INFLUENCE OF SAND MOLDING PROCESS PARAMETERS ON PRODUCT QUALITY OF AL-SI ALLOY CASTING - AN ANOVA APPROACH

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ABSTRACT

Sand mold casting is an age old metal casting process. Even today, though there are many advanced techniques present to produce metal castings, sand molding remains one of the most widely used casting process because of its ability to produce low cost and wide variety of castings. Sand casting process involves many parameters which affect the quality of the produced castings. In this study, an attempt has been made to optimize the sand molding parameters, and to study the influence of these parameters on quality of Al-Si alloy castings. Taguchi's experimental design approach is adopted to achieve optimum level of parameters, and Analysis of Variance (ANOVA) technique is used to identify the significant factors and their percentage contribution for improved mechanical properties. Experimental results show that amount of clay and amount of moisture are the parameters making significant influence on mechanical properties of these castings. Based on optimum level of parameters, verification test is performed and the results are found to be in confidence level. Experimental results confirmed the validity of selected approach in enhancing and optimizing the sand mold casting process for aluminium alloys.

Keywords: Al-Si alloy, Analysis of Variance, Product quality, Sand casting, Taguchi design

I. INTRODUCTION

Aluminum is the third most abundant element in the earth's crust. After iron and steel, the most popular metal used is aluminium. It is widely used in transportation, defense, construction, aerospace, maritime, domestic, and general engineering purpose. This is because of its unusual combinations of properties such as light weight (high strength to weight ratio), resistance to corrosion, good cast-ability, good machinability, chemical resistance, excellent conductor of heat and electricity, etc. Pure aluminium is soft having comparatively poor casting features and little strength, that's why aluminium castings are prepared from aluminium alloys. The main alloying elements are silicon, copper, magnesium, zinc, etc. Fluidity of aluminium increases with silicon addition. Al-Si alloys have good casting and corrosion resistance properties. In transportation industry, more use of these alloys decreases weight of vehicle, improve its performance and reduces fuel consumption.

Sand mold casting is an important process for casting aluminium alloys. It is used to create castings of any shape and size. The process involves, melting a metal, pouring it into a previously prepared mold cavity formed out of natural or synthetic sand, allowing liquid metal to solidify, and breaking sand mold to get the castings. For every single casting new mold is to be prepared, quality of mold determines the quality of produced castings. For this reason aluminium foundries have to focus more on optimizing on sand molding process to improve the quality of products and reduce cost.

According to Taguchi, the key element for achieving high quality and low cost product is parameter design. Through parameter design optimal levels of process parameters are selected and these parameters should be controlled to improve the quality of both casting process and the product [1]. A number of automotive suppliers have achieved quality and cost improvement through Taguchi's robust design. These applications include improvement in metal casting, injection molding of plastic parts, etc. [2]. Taguchi has introduced several statistical tools and concepts of quality improvement that depend heavily on the statistical theory of experimental design [3]. To overcome the problems of defects, flaws and imperfections in castings, and improve the quality of products produced, optimization of process parameters for sand mold casting should be carried out [4].

In this study, the experiments are designed by selecting four parameters (sand grain size, amount of clay, amount of moisture and number of ramming) all at three levels. The required number of experiments under full factorial method was 3^4 = 81. Using Taguchi's L9 orthogonal array, the number of experiments are reduced to nine. All these nine experiments are performed to produce test castings which are then examined for improved mechanical properties – tensile strength and hardness.

The signal to noise (S/N) ratio for each parametric setting is computed. The optimal level of process parameters promotes highest S/N ratio [5]. Analysis of variance (ANOVA) on the collected data from the Taguchi design of experiments is used to select new parameter values to optimize the performance characteristic. The data from the arrays is analyzed by performing a visual analysis. ANOVA and Fisher's exact test (F-Test) is applied to find significant factors and test the level of significance. The percentage contribution of significant factors is also obtained.

II. LITERATURE REVIEW

Mekonnen Liben Nekere and Ajit Pal Singh [1] has examined optimal settings of two groups of aluminum blank sand casting processes. Single aluminum blank sand casting and double aluminum blanks sand casting for process robustness comparison. The results have shown that single aluminum blank sand casting process is more robust than double aluminum blank sand casting process. The experimental results confirmed the validity of used Taguchi robust design method for enhancing sand casting process and optimizing the sand casting parameters in aluminum blank casting process.

