https://doi.org/10.1007/s41230-018-7188-1

Optimization of green sand mould system using Taguchi based grey relational analysis

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Abstract: The strength of the mould cavity in sand casting is very much significant to attain high-quality castings. Optimization of green sand process parameters plays a vital role in minimizing casting defects. In the present research work, the effect of process parameters such as AFS grain fineness number, water, molasses, bentonite, fly ash, and ramming, and their levels on the resultant mould properties were investigated and optimized using Taguchi based grey relational analysis. The Taguchi L18 orthogonal array and analysis of variance (ANOVA) were used. The quality characteristics viz., green compression strength, permeability, bulk density, mould hardness and shatter index of green sand mould were optimized using grey relational grade, based on the experiments designed using Taguchi's Design of Experiments. ANOVA analysis indicated that water content is the most influential parameter followed by bentonite, and degree of ramming that contributes to the quality characteristics. The results are confirmed by calculating confidence intervals, which lies within the interval limits. Finally, microstructure observations and X-ray diffraction analysis have been performed for the optimal sand parametric combination. Results show that presence of maximum amount of SiO_2, which might be the reason for enhancement of the physical properties of the sand.

Key words: green sand; bentonite; fly ash; molasses; Taguchi based grey relational analysis; grain fineness number

CLC numbers: TG221 **Document code:** A **Article ID:** 1672-6421(2018)02-152-08

The green sand composition and optimization of the process parameters affect the sand mould properties and ultimately the quality of the final casting [1]. The major reasons for casting defects are mainly due to a fall in green sand properties, which mainly depend upon key input process parameters, such as grain fineness number, the percentage of clay and water, binder, additives (molasses, fly ash, dextrin, and starch) and degree of ramming, etc. Modern foundries prefer coal-free green sand moulds because they have some positive aspects in terms of health and eco-friendly; besides, it has an adverse effect on the green sand properties which results in stress crack, scabbing defects, etc. mostly at higher temperatures [2]. Also, various types of clays are used in moulding sand for the purpose of increasing the bonding strength of the moulding sand. However, when the clays get baked above or equal to 800 °C; they lose their plasticity and converts into dead clays. Molasses does possess adhesive in nature, caused to restore some quantity of plasticity to the dead clays, and causes enhancement of the green compression strength of the mould [3]. It was also observed that fly ash mould without bentonite addition might have a slight reduction in sand properties such as compactibility, tensile strength, and permeability [4]. Thus, it is important to have the proper selection of the control parameters for green sand moulds for a substantial increase in the green sand properties.

Few researchers attempted to identify the efficiency of sand process parameters by means of the statistical design of experiments in order to determine the optimal proportions of green sand combination [5-8]. Typically, Taguchi design of experiments was frequently used for optimization green sand casting process parameters [9-11]. The Taguchi method consists of orthogonal array design and uses the signal-to-noise ratio (S/N ratio), which was limited to single objective function optimization (maximization) within the experimental realm. From the extensive literature survey, it was observed that not much work was found

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Received: 2017-08-31; Accepted: 2018-01-02

related to the effect of process parameters mainly on American foundry society (AFS) grain fineness number (GFN), water, molasses, bentonite, fly ash, and degree of ramming, and their levels on the resultant mould properties. Further, there appears to be no report of any multi-objective optimization of green sand mould system to achieve the desired sand mould properties, which may be recommended to the foundry industries. Therefore, in the present investigation, the Taguchi based grey relational analysis is adopted because the method is the widely used multi-objective optimization technique in manufacturing related processes [12-13]. In this technique, optimization of the complex multiple quality characteristics of green sand was converted into optimization of a single grey relational grade. Based on grey relational grade, the optimal combination of the sand process parameters was predicted. Further, analysis of variance (ANOVA) has been performed to determine the significant contribution of aforesaid individual process parameter on the multi-quality characteristics of the sand mould.

