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Optimization of sand casting AlSi10Mg alloy for multiple performance characteristics by using Taguchi based Grey relational Analysis

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Abstract

The AlSi10Mg alloy falls into the hypoeutectic aluminum alloys category, prized for its blend of robust mechanical properties, lightweight nature, corrosion resistance, and excellent castability. Widely utilized in automotive, aerospace, and military sectors, its composition includes the eutectic Al + Si phase, influencing both its strength and ductility, albeit making it challenging to machine. Notably, this alloy exhibits low shrinkage and a relatively modest melting point, rendering it ideal for casting processes. In a recent study, researchers endeavored to optimize the sand casting of AlSi10Mg alloy through a multi-response optimization approach. They investigated the impact of metallurgical variables such as Al-0.5Ni, Al-RHA, Al−2.5Ti−0.25C, and scrap, alongside sand casting parameters like pouring temperature and molasses content, utilizing Taguchi-based grey relational analysis. Experiments were structured using Taguchi's Design of Experiments (DoE), employing an L18 orthogonal array.

Key performance characteristics including grain size, tensile strength, Vickers Hardness Number (VHN), and Brinell Hardness Number (BHN) were optimized using grey relational grade. Analysis of variance underscored pouring temperature as the most influential parameter, with Al-2.5Ti-0.5C,Molasses, Al-RHA, and Al-0.5Ni following suit in impacting output responses. Confirmation results were validated through the calculation of confidence intervals, falling within the expected range. Microstructure examination via Scanning Electron Microscopy (SEM) revealed a prevalence of equiaxed grains under optimal conditions, correlating with the attainment of maximum properties.

Index Terms: *Sand casting, AlSi10Mg alloy, RHA, Mechanical properties, Scrap, Taguchi based GRA.*

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1. Introduction

The AlSi10Mg alloy falls within the hypoeutectic aluminum alloys category, prized for its advantageous blend of robust mechanical properties, lightweight nature, corrosion resistance, and superb castability, rendering it extensively utilized across automotive, aircraft, and military sectors [1,2]. The presence of the eutectic Al + Si phase in this alloy notably impacts both its ductility and strength, albeit posing challenges for machining processes. Notably, the AlSi10Mg alloy exhibits low shrinkage and a relatively modest melting temperature, characteristics that make it particularly well-suited for casting applications [3-5]. Unlike forgings and other wrought parts shaped in the solid state, the mechanical properties and the performance of cast components depend strongly on the as-cast microstructure [6]. The refinement of the microstructure improves melt feeding, promotes soundness and thus leads to substantial improvement in mechanical properties and pressure tightness [7–11]. Structural refinement in cast components almost always refers to the refinement of the dendrites, the predominant feature of hypoeutectic aluminum foundry alloys under most conditions of solidification While foundry people focus on refining the secondary dendrite arm spacing (DAS), the refinement of the grain structure cannot be ignored. It has been reported that Si promotes the formation of twinned columnar grains that have an adverse impact on the properties [12, 13]. It is thus essential to add master alloys to molten Al–Si alloys in order to achieve fine, equiaxed grains after solidification. Lu Yang et. al [14] investigated that the grain size increased with the addition of Si from 0 to 3 wt.

% and Ni from 2 to 6 wt. %, and decreased slightly with increasing Ni content up to 8 wt.%. Also, the ultimate tensile strength of Al-Ni-Si alloys was enhanced by the addition of Si and Ni, whereas its elongation decreased. Marisa Di Sabatino and Lars Arnberg [15] reviewed the phenomena that limit castability of aluminum alloys and the effect of alloy composition on fluidity, macro-segregation, hot tearing and porosity will be described. Also, models for castability prediction will be briefly reviewed and data on coherency, fluidity, permeability and shrinkage will be presented. Zhenguo Wang et. al [16] studied the relationship between microstructure and mechanical properties of a novel Ti–3.0Al–3.7Cr–2.0Fe alloy. It was found that the strength of Ti–Al–Cr–Fe system alloys are increased with increasing the β alloying elements Cr and Fe, according to the Ti–3Al–2.1Cr–1.3Fe and Ti–3.0Al–7.1Cr–4.3Fe and Ti– 3.0Al–3.7Cr–2.0Fe alloys.

Sabatino and Arnberg [17] studied the phenomena of limit castability of aluminum alloys, with respect to major alloying elements like copper and magnesium, which are also the basis of the 200 and 500 series alloys. These additions resulted in large freezing ranges which made the alloys vulnerable to hot tearing.