Lakshmanan Singaram [6] has studied the analysis of green sand process parameters strength, moisture content, permeability, mold hardness using Taguchi method and ANN Analysis. Outcome is optimized green sand process parameters which lead to improved process performance, reduced process variability and thus minimum casting defects.

Rasik A Upadhye and Dr. Ishwar P Keswani [7] has studied the sand casting process parameters of the castings manufactured in iron foundry by maximizing the signal to noise ratios and minimizing the noise factors using Taguchi method. The process parameters considered are moisture, sand particle size, green compression strength, mold hardness, permeability, pouring temperature, pouring time and pressure test. The results indicated that the selected process parameters significantly affect the casting defects in the foundry.

P. Senthil and *K. S. Amirthagadeswaran* [8] has investigated the influence of process parameters on mechanical properties of the castings prepared through squeeze casting process using Taguchi method. Experimental results showed that squeeze pressure, die preheating temperature and compression holding time were the parameters making the significant improvement in mechanical properties.

Jhon O. OJI et. al. [9] has investigated the effect of mold temperature and pouring temperatures on ultimate tensile strength of aluminum alloy sand castings. The result shows that mold temperature is the significant factors which influence the casting quality.

L. Ceschini et. al. [10] has investigated the relationships between ultimate tensile strength and micro structural parameters for the sand cast A357 aluminum alloy. Starting from the micro structural parameters and taking in to account the material hardness, a relationship able to predict the ultimate tensile strength of the alloy was found.

III. EXPERIMENTAL APPROACH

To find the optimum conditions of the control factors, Taguchi's robust experimental design methodology is used to design the experiments. This methodology is used by applying eight experimental steps that can be grouped into three major categories as follows [1, 2]:

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

Experimental data can also analyzed using Analysis of Variance (ANOVA) where the relative percentage contribution of all factors is determined by comparing with the relative variance. In ANOVA calculations, the degree of freedom for all factors is obtained first, the values of variance for all factors are then calculated and finally F-ratio and percentage contributions for the factors are calculated. The intention is to determine the significant control factors and their level of significance to optimize the process.

3.1 Sand Mold Casting Process and its Main Function

Initially, two solid square cross section wooden patterns are prepared with dimensions 3cm x 3cm x 16cm to make mold cavities in which molten metal is poured to produce castings which are used to prepare test specimens. Molding sand is prepared using silica sand as base sand, bentonite powder as clay or binder, and water as moisture. Nine molds are prepared by varying grain fineness of silica sand, amount of clay, amount of moisture and number of ramming, as per the experimental design. Molds are then dried in air to remove the moisture completely. Aluminium alloy LM25 (AlSi7Mg) is melted for pouring into the molds. Melting is done in lift out crucible type coke fired pit furnace.

After melting degassing is done using Hexa-chloro-ethane (C_2Cl_6) tablets which are added to the molten metal which liberates stable chlorine gas to flush out the dissolved hydrogen gas by creating partial pressure in molten metal. To protect the molten charge from getting oxidized, coveral-36 is used as a flux powder to cover the molten metal from atmospheric gases. Thermocouples with digital temperature indicator are used to measure the temperature of molten metal. All nine molds are poured to produce test castings. After solidification the molds are broken to obtain the castings. Finally machining operations are performed on CNC machine to prepare standard test specimen as per ASTM A370 standard, 12.5 mm round tension test specimen with 50 mm gauge length, for measuring tensile strength. Universal Testing Machine is used for measuring tensile strength and Dynamic Hardness Tester is used for measurement of Brinell Hardness.

3.2 Quality Characteristics and Objective Functions

To determine the effect each parameter has on the response, the signal-to-noise ratio, or the SN ratio, needs to be calculated for each experiment conducted. Taguchi defines it as three categories of quality characteristics which are: Lower-the-better, Larger-the-better and Nominal-the-best. As in this study, tensile strength and hardness are selected as response; both are larger-the-better type of quality characteristics. The objective function is to be maximized by using the S/N ratio: $S/N = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{{y_i}^2}\right)$ ------------ (1)

Where ‘n’ is trial number, ‘y’ is response and ‘i' is experiment number. After calculating the S/N ratio for each experiment, the average SN value is calculated for each factor and level.

