PRODUCTIVITY IMPROVEMENT IN A NON-FERROUS FOUNDRY THROUGH DESIGN OF EXPERIMENTS APPROACH

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Abstract-- Production of casting involves various processes like pattern making, moulding, core making and melting etc. It is very difficult to produce defect free castings. A defect may be the result of a single cause or a combination of causes. The castings may have one or more defects and due to which they get rejected. These defects can be minimized by taking correct remedial actions in the tooling like pattern, core box and foundry processes like moulding, core making and melting. However, with all the corrective measures, the process variations still lead to rejection of castings due to defects. This project focuses on the empirical application of DoE and mathematical models to reduce casting defects and rejections of non- ferrous castings within a pump manufacturing company. The castings are produced in a medium scale foundry using green sand process in machine moulding. The root cause for this major defect was identified through defect diagnostic study approach. This study followed the Design of Experiments (DoE) methodology and provided solution by optimizing the process parameters. Finally, by implementing the optimized process parameters the rejection rate is minimized from 6.40% to 4.99%.

***Keywords: Casting defect analysis, DoE, Taguchi method, Non-ferrous castings, Rejection minimization, ANOVA analysis, process parameter control*.**

I. INTRODUCTION

The Casting is a process which carries risk of failure occurrence during all the process of accomplishment of the finished product. Hence necessary action should be taken while manufacturing of cast product so that defect free parts are obtained. Mostly casting defects are concerned with process parameters. Hence it is needed to control the process parameter to achieve zero defect parts. For controlling process parameter, one must have knowledge about effect of process parameter on casting and their influence on defect. In order to obtain this all knowledge about casting defect, their causes, and defect remedies it is needed analyse casting defects. Casting defect analysis is the process of finding root causes of occurrence of defects in the rejection of casting and taking necessary step to reduce the defects and to improve the casting yield. In this study paper an attempt has been made to provide all casting related defect with their causes and remedies. During the process of casting, there is always a chance where defect will occur. Minor defect can be adjusted easily but high rejected rates could lead to significant change at high cost. Therefore, it is essential for the casting manufacturer to have knowledge on the type of defect and be able to identify the exact root cause, and their remedies.

Mostly casting defects are concerned with process parameters such as sand moisture, permeability, pouring temperature etc. Hence it is obvious we need to control the process parameters to achieve zero defect parts. For controlling process parameters, it is essential have knowledge about effect of process parameters on casting and their influence on defect.

II. LITERATURE SURVEY

In order to reduce the rejection rate of castings, an in depth literature review and analysis was carried out for rejection control of non-ferrous castings in foundry using DoE tools and mathematical models and also gone through various research papers which gives solutions to solve the major defects of non-ferrous castings by controlling process parameters during casting manufacturing.

Narayanswamy and Natrajan [1] reviewed various casting defects. They categorise defects into filling related defects (FRD), shape related defects (SRD), Thermal defects (TD) and defects by Appearance. The monthly percentage of rejection due to these defects is varying from 13.86 % to 15.01 %. The filling related defects are further classified as sand inclusion, rough surface, scabbing, blow holes, chill blow, clay ball hole, sand fusion, and pin holes. Sand related defects are also further classified as mould lift, mould broken, and shift, leakage. The defects by appearance are categorized as DBS blast core missing, swelling, and no core. Out of these defects the filling related defects are to be given importance for the analysis and it is mainly due to the quality of sand. The shape related defects, defects by appearance and thermal defects are due to various factors in mould making process and melting process. Using the modern method and suitable techniques, it is really a boon for the foundry sector to produce quality casting to satisfy the customer requirement. They concluded that quality of castings depends on quality of sand, method of operation, quality of molten metal and environmental conditions etc. Kinagi and Dr.Mench [5] analysed casting defects like cold shut and blow holes by combining tools of design of experiments and FMEA techniques. Defect analysis is carried using FMEA tool and Pareto analysis to know potential causes of failure and their effects along with correct actions to improve quality strength and productivity. Their main objective is to optimize sand casting process parameter using DOE method through Taguchi method. Taguchi based L9 orthogonal array was used for experimental purpose and analysis was carried out using Minitab software for analysis of mean (ANOM) plot. The optimized levels of selected process parameters obtained by Taguchi method pouring temperature (13800c&14400c), inoculants (0.3), moisture-content (3.3), sand-binder ratio (60:1).

C.C Tai and J.C Lin [11] (1996) optimized the techniques used to design a runner in die casting process. The entire process was mathematically modelled using Abductive network technique. This helped them to optimize the runner design in the making stage by ruling out the various discrepancies in the system in the development stage itself.