The castability of type 200 and 500 series aluminum alloys is generally regarded as poor. In the present literature not much work is found related to the suitability study of sand castings using AlSi10Mg alloy. There is, therefore, a need to study the grain size and mechanical properties of the sand casting of these alloys. The current study is focused on optimization of sand casting parameters of AlSi10Mg alloys. The microstructures of the aforementioned alloy were also studied using optical and scanning electron microscopy.

In the current research, not much work is found related to study of the grain size and mechanical properties sand casting of AlSi10Mg alloy. Hence, an attempt has been made to conduct investigations on AlSi10Mg aluminum cast alloys, which have long freezing range and poor castability. It would help the foundrymen to understand and minimize such defects that are associated with grain size. In this work, the sand casting process parameters which would enhance the grain size and mechanical properties of castings have been investigated and optimized by grey relational analysis.

1.1 Grey relational analysis

The Taguchi method optimizes process parameters efficiently by employing special orthogonal arrays, reducing the number of experiments needed. While this is effective for a single quality characteristic, the grey-based Taguchi method extends optimization to multiple quality characteristics. It measures the degree of approximation among sequences using grey relational grade, normalizing experimental results and calculating grey relational coefficients. These coefficients determine grey relational grades, representing overall performance. Consequently, optimization focuses on maximizing this single grey relational grade, simplifying the process. Additionally, ANOVA identifies significant process parameters affecting quality characteristics, aiding in predicting optimal parameter combinations. Confirmation experiments validate the optimal parameters. This method streamlines optimization by converting complex multi-characteristic optimization into a single grey relational grade optimization, enhancing efficiency and accuracy. Detailed procedures are elaborated in subsequent sections.

2 Experimental Investigations

The designed pattern consists of 250 mm long, with rectangular cross-sections of (8) mm thickness and 30 mm across as shown in Fig. 1.

Table 1 Chemical composition of AlSi10Mg aluminum Casting alloy

Alloy	**Composition (wt. %)**										
AlSi10Mg	**Al**	**Si**	**Mg**	**Cu**	**Mn**	**Fe**	**Ni**	**Zn**	**Pb**	**Sn**	**Ti**
	Balancing	9.51	0.349	0.008	0.126	0.294	0.0043	0.0095	0.0019	-	0.13

Experiments have been carried out as per L_{18} OA and corresponding fluidity, hardness, and tensile strength were measured. Figure 2 shows the schematic illustration of the preparation of specimens by green sand moulds. The cope half of the pattern consists of Aluminum alloy pouring cup and down sprue. The drag half of the pattern consists of aluminum alloy designed pattern.

Fig. 1 a) Drag b) Cope

About 30 kg of 99.9 % pure aluminum ingots were cut into suitable sizes for charging into the 5 kg capacity graphite crucible. The cut pieces were first mechanically cleaned with acetone to remove the adherent dust and oily materials. The ingots were preheated before charging for melting. The melting process was carried out in a lift-out crucible furnace. When the crucible kept in the furnace attains 700°C, the preheated ingots were charged into it. The melting temperature was maintained at 850 ±10°C. The temperature of the molten metal was measured using calibrated K type thermocouple before pouring it into the mould. The alloying elements (RHA, Mg, Ni, and Ti) in the master alloy form are added in proportions as listed Table 1. The melt was degassed by coverall flux to remove the oxide inclusions. The melt was poured directly into the prepared soap stone powder coated sand moulds and allowed the metal to cool down to room temperature.

2.1 Process parameters of green sand casting

An Ishikawa diagram (cause and effect diagram) of sand casting process involves various input control parameters such as metal and mould variables and metal composition as shown Fig.2.

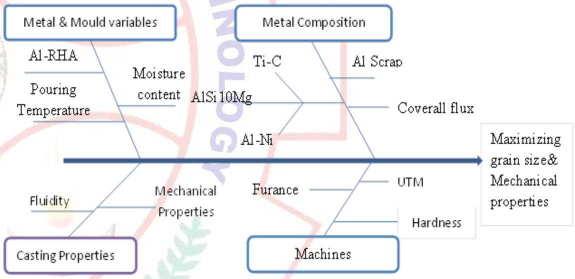

Fig.2 Cause and Effect diagram

The selected sand-casting process parameters, along with their ranges, are given in Table 3.

