ii) Moisture content (Factor B): It has very small effect on both single casting and double casting yield. It has large effect on single casting and negligible effect on double casting surface defect; and also it has large effect on single casting and small effect on double casting density. By changing the moisture content from starting level 8% to level 15%, $\eta_s^{'}$ can be improved by 4.5dB.

(iii) Clay content (Factor C): The optimum setting of clay content observed for single casting yield is 16% which is the starting level. This factor has moderate effect on both single and double casting yield, small effect on surface defect of single and double casting, and small effect on single casting and moderate effect on double castings density. The optimum setting of clay content observed for double casting yield is 12%.

(iv) Ramming (Factor D): The optimum setting of ramming for casting yield and surface defect, both for single and double castings is found to be 2 and for casting density, 6 and 4 respectively in the two cases. However, the effect of ramming on casting yield and surface defect is moderate in all cases; and small effect on single casting and large effect on double casting density. Changing the ramming from starting level 4 to optimum level 2 will improve $\eta_d^{'}$ by 3.5dB.

(v) Sprue size (Factor E): The optimum settings of sprue size for casting yield and casting density is 0.5inch for single and double casting, and 1inch for surface defect for single and double castings. Sprue size has large effect on single and double casting yield, small effect on single casting and moderate effect on double casting surface defect, negligible effect on single casting and small effect on double casting density. Changing of the sprue size from starting levels to their respective optimum levels will improve $\eta_s^{'}$ and $\eta_d^{'}$ by 1.4dB and 2.81dB respectively for single and double castings.

(vi) Riser size (Factor F): It has largest effect on single and double casting yield, largest effect on double casting surface defect, moderate effect on single and double casting density and negligible effect on single casting surface defect. Casting yield is best when riser size is set to optimum level, but this will lead to a slight increase in surface defect. Changing the riser size from starting level 0.75inch to its optimum level 1inch for surface defect of double casting will improve $\eta_d^{'}$ by 4.22dB, but this will also lead to a reduced casting yield.

Therefore, some trade-off should be made in choosing optimum levels to have better casting yield and minimum surface defects.

(vii) D/t ratio (Factor G): It has largest effect on single and double casting yield, small effect on surface defect and density of single casting, but negligible effect on double casting. Changing D/t ratio from starting to optimum level shows improvement of η_s and η_d by about 1.44dB.

As seen from the above observations, in single casting, the optimum settings for control factors A, B, D, E, and G are found to be A_2, B_1, D_1, E_1, and G_3. In double casting, the optimum settings are A_1, B_1, C_1, D_1 and G_3. However, for factors C and F in single casting and for factors E and F in double casting, the direction in which the quality characteristics of casting yield and density improve tend to increase the surface defect. Thus, some trade-off between quality loss and productivity must be made in choosing their optimum levels. In this study of aluminum blank sand casting process, in deciding for the remaining optimum levels, the following considerations have been taken into account:

- To avoid any quality problem that can cause rejection and significant scrap, we decided to take care of the casting yield and the surface defect;
- To avoid incurring any extra cost and unnecessary time consumption, we have tried to create a common experimental condition for verification experiment which is to be done. Therefore, for the single casting case, initial levels C_2 and F_2 were changed to levels C_1 and F_1 and for the double casting the initial levels E_2 and F_2 were changed to E_1 and F_1. Thus, the optimum settings chosen were A_2, B_1, C_1, D_1, E_1, F_1, and G_3.

2.7.3 Prediction of performance for selected levels

After deciding the optimum conditions, the next step is to predict the anticipated improvement under the chosen optimum conditions.

To do this, first of all, we must predict the S/N ratio for casting yield, surface defect, and casting density using additive model; computation was done for two conditions: (i) for starting condition that is using levels A_3, B_2, C_2, D_2, E_2, F_2, and G_1 for both single and double castings; (ii) for optimum conditions, using chosen optimum settings A_2, B_1, C_1, D_1, E_1, F_1, and G_3 for both cases.

Calculation is based on the additive model formula (Phadke, 1989) and computed as under:

The effect of control factor at level i =The average S/N ratio of factor of interest at level i -Overall mean

(8)Calculation for factor A_3 starting condition, for single casting yield:

The effect of sand grain size at level $A_3=m_{A3}-m=-5.51+5.44=-0.07$dB

The effect of moisture content at level $B_2=m_{B2}-m=-5.64+5.44=-0.20$dB

The effects of the remaining control factors on casting yield, surface defect and casting density for both starting and optimum conditions are calculated in similar way (Tables 11 (a) and (b)) by using Eq. (8).