Mekonnen Liben Nekere and Ajit Pal Singh [13] (2012) conducted a study on various optimization techniques used for Aluminium blank sand casting process. During their study they came across Design of Experiments (DOE) Taguchi's technique which helped them to find out major contributing factors in the die casting process. They carried out experimental runs on two batches of blanks of aluminium casting which indicated the major factors responsible such as grain size, clay content, moisture content, ramming, sprue size, riser size, and diameter to thickness (D/t) ratio of the blank. An orthogonal array was constructed for the seven factors identified and performed eighteen sets of experiments to generate the required data. A statistical analysis of variance (ANOVA) was also performed to see which process parameters are statistically significant. They verified the readings by performing a verification experiment in which the new data proved to be promising and hence the sand casting process was enhanced by Taguchi robust design method.

III. METHODOLOGY

The following methodology is adopted to meet the desired output of this work. It is shown in Fig 1 in the form of flow chart. The existing process method is studied, and trials performed in foundry which producing non-ferrous casting components. It was identified that the part "Segment holder 6" has the highest value in rejections (6.40 %). The analysis began with month wise rejections, weight wise rejections, defect wise rejections etc., Quality tools such as cause and effect diagram, pareto diagrams are used for the analysis. The study concluded that air holes / blow holes are the most important defects that caused highest rejection rate. Secondly, three process parameters are identified which are influencing air holes /blow holes defects. The parameters are listed below.

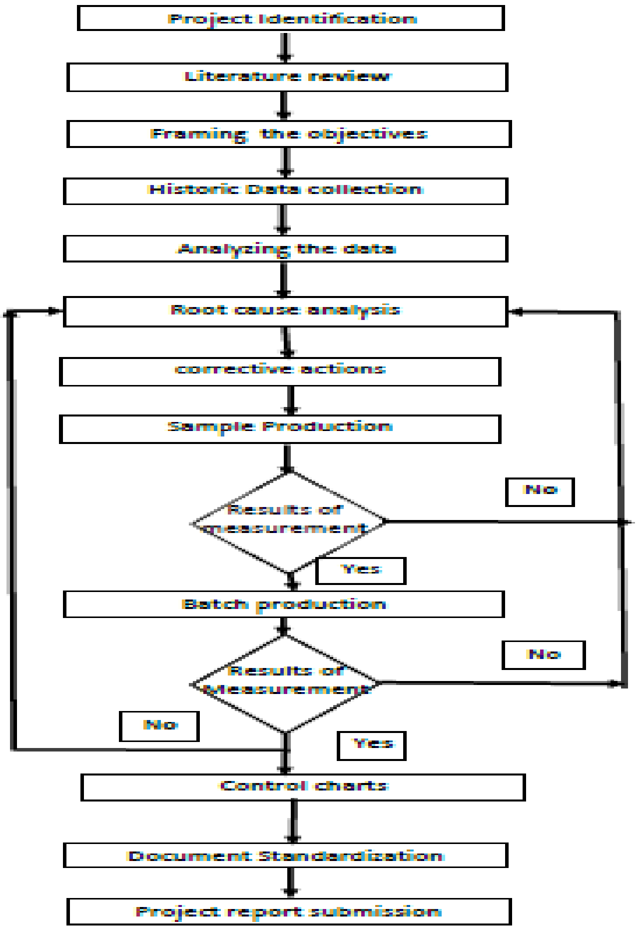

Fig 1. Flow chart of Methodology

1. Pouring temperature
2. Permeability
3. Sand moisture

The foundry used process parameters in a range of pouring temperature (1040o C to 1070o C), Permeability (number) (80 to 90) and sand moisture (3.3% to 3.6%). These process parameters are optimized by using DoE tools. Taguchi method and ANOVA are used for optimization and the results are applied into the process and number of trails have been conducted. Finally, the results of trials have been compared with the older rejection statics and the improvements were evident.

IV. ANALYSIS OF DATA

The following Table1 was made to explain the components which we rejected as casting defects. All data gathered from the industry for a period of 6 months.

Table 1. Analysis of Rejection Data

Month	Machined Qty	Air Holes	Blow Holes	Mould Broken	Sand / Slag Inclusion	Mismatch h/runout	Unwash	Porosity
Jan-19	35493	1339	1145	391	356	111	32	56
Feb19	62864	1092	994	445	334	398	32	15
Mar19	61612	1175	1355	107	373	87	141	37
Apr19	36262	891	1063	82	178	138	50	39
May19	50464	1531	1341	164	476	92	134	69
Jun-19	48980	1232	904	116	580	254	281	200

The rejected castings were categorized for various foundry defects such as Airholes, mould breakage, sand inclusion, blow holes, porosity and etc.In order to understand clearly due to which defects the castings are rejected in more quantity.