1 Experimental procedure

1.1 Materials

The materials used in the present investigation were green sand (53 and 75 AFS GFN) which was made in the foundry shop at NIT, Department of Mechanical Engineering, Manipur, Imphal-India. In order to enhance the green sand properties, namely green compression strength (GCS), permeability, bulk density, mould hardness and shatter index, various combinations of green sand varied with bentonite, molasses and fly ash in different percentages were prepared according to Taguchi design of experiments. Sieve analysis testing was conducted to determine the AFS grain fineness number of the silica sand. Moreover, the strength of the bentonite clay was obtained by performing a gelling index test [14]. The sodium-based bentonite clay having a gelling index of 14.28 was used for the investigation. The molasses is a byproduct of sugar industries, which can be used as an organic binder to sand moulds in addition to the bentonite in order to enhance the sand properties [15]. The major properties of green sand moulds are efficiently controlled by the amount of AFS GFN sand, water, molasses, bentonite, fly ash, and degree of ramming, as shown in Fig. 1.

1.2 Methodology

Experiments have been carried out as per L18 orthogonal array with varying parameters like AFS GFN, different percentages of water, molasses, bentonite and fly ash, and degree of ramming. GFN was varied by sieving sand to create artificial grades and the mould hardness was varied by varying ramming density. Standard AFS sand specimens of dimension 50 mm in diameter and 50 mm in height were prepared for determining the mould properties. Every time, new and fresh green sand was used for preparing the sand specimens. The prepared sand specimens according to the design of experiments undergone for different tests to evaluate the green sand properties, namely the green compression strength, permeability, bulk density, mould hardness and shatter index.

The use of the Taguchi based grey relational analysis is to optimize the control parameters of the green sand mould for multiple quality characteristics, based on the following steps:

(1) Identify the quality characteristics and process parameters of green sand to be evaluated;

(2) Determine the number of levels for the process parameters;

(3) Select the suitable orthogonal array and assign the process parameters;

(4) Conduct the experiments based on the arrangement of the orthogonal array;

(5) Normalize data of the experiment results of sand properties or quality characteristics;

(6) Perform the grey relational generation and calculate the grey relational grade by averaging the grey relational coefficient;

(7) Analyze the experimental results using the grey relational grade and statistical ANOVA;

(8) Verify the optimal process parameters through the confirmation experiment and confidence interval.

The selected green sand mould process parameters, along with their ranges, are given in Table 1.

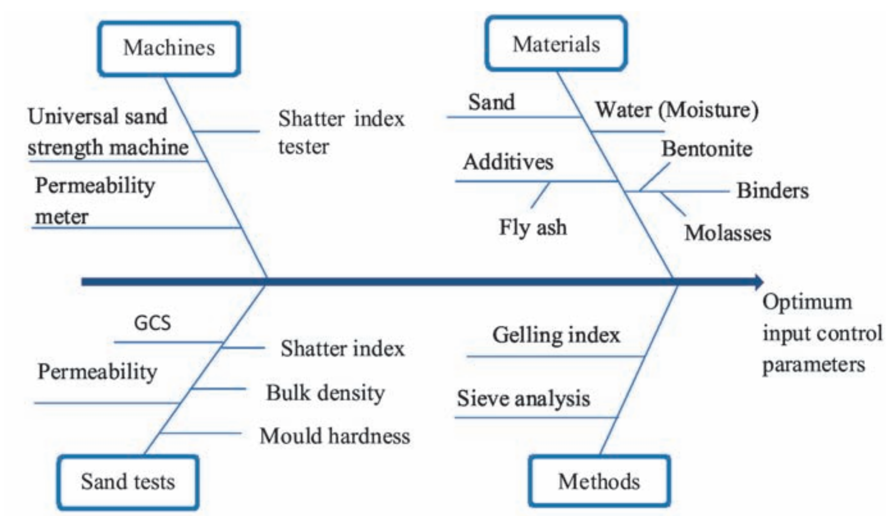

Fig. 1: Cause and effect diagram

Table 1: Green sand mould process parameters and their limits

Green sand process parameters	Range	Designation	Levels		
			1	2	3
AFS GFN	53–75	A	53	75	-
Water (wt.%)	1.25–3.25	B	2	4	6
Molasses (wt.%)	1.25–3.25	C	1.25	2.25	3.25
Bentonite (wt.%)	8–12	D	8	10	12
Fly ash (wt.%)	5–15	E	5	10	15
Degree of ramming	3–5	F	3	4	5

2 Taguchi based grey relational analysis

2.1 Selection of orthogonal array

The selection of orthogonal array depends upon the total degree of freedom of process parameters. Total degree of freedom associated with six parameters is equal to "11" (1×1+5×2). The degree of freedom of the orthogonal array should be greater than or at least equal to that of the process parameters. Essentially, the L18 orthogonal array having a degree of freedom equal to 17 is considered in the present case. The green sand properties were found as per the experimental conditions listed in Table 2. The experiments were conducted three times for the same set of parametric combinations.