Referring to the Table 11(a) last row, it is to be noted that, an improvement in single casting yield equal to [-2.68-(-7.21)]=4.53dB, in surface defect: [-40.4-(-51.5)]=11.1dB and in casting density: [9.11-8.30]=0.81dB can be observed. All these are anticipated improvements for single casting.

Table 11(a) Prediction using the additive model for single casting

Control factors	Starting condition				Optimum condition			
	Setting	Contribution* (dB)			Setting	Contribution (dB)		
		Casting yield	Surface defect	Casting density		Casting yield	Surface defect	Casting density
A	A_3	-0.07	-0.95	-0.15	A_2	0.01	1.95	0.10
B	B_2	-0.2	-1.75	0.00	B_1	0.15	2.75	0.11
C	C_2	-0.34	0.25	-0.02	C_1	0.18	0.55	0.03
D	D_2	-0.41	-1.55	-0.04	D_1	0.30	0.85	-0.04
E	E_2	-0.14	-1.25	-0.06	E_1	0.59	0.15	0.05
F	F_2	0.12	0.15	-0.06	F_1	0.82	-0.85	0.08
G	G_1	-0.73	0.25	-0.60	G_3	0.71	0.85	0.09
Overall mean		-5.44	-46.65	8.69		-5.44	-46.65	8.69
Total		-7.21	-51.5	8.30		-2.68	-40.4	9.11
* By contribution we mean the deviation from the overall mean caused by the particular factor level.								

Referring to the Table 11(b), it is to be noted that, an improvement in double casting yield equal to [-1.59-(-5.21)]=3.62dB, in surface defect: [-51.49-(-57.24)]=5.75dB and in casting density: [9.01-8.45]=0.56dB can be observed. All these are anticipated improvements for double casting.

Table 11(b) Prediction using the additive model for double casting

Control factors	Starting condition				Optimum condition			
	Setting	Contribution (dB)			Setting	Contribution (dB)		
		Casting yield	Surface defect	Casting density		Casting yield	Surface defect	Casting density
A	A_3	-0.01	-2.49	-0.01	A_2	-0.03	1.05	0.03
B	B_2	-0.16	0.02	-0.04	B_1	0.22	0.00	0.06
C	C_2	-0.03	-0.32	0.04	C_1	0.25	0.02	0.06
D	D_2	-0.29	-1.55	0.10	D_1	0.21	1.91	0.07
E	E_2	-0.01	-0.81	-0.06	E_1	0.44	-1.21	0.07
F	F_2	0.09	-1.09	-0.09	F_1	0.90	-2.07	0.03
G	G_1	-0.66	0.33	0.05	G_3	0.56	0.10	0.00
Overall mean		-4.14	-51.29	8.69		-4.14	-51.29	8.69
Total		-5.21	-57.24	8.45		-1.59	-51.49	9.01
* By contribution we mean the deviation from the overall mean caused by the particular factor level.								

2.8 Verification experiment

Conducting a verification experiment is a crucial final step of robust design project. Its purpose is to verify that the optimum conditions suggested by the matrix experiment do indeed give the projected improvement. If the observed S/N ratios under the optimum conditions are close to their respective predictions, then we conclude that the additive model on which the matrix experiment was based is a good approximation of the reality. Then, we adopt the recommended optimum conditions for our process or product, as the may be.For aluminium-blank sand casting process study, it was felt to conduct the verification experiment in two ways-Case (i) Using the optimum settings chosen, and Case (ii) Using ordinary silica sand (unsorted) as a substitute for the chosen optimum sand grain size with the other factors remaining at optimum setting. This was done to avoid sorting the sand which is time consuming and not practical in industry. The summary of the data are given in Table 12 for single and double castings respectively, results of verification experiment are given in Table 13 for single and double castings for the two cases respectively, and comparison between predicted and achieved results are shown in Table 14 respectively for single and double castings.