3.3 Control Factors and Their Levels

In general, sand casting process involves many parameters such as type of sand, size of sand grain, clay type and amount, percentage of moisture, green compressive strength, shear strength, permeability, number of ramming, shatter index, mold type, mold hardness, pouring temperature, pouring time, pouring height, metal composition, metal fluidity, running and gating, risering and feeding, casting design, alloy type, and many more [4,7]. As this study aims to optimize sand molding process, four key sand molding parameters – sand grain size, amount of clay, amount of moisture and number of ramming are selected at three different levels as given in the *Table 1*, keeping other parameters constant.

Table 1: Control Factors with Levels

Control factor designation	Control factors	Levels		
		1	2	3
X_1	Sand grain size	40	55	70
X_2	Amount of clay (%)	6	9	12
X_3	Amount of moisture (%)	7	10	13
X_4	Number of ramming	2	3	4

3.4 Noise Factors and Testing Conditions

Number of noise factors affecting the casting process was identified from literature for sand mold casting process. Some of these factors are variation in humidity, pouring temperature, metal flow rate, ambient temperature and so forth. For this experiment the important noise factors considered were: pouring temperature, metal flow rate and humidity. To capture the effects of noise factors during the casting process, different sand mold castings were prepared and examined.

3.5 Matrix Experiment Design and Data Analysis Plan

The experiments are conducted by keeping four parameters at three levels; the number of experiments required was $3^4 = 81$ under full factorial method. Using Taguchi's orthogonal array table, for four parameters at three levels, L9 orthogonal array is selected. With this number of experiments is reduced to nine. These nine experiments are conducted in order to optimize the process parameters to achieve castings with less defects and improved mechanical properties.

The standard table of combinations for experiment for L9 orthogonal array is as given below.

Table 2: Standard L9 orthogonal array table

Experiment Run Order	Control Factors			
	X_1	X_2	X_3	X_4
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

3.6 Conducting Matrix Experiment

As per the nine rows of L9 standard orthogonal array table, nine experiments are conducted. To prevent the translation error, the table is translated incorporating level table to create experimental design sheet as shown in the *Table 3.* The responses of each experiment are tabulated in adjacent columns.

Table 3: Experimental Design Table and Responses

Experiment Run Order	Control factors (or) Process parameters				Responses	
	Sand Grain Size X_1	Amount of Clay (%) X_2	Amount of Moisture (%) X_3	Number of Ramming X_4	Tensile Strength (MPa) Y_{TS}	Hardness (BHN) Y_H
1	40	6	7	2	104.5	41
2	40	9	10	3	106.8	41
3	40	12	13	4	125.7	51
4	55	6	10	4	102.9	40
5	55	9	13	2	119.2	46
6	55	12	7	3	117.7	44
7	70	6	13	3	111.1	42

8	70	9	7	4	108.9	42
9	70	12	10	2	114.8	42

3.7 Analyzing Data, Determining Optimum Levels And Predicting Performance Under These Levels

For analysis of results obtained from the experiment, the SN ratios are to be calculated [2]. Test samples are prepared for each experiment, tensile strength and hardness tests are performed on each sample. The results obtained for tensile strength and hardness are listed under responses in *Table 3*. Based on these responses S/N ratio calculations and ANOVA calculations are carried out.

3.7.1 S/N Ratio Calculations [4, 11]

S/N ratio for tensile strength and hardness are calculated using 'larger-the-better' quality characteristics for each experiment run order by using expression (1) of Para 3.2, the calculated values are tabulated in the *Table 4* as shown below. The *Table 5* gives the calculated average S/N values for each factor and each level for both tensile strength and hardness.