Table 2: Taguchi's L18 orthogonal array design

Control parameters						Green sand properties				
A	B	C	D	E	F	Green compression strength (kPa)	Permeability (mmws)	Bulk density (%)	Mould hardness number	Shatter index (%)
1	1	1	1	1	1	140.12	240.45	1.35	70.32	71.20
1	1	2	2	2	2	157.34	235.15	1.50	72.24	66.30
1	1	3	3	3	3	170.24	210.10	1.53	78.40	62.44
1	2	1	1	2	2	152.56	230.39	1.45	69.30	69.32
1	2	2	2	3	3	165.45	173.20	1.47	65.10	63.62
1	2	3	3	1	1	158.28	202.80	1.40	64.70	64.12
1	3	1	2	1	3	160.31	205.47	1.55	75.60	71.14
1	3	2	3	2	1	159.10	190.18	1.48	71.70	81.10
1	3	3	1	3	2	165.44	222.40	1.53	75.10	78.20
2	1	1	3	3	2	173.40	185.13	1.56	76.40	73.00
2	1	2	1	1	3	159.20	238.23	1.52	74.45	67.20
2	1	3	2	2	1	162.12	180.22	1.39	77.12	72.30
2	2	1	2	3	1	150.49	170.19	1.32	73.11	75.40
2	2	2	3	1	2	182.14	163.50	1.36	66.36	64.26
2	2	3	1	2	3	156.36	178.34	1.38	75.40	68.40
2	3	1	3	2	3	172.10	161.10	1.63	64.80	76.50
2	3	2	1	3	1	166.46	164.60	1.54	68.60	85.90
2	3	3	2	1	2	145.50	160.80	1.34	87.10	72.50

2.2 Data pre-processing

The effect of some factors has to be neglected if the optimum value of the quality characteristic is too large. In order to eliminate such effect, the data pre-processing or normalization of data must be required. For this reason, the experimental results need to be normalized between the values of range zero and one. Typically, there are three principles for normalization of data based upon quality characteristics, which might be: the lower-the-better, the larger-the-better, or the nominal-the-best. In the present investigation, our main objective is to enhance the green sand properties. Therefore, the larger-the-better criterion was selected for normalization of experimental data, which is done by the following equation:

$$x_i^*(k) = \frac{x_i(k) - \min x_i(k)}{\max x_i(k) - \min x_i(k)} \quad (1)$$

where, $x_i^*(k)$ and $x_i(k)$ are the data after pre-processing and the experimentally observed data, respectively, for i^{th} number of experiment and the k^{th} response.

All the sequences after data pre-processing (grey relational generation) using Eq. (1) are listed in Table 3.

2.3 Grey relational coefficient and grey relational grade

After data pre-processing is carried out, a grey relational coefficient might be calculated with the pre-processed sequence. It expresses the relationship between the ideal and actual normalized experimental results. The grey relational coefficient is defined as follows:

$$\xi_i(k) = \frac{\Delta_{min} + \zeta\Delta_{max}}{\Delta_{0i}(k) + \zeta\Delta_{max}} \quad (2)$$

where, $\Delta_{0i}(k)$ is the deviation sequence of the reference sequence $x_0^*(k)$, and the comparability sequence is $x_i^*(k)$, ζ is distinguishing or identification coefficient, and Δ_{min} and Δ_{max} are the smallest and largest value of $\Delta_{0i}(k)$. If all the parameters are given equal preference, ζ is taken as 0.5. The grey relational coefficient in each experiment of the L18 orthogonal array obtained by using Eq. (2) has been furnished with Table 4.