Table 3 Control sand casting process parameters

Parameters	Range	Designation	Levels of factors		
			1	2	3
Molasses (wt. %)	1.25-2.25	A	1.25	2.25	---
Al-0.5Ni (wt. %)	0.5-1.5	B	0.5	1	1.5
Al-RHA (wt. %)	0-10	C	5	10	15
Al-2.5Ti-0.5C (wt. %)	0-2.5	D	0.5	1.5	2.5
Scrap (wt. %)	5-15	E	5	10	15
Pouring Temperature (°C)	750 – 850	F	750	800	850

2.2 Experimental results

Grain size was measured average grain size method. Tensile strength value (in MPa) was measured by Universal Testing Machine (UTM). Micro hardness and Macro hardness values were measured by VHN, BHN testers. Average values of observed results are depicted in experimental layout Table 4.

Table 4 Experimental layout and observed results

Exp. No.	**A**	**B**	**C**	**D**	**E**	**F**	**Grain size[a] (µm)**	**Tensile strength[a] (MPa)**	**VHN[a]**	**BHN [a]**
1	1	1	1	1	1	1	71.60	115.345	88.95	77.9
2	1	1	2	2	2	2	70	78.219	83	62.98
3	1	1	3	3	3	3	65.20	129.931	71.9	87
4	1	2	1	1	2	2	54.50	123.601	75.78	66
5	1	2	2	2	3	3	75.00	116.27	83.4	63.2
6	1	2	3	3	1	1	98.20	75.97	64.68	65.66
7	1	3	2	1	1	3	88.20	106.316	72.67	67.3
8	1	3	3	2	2	1	75.20	93.695	79.9	68
9	1	3	1	3	3	2	76.70	106.816	70.6	61
10	2	1	3	1	3	2	84.70	98.556	75	73.12
11	2	1	1	2	1	3	82.14	105.7	77.1	75.5
12	2	1	2	3	2	1	79.00	84.6	65.67	70
13	2	2	2	1	3	1	85.20	101.3	76.58	69.34
14	2	2	3	2	1	2	77.10	91.141	78.8	67.5
15	2	2	1	3	2	3	55.50	121.11	89.2	59.69
16	2	3	3	1	2	3	80.69	119.46	65.5	68.39
17	2	3	1	2	3	1	80.00	96.01	61.4	55.3
18	2	3	2	3	1	2	90.00	68.843	64.56	66.21

3 Grey Relational Coefficient and Grey Relational Grade

Data pre-processing in GRA is essential to handle variations in range, unit, and direction among data sequences. It involves normalizing experimental results to a range between zero and one. For optimizing sand casting properties like fluidity, VHN, and BHN, the "larger-the-better" quality characteristic guides the normalization process

$$x_i^*(k)=\frac{x_i(k)-\min x_i(k)}{\max x_i(k)-\min x_i(k)} \qquad (3.1)$$

Where, $x_i^*(k)$ and x_i (k) are the sequence after the Data pre-processing and comparability sequence respectively, k= 1 for green sand properties; i= 1, 2, 3……., 18 for experiment numbers 1 to 18.

Similarly the subsequent calculations are also made and all the sequences after Data pre-processing (Grey relational generation) using Equation (6.1) are depicted in Table 5.

Now, $\Delta_{0i}(k)$ is the deviation sequence of the reference sequence $x_0^*(k)$ and the comparability sequence $x_i^*(k)$, i.e.

$$\Delta_{0i}(k)=\left|x_0^*(k)-x_i^*(k)\right| \qquad (3.2)$$

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:

$$\xi_i(k)=\frac{\Delta_{min}+\zeta\Delta_{max}}{\Delta_{0i}(k)+\zeta\,\Delta_{max}} \qquad (3.3)$$

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. If all the parameters are given equal preference, ζ is taken as 0.5. The grey relational coefficient and Grey relational grade for each experiment of the L_{18} OA obtained using Equation (3.3) has been furnished in Table 4.

The overall evaluation of the multiple quality characteristics is based on the grey relational grade, that is:

$$\gamma_i=\frac{1}{n}\sum_{k=1}^{n}\xi_i(k) \qquad (3.4)$$

Where γ_i is the grey relational grade for the ith experiment and n is the number of quality characteristics. Table 5 shows the grey relational grade for each experiment using L_{18} OA

Table 5 Data pre-processing, grey relational coefficients and grey relational grade