Table 4: S/N ratio calculations

Experiment Run Order	S/N Ratio	
	Tensile strength	Hardness
1	40.38	32.25
2	40.57	32.25
3	41.98	34.15
4	40.24	32.04
5	41.52	33.25
6	41.41	32.86
7	40.91	32.46
8	40.74	32.46
9	41.19	32.86

Table 5: S/N ratio response table

	Tensile Strength				Hardness			
LEVEL	X_1	X_2	X_3	X_4	X_1	X_2	X_3	X_4
1	40.97	40.51	40.99	41.03	32.88	32.25	32.52	32.78
2	41.05	40.94	40.64	40.96	32.71	32.65	32.38	32.52
3	40.94	41.52	41.47	40.98	32.59	33.29	33.28	32.88
Max-Min	0.11	1.01	0.83	0.07	0.29	1.04	0.90	0.36
Rank	3	1	2	4	4	1	2	3
Optimum level	$X_{1,2}$	$X_{2,3}$	$X_{3,3}$	$X_{4,1}$	$X_{1,1}$	$X_{2,3}$	$X_{3,3}$	$X_{4,3}$

3.7.2 ANOVA Calculations

In order to find out the level of significance of control factors and their percentage contribution towards tensile strength and hardness in sand mold casting process, Analysis of Variance approach is followed and ANOVA calculations are made.

3.7.3 ANOVA Calculations for Tensile strength

ANOVA calculations are made using the experimental results data from *Table 3*. Sample calculation is presented below.

Number of experiments, N = 9

Total Degrees of Freedom (DOF) = N-1 = 9-1 = 8

Sum of the response, T = 1011.6

Correction Factor, C.F. = T^2/N = 113703.84

Total of response for factor X_1 at level 1, $X_{1,1}$ = 337

Similarly total response for all four factors at all three levels are calculated for both tensile strength and hardness and are tabulated in *Table 6*.

Table 6: Level totals table

Control factor designation	Control factors	Level Total for Tensile Strength			Level Total for Hardness		
		1	2	3	1	2	3
X_1	Sand grain size	337	339.8	334.8	133	130	128
X_2	Amount of clay	318.5	334.9	358.2	123	129	139
X_3	Amount of moisture	331.1	324.5	356	127	125	139
X_4	Number of ramming	338.5	335.6	337.5	131	127	133

S_T (Total Sum of square) $= \sum_{i=1}^{n} y_i^2 - CF \quad S_T = \sum_{i=1}^{n} y_i^2 - \frac{T^2}{N}$

Where 'i' is experiment run order number.

Total sum of square, S_T = 454.94

Number or repetitions of factor X_1 at level 1, $n_{X_{1,1}}$ = 3

Sum of squares of X_1, $S_{X1} = \frac{X_{1,1}^2}{n_{X_{1,1}}} + \frac{X_{1,2}^2}{n_{X_{1,2}}} + \frac{X_{1,3}^2}{n_{X_{1,3}}} - CF$ = 4.18

Similarly S_{X2}, S_{X3} and S_{X4} are calculated.

In this case, since there are no empty columns or repetitions, experimental and reputational error cannot be calculated. Pooling the smallest variance factors X_1 and X_4 would provide some information of error so that we could proceed with the construction of ANOVA Table.

Sum of square of pooled error, $S_e = S_{X1} + S_{X4}$ = 5.62

DOF of pooled error = DOF of X_1 + DOF of X_4 = 2 + 2 = 4

DOF of X_3 = 2

Variance of X_3, $V_{X3} = \frac{S_{X3}}{\text{DOF of X3}}$ = 132.66

Similarly V_{X2}, V_{X1} and V_{X4} are calculated.

Variance of error, $V_e = \frac{S_e}{DOF\ of\ error}$ = 1.40

Pure variation of X_2, $S'_{X2} = S_{X2} - (DOF\ of\ X2 * V_e)$ = 262.52

Similarly S'_{X3} is calculated.

Pure variation of pooled error, $S'_e = S_e + [(DOF\ of\ Total - DOF\ of\ error) * V_e]$ = 11.22

Percentage contribution of factor X_2, $P_{X2}\% = \left(\frac{S'_{X2}}{S_T}\right) * 100$ = 57.70%

Percentage contribution of pooled error, $P_e\% = \left(\frac{S'_e}{S_T}\right) * 100$ = 2.46

Similarly ANOVA for hardness is calculated.

Table 13: ANOVA table for tensile strength

Source	Pool	S	DOF	Variance	F-ratio	S'	P%
X_1	yes	4.18	2	2.09	-	-	-
X_2		265.32	2	132.66	94.75	262.52	57.70
X_3		183.98	2	91.99	65.70	181.18	39.82
X_4	yes	1.44	2	0.72	-	-	-
Pooled error		5.62	4	1.40	1.00	11.22	2.46
Total		454.92				454.92	100.00

From the ANOVA table for tensile strength, F-ratio for amount of clay and amount of moisture is greater than F critical value, which is 18 at 0.01 level of significance, this makes them the significant factors.