Table 3: Grey relational generation of sand quality characteristics

Expt. No.	GCS	Permeability	Bulk density	Mould hardness	Shatter index
1	0.000	1.000	0.097	0.251	0.373
2	0.410	0.933	0.581	0.337	0.165
3	0.717	0.619	0.677	0.612	0.000
4	0.296	0.874	0.419	0.205	0.293
5	0.603	0.156	0.484	0.018	0.050
6	0.432	0.527	0.258	0.000	0.072
7	0.480	0.561	0.742	0.487	0.371
8	0.452	0.369	0.516	0.313	0.795
9	0.603	0.773	0.677	0.464	0.672
10	0.792	0.305	0.774	0.522	0.450
11	0.454	0.972	0.645	0.435	0.203
12	0.524	0.244	0.226	0.554	0.420
13	0.247	0.118	0.000	0.375	0.552
14	1.000	0.034	0.129	0.074	0.078
15	0.386	0.220	0.194	0.478	0.254
16	0.761	0.004	1.000	0.004	0.599
17	0.627	0.048	0.710	0.174	1.000
18	0.128	0.000	0.065	1.000	0.429

After obtaining the grey relational coefficient, the grey relational grade is computed by averaging the grey relational coefficient corresponding to each quality characteristic. The overall evaluation of the multiple quality characteristics is based on the grey relational grade (γ_i), that is:

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n}\xi_i(k) \quad (3)$$

where n is number of sand properties. Table 4 also shows the grey relational grade for each experiment using L18 orthogonal array. Experiment number 9 (nine) has the best multiple quality characteristics among eighteen experiments because it has achieved the highest grey relational grade.

Basically, the larger the grey relation grade, the closer will be the product quality to the ideal value. Therefore, the optimal levels of green sand mould parameters setting for improved green sand properties $A_2B_3C_2D_1E_3$ and F_2 are represented in Table 5. The difference between the maximum and the minimum values describes the level of significance of the controllable factors, which is considered the main effect over the multi-quality characteristics. The maximum main effect value from the results indicated that water has the strongest effect on the multi-quality characteristics of green sand among the other process parameters.

3 ANOVA of experimental results and discussion

Analysis of Variance (ANOVA) was performed using statistical software MINITAB 17 on grey relational grade values to evaluate the influence of process parameters on multi-quality characteristics, as shown in Table 6. ANOVA results indicate that three parameters such as water content (B), bentonite (D), and degree of ramming (F) are the most significant parameters that affect the sand quality characteristics (p-value< 0.05) under 95% confidence levels.

The regression plot obtained during the generation of multiple regression models for the grey relational grade is shown in Fig. 2. The normal probability plot of the residuals for the grey

Table 4: Grey relational coefficient and grey relational grade

Expt. No.	Grey relational coefficients					Grey relational grade (γ_i)	Rank
	GCS	Permeability	Bulk density	Mould hardness	Shatter index		
1	0.333	1.000	0.356	0.400	0.444	0.5068	10
2	0.459	0.883	0.544	0.430	0.374	0.5378	7
3	0.638	0.568	0.608	0.563	0.333	0.5420	6
4	0.415	0.798	0.463	0.386	0.414	0.4954	12
5	0.557	0.372	0.492	0.337	0.345	0.4207	16
6	0.468	0.514	0.403	0.333	0.350	0.4137	17
7	0.490	0.532	0.660	0.493	0.443	0.5237	8
8	0.477	0.442	0.508	0.421	0.710	0.5116	9
9	0.557	0.688	0.608	0.483	0.604	0.5879	1
10	0.706	0.419	0.689	0.511	0.476	0.5603	5
11	0.478	0.947	0.585	0.470	0.385	0.5730	4
12	0.512	0.398	0.392	0.529	0.463	0.4589	14
13	0.399	0.362	0.333	0.445	0.528	0.4133	18
14	1.000	0.341	0.365	0.351	0.352	0.4816	13
15	0.449	0.391	0.383	0.489	0.401	0.4226	15
16	0.677	0.334	1.000	0.334	0.555	0.5801	3
17	0.573	0.344	0.633	0.377	1.000	0.5853	2
18	0.364	0.333	0.348	1.000	0.467	0.5026	11

Table 5: Mean responses for overall grey relational grades

Symbol	Green sand process parameters	Grey relational grade			Main effect (Max-Min)	Rank
		Level 1	Level 2	Level 3		
A	AFS GFN	0.5044	0.5086*	-	0.0042	6
B	Water	0.5298	0.4412	0.5485*	0.1073	1
C	Molasses	0.5132	0.5184*	0.4879	0.0304	4
D	Bentonite	0.5285*	0.4762	0.5149	0.0523	2
E	Fly Ash	0.5002	0.5010	0.5183*	0.0180	5
F	Degree of ramming	0.4816	0.5276*	0.5103	0.0460	3