Expt. No.	Normalized values of experimental results				Grey relational coefficients				GRG	Rank
	Grain size (µm)	Tensile strength	VHN	BHN	Grain size (µm)	Tensile strength	VHN	BHN		
1	0.609	0.239	0.009	0.287	0.4510	0.6768	0.9823	0.6353	0.6863	2
2	0.645	0.847	0.268	0.758	0.4366	0.3713	0.6512	0.3975	0.4642	15
3	0.755	0.000	0.644	0.000	0.3984	1.0000	0.4370	1.0000	0.7088	1
4	1.000	0.104	0.513	0.662	0.3333	0.8283	0.4938	0.4301	0.5214	11
5	0.531	0.224	0.254	0.751	0.4850	0.6910	0.6629	0.3997	0.5597	4
6	0.000	0.883	0.889	0.673	1.0000	0.3614	0.3600	0.4262	0.5369	6
7	0.229	0.387	0.618	0.621	0.6860	0.5640	0.4472	0.4459	0.5358	7
8	0.526	0.593	0.373	0.599	0.4872	0.4574	0.5728	0.4548	0.4930	12
9	0.492	0.378	0.688	0.820	0.5040	0.5692	0.4208	0.3787	0.4682	14
10	0.309	0.514	0.539	0.438	0.6181	0.4933	0.4812	0.5331	0.5314	9
11	0.368	0.397	0.468	0.363	0.5764	0.5576	0.5166	0.5795	0.5575	5
12	0.439	0.742	0.855	0.536	0.5323	0.4026	0.3689	0.4825	0.4466	17
13	0.297	0.469	0.485	0.557	0.6270	0.5162	0.5074	0.4730	0.5309	10
14	0.483	0.635	0.410	0.615	0.5087	0.4405	0.5493	0.4484	0.4867	13
15	0.977	0.144	0.058	0.862	0.3385	0.7759	0.8967	0.3672	0.5946	3
16	0.401	0.171	0.861	0.587	0.5551	0.7447	0.3674	0.4600	0.5318	8
17	0.416	0.555	1.000	1.000	0.5456	0.4738	0.3333	0.3333	0.4215	18
18	0.188	1.000	0.893	0.656	0.7271	0.3333	0.3590	0.4326	0.4630	16

^{a} Averaged of three experiment results

Figure 3 shows the grey relational grade obtained for different process parameters. The mean of grey relational grade for each parameter is shown by vertical line. Basically, the larger the grey relation grade is, the closer will be the product quality to the ideal value. Thus, larger grey relational grade is desired for optimum quality. Optimal level of the process parameters is the level with the highest grey relational grade. The mean of the grey relational grade values for each level of the green sand mould parameters was calculated using the same method. The grey relational grade represents the level of correlation between the reference sequence and the comparability sequence, the greater value of the grey relational grade means that the comparability sequence has a stronger correlation [18]. The mean of the grey relational grade for each level of the sand mould parameters is summarized and shown in the multi-response performance obtained for different sand mould parameters. Basically, the larger the grey relational grade is, the closer will be the product quality to the ideal value. Therefore, the optimal levels of sand casting parameters setting for improved grain size and mechanical properties are (A_1, B_1, C_1, D_3, E1, and F3) are depicted in Table 68. The optimal level of the sand casting parameters is the level with the highest grey relational grade. Based on the grey relational grade values given in Table 6, Optimum control parameters of sand casting process parameters for maximum grain size and mechanical properties are shown in Table 6. The greater values in Fig. 3 give the higher casting properties and good quality. Therefore, experiment 3, as shown in Table 4 and Fig. 3, may be considered as very close to fit the optimal process conditions. As shown in Table 6, the difference between the maximum and the minimum value of the grey relational grade of the sand casting process parameters. This comparison will give the level of significance of the controllable factors over the multi-quality characteristics.

Table 6 Mean Responses for overall Grey relational grade

Designation	**Sand casting process parameters**	**GRG**			**Main effect**	**Rank**
		Level 1	**Level 2**	**Level 3**	**(Max-Min)**	
A	Molasses (wt. %)	**0.5527**	0.5071		0.0456	5
B	Al-2.5Ti-0.5C (wt. %)	**0.5658**	0.5384	0.4856	0.0803	2
C	Al-RHA (wt. %)	**0.5563**	0.4971	0.5364	0.0592	3
D	Al-0.5Ni (wt. %)	0.5416	0.5	**0.5481**	0.0481	4
E	Scrap (wt. %)	**0.5444**	0.5086	0.5368	0.0358	6
F	Pouring Temperature (°C)	0.5192	0.4892	**0.5814**	0.0922	1
Total mean value of the GRG = 0.5229, ***** Optimum levels for GRG						