Table 12 Summary of the data of verification experiment

Case (i)						Case (ii)					
Single Casting			Double Casting			Single Casting			Double Casting		
Trial 1	Trial 2	S/N ratio	Trial 1	Trial 2	S/N ratio	Trial 1	Trial 2	S/N ratio	Trial 1	Trial 2	S/N ratio
Quality characteristics											
Casting yield (%)											
62.1	68.7	-3.72	74.1	73.8	-2.62	60.09	-	-4.42	70.59	-	-3.03
Surface defect (defect/surface area)											
149	111	-42.4	274	502	-52.14	307	-	-49.74	757	-	-57.58
Casting density (gm/cm^3)											
2.72	2.78	8.79	2.75	2.79	8.85	2.80	-	8.94	2.79	-	8.91

Table 13 Results of the verification experiment

Conditions	Single casting			Double casting		
	Casting yield η_s (dB)	Surface defect η_s' (dB)	Casting density η_s'' (dB)	Casting yield η_d (dB)	Surface defect η_d' (dB)	Casting density η_d'' (dB)
Starting condition	-7.21	-51.5	8.30	-5.21	-57.24	8.45
Case (i) Optimum condition	-3.72	-42.4	8.79	-2.62	-52.14	8.85
Improvement	3.49	9.10	0.49	2.59	5.10	0.40
Case (ii) Optimum condition	-4.42	-49.79	8.94	-3.03	-57.58	8.91
Improvement	2.79	1.76	0.64	2.18	-0.34	0.46

Table 14 Comparison between predicted and achieved results

Improvement condition	Single casting			Double casting		
	Casting yield η_s (dB)	Surface defect $\eta_s^{'}$ (dB)	Casting density $\eta_s^{''}$ (dB)	Casting yield η_d (dB)	Surface defect $\eta_d^{'}$ (dB)	Casting density $\eta_d^{''}$ (dB)
Anticipated by prediction	4.53	11.10	0.81	3.62	5.75	0.56
Achieved by verification	3.49	9.10	0.49	2.59	5.10	0.40

As seen from Table 14, the experimental results and values predicted are much closer, show that the Taguchi's experimental robust design technique can be used successfully for both optimization and prediction in aluminium blank sand casting process.

3. CONCLUSION

From the results of verification experiment conducted at the optimum settings chosen (Table 13), the following conclusions are drawn:

- Agreement to predictions: The closeness of the results of predictions based on calculated S/N ratios and experimental values show that the Taguchi's experimental robust design technique can be used successfully for both optimization and prediction in Aluminium blank sand casting process. The results of verification experiment for single and double casting for case (i) have fair agreement with the predictions, where as case (ii) shows somewhat less agreement in comparison to case (i).
- Casting yield: Casting yield in case (i) has been improved by 3.49dB for single casting and 2.59dB for double casting. This shows that 132% reduction in yield variability for single casting and 83% for double casting from the starting condition. In case (ii) improvement by 2.79dB for single casting and 2.18dB for double casting is observed. This is 91% reduction in yield variability for single casting and 66% in double casting. It has been observed that the smaller D/t ratio of the casting the more its insensitivity to noise, and better will be the yield of the casting (Table 7).
- Surface defect: The surface defect in case (i) has shown 9.10dB improvement (i.e. decrease) in single casting and 5.10dB in double casting. This is 765% and 240% reduction in surface defects from the starting conditions respectively for single and double casting. In case (ii) the influence on surface defects is marginal.
- Casting density: It is observed that the casting density shows improvement by 0.49dB for single and 0.4dB for double casting. This is an improvement by about 12% for single casting 9% for double casting in case (i) from the starting condition. In case (ii) a slightly better improvement which is 0.64dB and 0.46dB is observed respectively for single and double casting. This is about 16% improvement in single casting and 11% in double casting.
- Finally, (a) As it is observed from the results, improvement achieved in single casting from the starting condition is better than improvement achieved in double casting both in cases (i) and (ii). (b) As it is observed from case (i) and (ii) optimum conditions, the optimum value of double casting yield is better than that of single casting. Therefore, from this point of view it can be concluded that casting yield is more insensitive to noise in double casting process than in single casting process. (c) The optimum value of single casting surface defect is much better· than that of double casting in both cases. Therefore, from this point of view it can be concluded that reduction in surface defect is much better in single casting process than in double casting process. Consequently, single casting process is more insensitive to influence of noise than double casting process.
- As a result, the fundamental principle of the Taguchi method is to improve the quality of a product by minimizing the effect of the causes of variation without eliminating them. In this methodology, the design desired is finalized by selecting the best performance under conditions that produce a consistent performance. The Taguchi approach provides systematic, simple an efficient methodology for the optimization of near optimum design parameters with only a few well-defined experimental sets and determines the main factors affecting the process.

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