Total mean value of the grey relational grade = 0.5065
* Levels of optimum grey relational grade

relational grade appears to follow a straight line of the maximum number of points lying on the lower side of the best fitted straight line. The Residuals versus Fits graph shows that the residuals are scattered randomly around zero and the points are accumulated on the higher side of the fitted value. The distribution of the residuals for all observations is given by the histogram, which is normally a bell-shaped curve [16]. ANOVA has been performed on grey relational grade to obtain a contribution to each process parameter affecting the quality characteristics of the green sand mould. Thus, the larger grey relational grade is desired for optimum quality. The S/N ratio is also observed maximum at the levels of the parameters $A_2B_3C_2D_1E_3$ and F_2 as the optimal values, as shown in Fig. 3.

4 Confirmation experiments

The estimated grey relational grade $\hat{\gamma}$ using the optimum level of the green sand mould process parameters can be calculated as:

$$\hat{\gamma} = \gamma_m + \sum_{i=1}^{q} (\overline{\gamma}_j - \gamma_m) \quad (4)$$

where, γ_m is the total mean of the grey relational grade, γ_j is the mean of the grey relational grade at the optimum level, and q is the number of green sand mould process parameters

Table 6: ANOVA results for grey relational grade

Source	DF	SS	Variance	*F*- value	*P*- Value	Percentage contribution
A	1	0.0001	0.0001	0.9412	0.726	0.13%
B	2	0.0395	0.0197	229.8971	0.001	62.73%
C	2	0.0032	0.0016	18.5673	0.15	5.07%
D	2	0.0088	0.0044	51.5491	0.024	14.06%
E	2	0.0012	0.0006	7.2518	0.411	1.98%
F	2	0.0065	0.0032	37.7743	0.046	10.31%
Error	42	0.003604	0.0001			
Total	53	0.062893				

Note: The term ‘DF’ indicates the degrees of freedom, which refers to the number of terms that will contribute to the error in prediction. The term ‘SS’ denotes the sum of squares for each term; it measures the variability in the data contributed by this term.