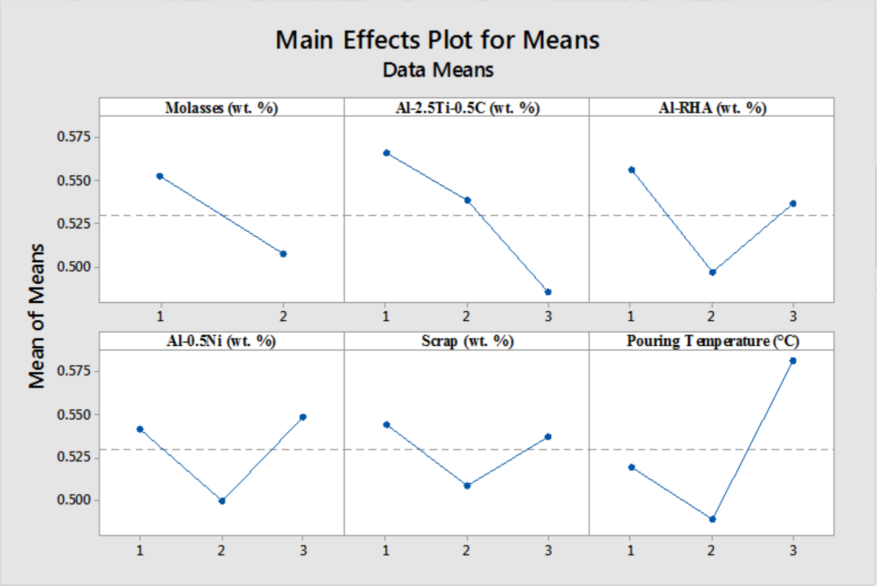

Fig. 3 Mean plot for overall Grey relational grade

The most effective controllable factor was the maximum of these values. Here, the maximum value among 0.5527, 0.5658, 0.5658, 0.5481, 0.5444, and 0.5814 is 0.5814. The value indicates that the pouring temperature is influenced on the multi-quality characteristics among the other sand casting process parameters.

4 Analysis of Variance (ANOVA) of experimental results

To determine which input factors have a significant effect on the response, and how much of the variability in the response variable is attributable to each factor, ANOVA is performed. Depending on F-value, P-value (probability of significance) is calculated. According to the present analysis, pouring temperature is the most prominent parameter contributing 44%, followed by GFN 16%, Moisture content by 16%, and Al-2.5Ti-0.5 C (Grain refiner) by 13%, whereas scrap and Al-Ni have no significant contribution the performance characteristics. The percent contributions of the control parameters are shown in Table 9 and Fig. 8.

Table 7 Results of ANOVA using adjusted SS for test

Source	DF	SS	MS	F-Value	P-Value	Percentage contribution
Molasses (wt. %)	1	0.009353	0.009353	3.15	0.126	9.64%
Al-2.5Ti-0.5C (wt. %)	2	0.019969	0.009985	3.36	0.105	20.58%
Al-RHA (wt. %)	2	0.010873	0.005437	1.83	0.24	11.21%
Al-0.5Ni (wt. %)	2	0.008176	0.004088	1.38	0.322	8.43%
Scrap (wt. %)	2	0.004266	0.002133	0.72	0.526	4.40%
Pouring Temperature (°C)	2	0.026536	0.013268	4.46	0.065	27.35%
Error	6	0.017836	0.002973			18.39%
Total	17	0.09701				

The sand casting properties are the "larger the better" type of quality characteristics. Larger the better S/N ratios of grey relational grade were computed for each of the 18 trials and the values are depicted in Table 8.

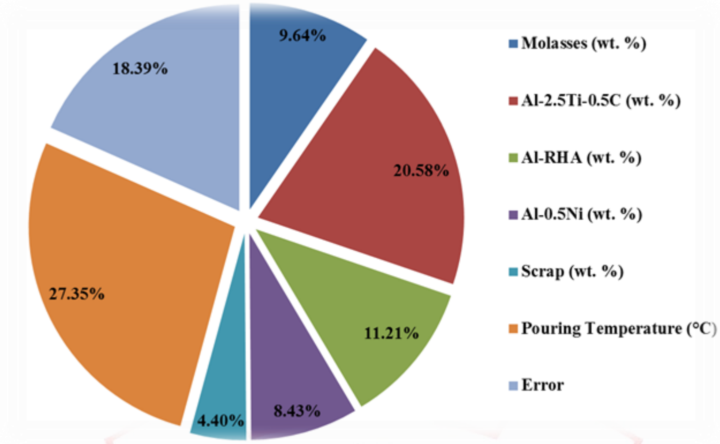

Fig. 4 Contributed percentage of the green sand casting parameter

S/N ratio (Larger the better)= $-10\log\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right]$