Table 14: ANOVA table for hardness

Source	Pool	S	DOF	Variance	F-ratio	S'	P%
X_1	yes	4.23	2	2.11	-	-	-
X_2		43.56	2	21.78	8.34	38.34	41.56
X_3		38.23	2	19.11	7.32	33.01	35.79
X_4	yes	6.23	2	3.11	-	-	-
Pooled error		10.46	4	2.61	1.00	20.9	22.66
Total		92.25				92.25	100.00

From the ANOVA table for hardness, F-ratio for amount of clay and amount of moisture is greater than F critical value, which is 6.94 at 0.05 level of significance, this also makes them the significant factors.

3.8 Verification Test

Based on optimum level of process parameters, verification test is performed; the results obtained are:
Tensile strength: 130 MPa, and Hardness: 53 BHN.

IV. RESULTS AND DISCUSSIONS

From the above experimentation, it is observed that amount of clay and amount of moisture are the significant factors which are affecting tensile strength and hardness of aluminum alloy sand mold castings.

Increase in the amount of clay decreases permeability, which increases porosity in castings hence reducing mechanical properties. If amount of clay is decreased, mold hardness, shatter index and green compressive strength will also decrease which decreases the quality of the sand mold. Therefore optimum amount of clay for making a sand mold is to be selected.

Increase in the amount of moisture will also decrease permeability which affects the quality of produced castings. If more amount of moisture present in sand mold, it creates more amount gases during pouring which in turn results in casting defects like blowholes, open holes, porosities, etc. Hence optimum amount of moisture is to be used while making a sand mold.

From S/N ratio response table, *Table 5*, it is found that the optimum level of significant parameters is 12% amount of clay and 13% amount of moisture.

Verification test conducted based on optimum level of process parameters shows that the values of tensile strength and hardness are 130 M Pa and 53 BHN respectively. These values were found to be in confidence level.

From ANOVA tables, it is observed that amount of clay (X_2) and amount of moisture (X_3) are the factors contributing 57.70% and 39.82% for tensile strength, 41.56% and 35.79% for hardness respectively; these are represented in the chart below.

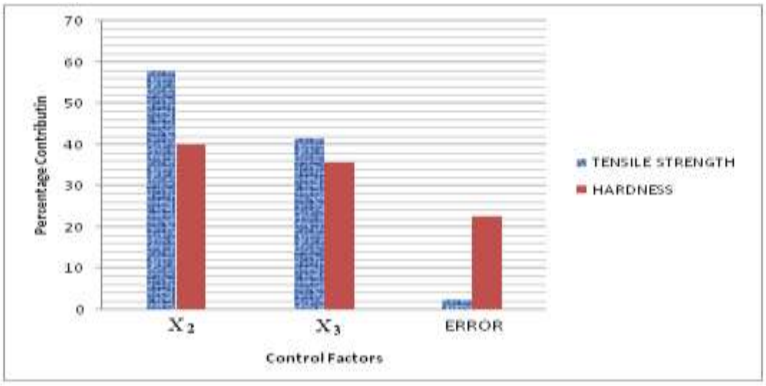

Figure 1: Bar chart of percentage contribution

V. CONCLUSIONS

On the basis of experiments conducted and analysis carried out in this study, many conclusions can be drawn; few of them are mentioned as follows:

- Study shows that this approach can be effectively applied in foundry shops for deciding optimum setting of process parameters to improve the quality of the castings produced.
- Results indicated that the selected process parameters are significantly affecting the selected mechanical properties.
- It is observed that amount of clay and amount of moisture are the significant control factors from among the selected factors.
- Amount of clay is the major contributing factor for the improvement of tensile strength and hardness of LM25 alloy casting.
- It is also observed that amount of clay and amount of moisture are the factors contributing 57.70% and 39.82% for tensile strength, 41.56% and 35.79% for hardness respectively.
- Verification test conducted based on optimum level of process parameters shows the increase in values of both tensile strength and hardness. Work is in progress to adopt ANOVA approach to study the influence of

other parameters such as melting and gating design and include other mechanical properties to optimize the process for improving the quality of Al-alloy castings.

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