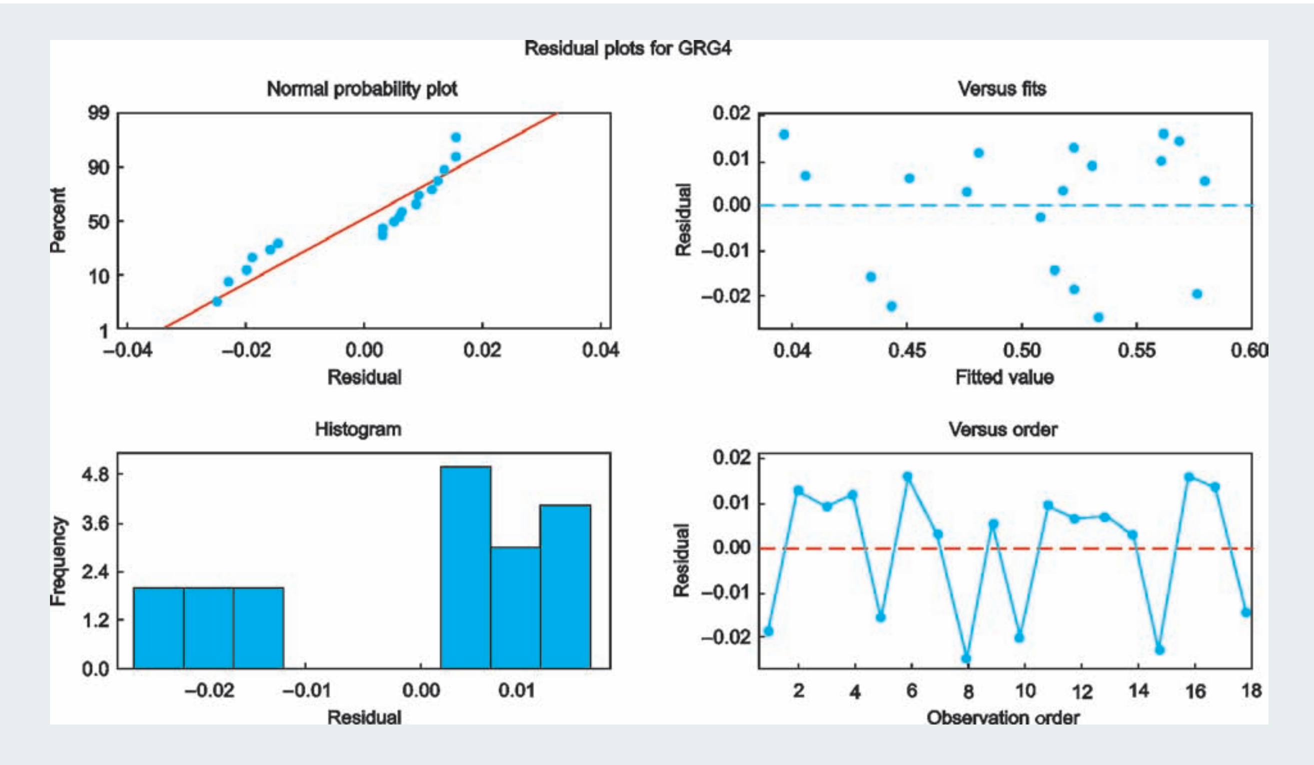

Fig. 2: Residual plot of weighted grey relational grade during regression modelling

at 95% confidence interval (CI). The predicted mean of the grey relational grade in confirmation test is estimated by the following equation:

$$CI = \mu \pm \sqrt{F_{\alpha};1;f_e \times V_e\left(\frac{1}{n_{\mathrm{eff}}}+\frac{1}{r}\right)} = 0.6174 \pm 0.0150$$

$$n_{eff} = \frac{N}{1+v}$$

where $F_{\alpha};1$ is the F ratio required for 100(1-α)% CI, f_e is the degree of freedom for error, V_e is the error of variance, r is the number of replications of the confirmation experiment, n_{eff} is the effective number of replications, N is the number of experiments in the orthogonal array, and v is the total number of degrees of freedom. Table 7 represents the results of confirmation experiments.

FE-SEM Supra 55 was used for characterization of optimal parametric moulding sand combination. The microstructure in Fig. 4 revealed that fly ash particle sizes having both spherical and rounded shapes are finer as compared to moulding sand particles. X-ray diffraction (XRD) analysis of optimal green sand including fly ash, molasses, and bentonite revealed that maximum amount of SiO_2 is presented in the sand mixture as depicted in Fig. 5. Because of the presence of high SiO_2, sand moulds are enhanced in terms of physical and thermal properties, which are very much essential in sand casting to