Table 8 Signal to Noise ratio of Grey relational grade

Expt. No.	Grey relational grade (γ_i)	S/N ratio
1	0.6863	-3.26914
2	0.4642	-6.66661
3	0.7088	-2.98892
4	0.5214	-5.65659
5	0.5597	-5.04148
6	0.5369	-5.40191
7	0.5358	-5.42040
8	0.4930	-6.14225
9	0.4682	-6.59127
10	0.5314	-5.49089
11	0.5575	-5.07450
12	0.4466	-7.00228
13	0.5309	-5.50005
14	0.4867	-6.25394
15	0.5946	-4.51583
16	0.5318	-5.48519
17	0.4215	-7.50383
18	0.4630	-6.68833

ANOVA has been performed on grey relational grade to obtain contribution of each process parameter affecting the quality characteristics of the green sand mould. Fig. 9 shows S/N ratio of the grey relational grade obtained for different process parameters. The S/N ratio of grey relational grade for each parameter is shown by vertical line. Basically, the larger the grey relation grade is, the closer will be the product quality to the ideal value. Thus, larger grey relational grade is desired for optimum quality. The S/N ratio values are found maximum at the levels of the parameters (A_2, B_3, C_3, and D_3) as the best values for getting maximum grain size and mechanical properties of sand casting process.

5. Effect of casting process parameters

he multi-quality characteristic called grey relational grade was found to be significantly affected by pouring temperature, Al-2.5Ti-0.5C, scrap, and Al-0.5Ni. Figure 5 shows the effects of casting process parameters on the multi-performance characteristics (the fluidity, micro-hardness, and macro-hardness) and the response graph of each level of the casting process parameters. The response surfaces are developed by using the response surface methodology referred by Montgomery [30]. The multi-quality characteristic called grey relational grade was found to be significantly affected by pouring temperature, Al-2.5Ti-0.5C, scrap, and Al-0.5Ni. Figure 5 shows the effects of casting process parameters on the multi-performance characteristics (the fluidity, micro-hardness, and macro-hardness) and the response graph of each level of the casting process parameters. The response surfaces are developed by using the response surface methodology referred by Montgomery [19]. Basically, the larger the grey relational grade, the better are the multi-quality characteristics. The greater values in Figure 5 give the larger grain size and mechanical properties of castings. Figure 5 shows the response surface of grey relational grade. It is clear from Fig. 6 that the pouring temperature and Al-2.5Ti-0.5C are the most significant factors that affect the grey relational grade. As the pouring temperature increases, considerable increment in grain size micro-hardness and macro-hardness which in turn increases grey relational grade or vice versa.

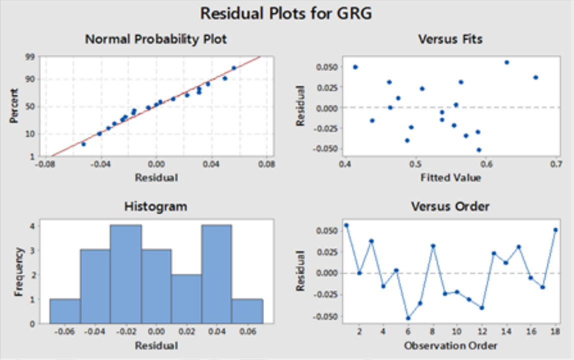

Fig. 5 Effect of casting parameters on the multi-performance characteristics

6. Conclusions

Based on the present investigation following conclusions were made.

1) It was found that the pouring temperature has the strongest influence among the other parameters used on the multi-quality characteristics.
2) Experimental results have shown clearly that the sand casting properties can be improved effectively through the proposed approach. As a result, optimization of the complicated multiple quality characteristics can be greatly simplified through this approach
3) According to the present analysis, pouring temperature is the most prominent parameter contributing 27.35%, followed by Al-2.5Ti-0.5C by 20.58 (wt. %), Al-RHA by 11.21%, and Molasses by 9.64%, whereas scrap and Al-Ni have no significant contribution the performance characteristics. The improvement in grey

relational grade for sand casting properties at optimum combination of parameters is 0.596, respectively

4) It is proposed that this method is an approach for optimization and control parameters analysis of the sand casting process parameters based on L_{18} orthogonal array design matrix table.

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