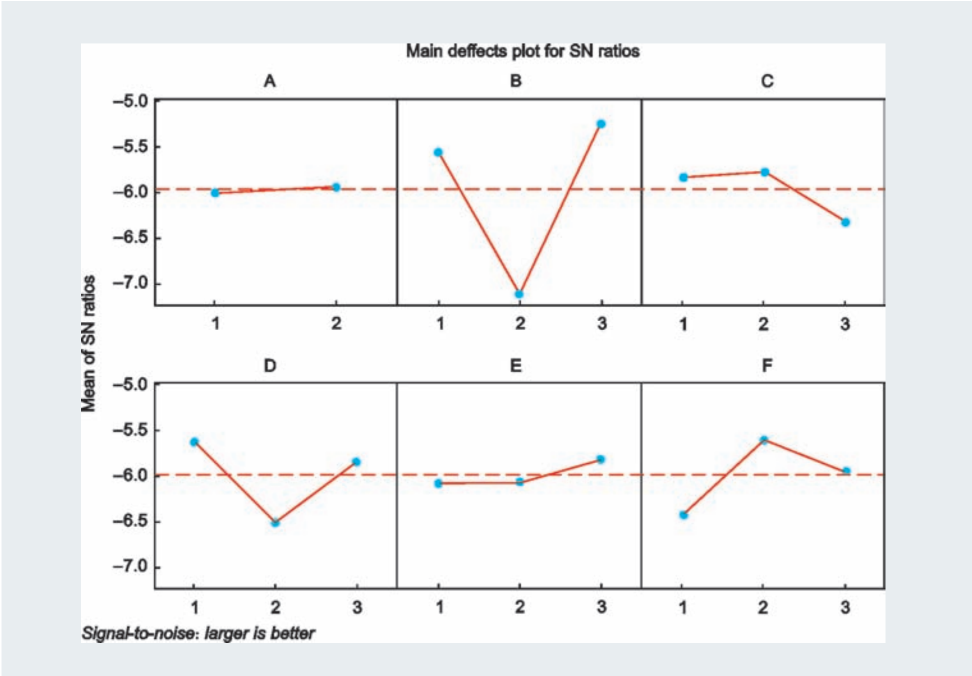

Fig. 3: Effect of green sand process parameters on grey relational grade

Table 7: Results of confirmation experiments

	Initial GS process parameters	Optimal GS process parameters	
		Prediction	Experiment
Factors and levels	$A_1B_1C_1D_1E_1F_1$	-	$A_2B_3C_2D_1E_3F_2$
GCS	140.12	-	165.44
Permeability	240.45	-	222.4
Bulk density	1.35	-	1.53
Mould hardness	70.32	-	75.1
Shatter index	71.2		78.2
S/N ratio	-5.934	-	-4.614
Overall GRG	0.5050	0.6174	0.5879

Percentage improvement in grey relational grade = 22.25%.

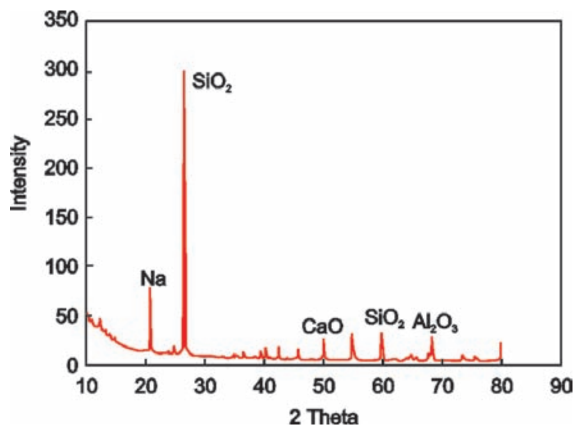

Fig. 5: Diffraction of optimum green sand

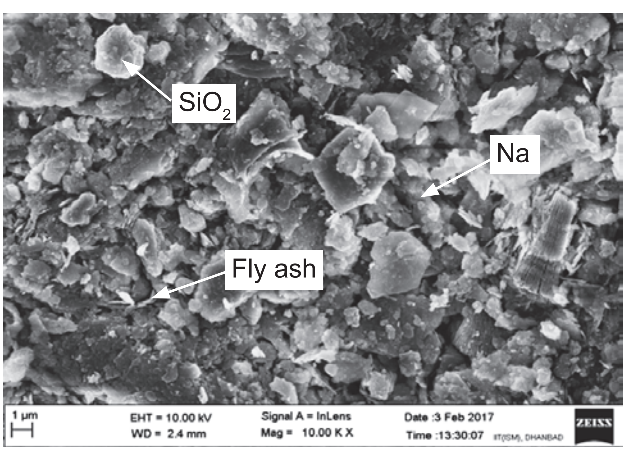

Fig. 4: SEM image of optimized green sand combination

produce quality castings [17]. Generally, by the addition of fly ash, the properties of a green sand mould might be decreased due to smooth spherical particles and are weak in interlocking capacity among the particles of the fly ash. However, it was observed from Fig. 5 that the presence of bentonite (Na) and molasses (CaO) might enhance the bonding strength; therefore the green sand properties might be restored and improved [18]. Thus, the optimal combination of the green sand composition obtained, which is: GFN 75, water 6%, molasses 2.25%, bentonite 8%, fly ash 15%, and degree of ramming 4.

5 Conclusions

Based on the present investigation, the following conclusions have been drawn for the green sand mould with various combinations of process parameters by Taguchi based grey relational analysis:

(1) By implementing Taguchi based grey relational analysis,

optimal green sand properties were obtained at an optimal parametric combination of GFN 75, water 6%, molasses 2.25%, bentonite 8%, fly ash 15%, and degree of ramming 4.

(2) Based on ANOVA analysis, the water content, contributing by 62.73%, has the strongest influence in comparison with other parameters, while bentonite has an effect of 14.06% and degree of ramming at 10.31% on the multi-quality characteristics.

(3) Confirmation experiments performed with the optimum conditions shows a percentage of improvement in grey relational grade at 22.25%. The reliability of the grey relational grade is determined by calculating the confidence interval. The 95% confidence interval of the grey relational grade obtained from confirmation test lies within 0.6024 and 0.6324.

(4) SEM and XRD analysis of optimal green sand combination including fly ash, molasses, and bentonite revealed that presence of maximum amount of SiO_2, which might be the reason for enhancement of the physical properties of the sand. It was also observed that the fly ash in addition with bentonite and molasses might enhance the bonding strength of the sand, hence the properties might be improved.

References

[1] Karunakar D B, Datta G L. Controlling green sand mold properties using artificial neural networks and genetic algorithms – A comparison. Applied Clay Sci., 2007, 37(1–2): 58–66.

[2] Corenelis Gefhorst, Wim Seden, Resat Ilman, et al. Reduction of green sand emission by minimum 25% – Case study. China Foundry, 2010, 7(4): 419–424.

[3] Gadag S P, Sunni Rao K S, Mawr N Srinivasan, et al. Effect of Organic Additives on the Properties of Green Sand Assessed from Design of Experiments. AFS Transactions, 1987, 42: 179–186.

[4] Karunakaran P, Jegadheesan C, Dhanapal P. Sugar Industry Fly Ash: An Additive for Molding Sand to Make Aluminium Castings. Russian Journal of Non-Ferrous Metals, 2014, 55 (3): 247–253.

[5] Kundu R R, Lahiri B N. Study and statistical modelling of green sand mold properties using RSM. International Journal of Materials and Product Technology, 2008, 31 (2):143–158.

[6] Parappagoudar M B, Pratihar D K, Datta G L. Non-linear modeling using central composite design to predict green sand mould properties. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 2007, 221: 881–894.

[7] Saikaew C, and Wiengwiset S. Optimization of molding sand composition for quality improvement of iron castings. Applied Clay Science, 2012, 67–68 (5): 26–31.

[8] Surekha B, Lalith K K, Abhishek K P. Multi-objective optimization of green sand mould system using evolutionary algorithms. Int. J. Adv. Manuf. Technol., 2012, 58: 9–17.

[9] Kumar S, Satsangi P S, and Prajapati D R. Optimization of Green Sand Casting Process Parameters of a Foundry by Using Taguchi's method. Int. J. of Adv. Manu. Tech., 2011, 55: 23–34.

[10] Guharaja S, Noorul H A, Karuppannan K. Optimization of green sand casting process parameters by using Taguchi's method. Int. J. of Adv. Manu. Tech., 2006, 30: 1040–1048.

[11] Johnson S A, Lakshmanan A R. Investigation of ductile iron casting process parameters using Taguchi approach and response surface methodology. China Foundry, 2016, 13 (5): 352–365.

[12] Datta S, Bandyopadhyay A, Pal P K. Grey-based Taguchi method for optimization of bead geometry in submerged arc bead-on-plate welding. Int. J. Adv. Manuf. Technol., 2008, 39: 1136–1143.

[13] Lin Z C, Ho C Y. Analysis and application of grey relation and ANOVA in chemical-mechanical polishing process parameters. Int. J. Adv. Manuf. Technol., 2003, 21: 10–14.

[14] Krishnamoorthy A R. Sand Practices. The Institute of Indian Foundrymen, Calcutta, 1996.

[15] Mandal A, Roy P. Modeling the compressive strength of molasses–cement sand system using design of experiments and back propagation neural network. Journal of Materials Processing Technology, 2006, 180: 167–173.

[16] Senthilkumar N, Tamizharasan T, Anandakrishnan V. Experimental investigation and performance analysis of cemented carbide inserts of different geometries using Taguchi based grey relational analysis. Journal of Measurement, 2014, 58: 520–536.

[17] Sobczak J, Purgert R M. The use of fly ash as an aggregate for foundry sand mold and core production. United States Government sponsored project, 2002, CBRC/DOE Grant Number CBRCE42.

[18] Jain P L. Principles of Foundry Technology, New Delhi: Tata McGraw-Hill Publishing Company Limited, 2003, 4(58): 85–86.

This study was financially supported by the National Institute of Technology, Manipur, India.