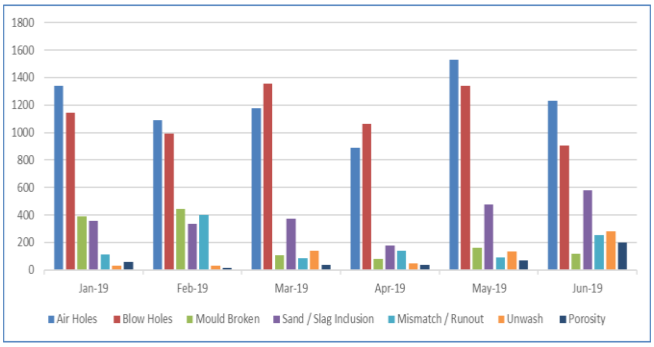

Fig 2. Bar chart showing the nature of defects Vs quantity

These data are graphically demonstrated in Fig 2. From the graph it is known that the major reasons for rejections were due to air holes and blow holes. This data analysis helped to focus on the possible causes for the air holes and blow hole defects so that the rejection can be minimized.

4.1 Weight Wise Rejection Components

The rejected quantity again analysed on the weight of the components which were rejected during a period of 6 months. This analysis was made to focus on the economic loss to the foundry due to the rejections. Fig 3 shows the pareto diagram of the analysis of weight wise rejection details.

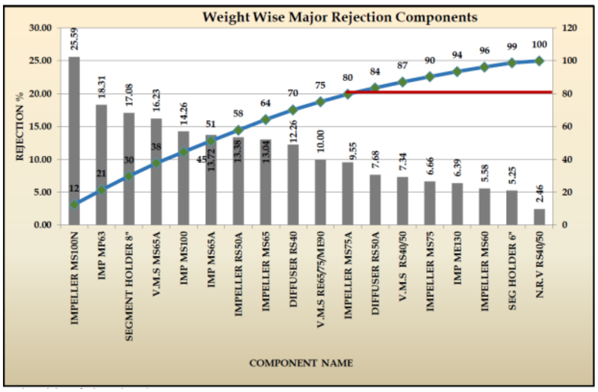

Fig 3. Pareto diagram showing contribution of rejected parts based on weight.

On analysis it is found that 3 different part codes have the major rejections viz Impller, Imp MP63 and Segment holder 8” based on the pareto 80-20 rule. Hence it is evident that when these parts are produced as per the product quality requirments, the rejection rate can be brought down to a maximum extent.

4.2 Repeated rejections

Fig 4 shows the analysis of repeated components that were rejected due to the same defect. This analysis was made to investigate critically on which defect that cause more rejection on a particular product. The details are shown in fig 4. Hence, it what observed that the component “Segment holder 8” was getting rejected repeatedly for the same defect.

By comparing all the different analysis results it was obvious that if the quality of “Segment holder 8” is improved as per the product specification and requirements, the rejection rate would be drastically reduced and thereby increase the productivity in the foundry plant. This will also reduce the production cost and lead to increase in profit.

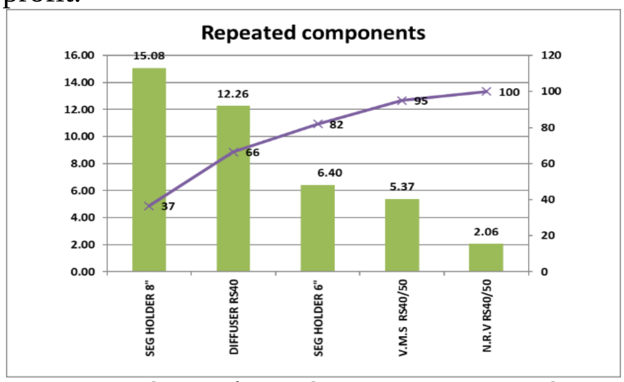

Fig 4. Pareto diagram of repeated component rejection over the period.

***4.3** Mathematical model approach*

Foundry industries suffer from poor quality and productivity due to involvement of number of process parameters in casting process. Even in a completely controlled process, defects in casting are observed. Thus, casting manufacturing is process of uncertainty which challenges explanation about the cause of casting defects. Casting defects analysis is the process of finding the root cause of occurrence of defects in the rejection of casting and taking necessary steps to reduce the defects and to improve the casting yield. Techniques like cause-effect diagrams, Design of Experiments (DoE), casting simulation, if-then rules (expert systems) and artificial neural networks (ANN) are used by various researchers for analysis of casting defects.

In this paper, a method of casting defects analysis is proposed which is combination of DoE (Taguchi method) and ANOVA technique and discussed in the following sections.

The proposed method of casting defect analysis, the DoE (Taguchi method) is used for analysis of sand and mould related defects such as air holes, sand drop, bad mould, blow holes, cuts and washes, etc. The ANOVA on the other hand verifies the experimented results and thus provides a great deal of validation.

***4.4** Static problem*

A process to be optimized has several control factors which directly decide the target or desired value of the output. The optimization then involves determining the best control factor levels so that the output is at the target value. Such a problem is called as a static problem.

***4.5** Dynamic problem*

If the product to be optimized has a signal input that directly decides the output, the optimization involves determining the best control factor levels so that the input signal / output ratio is closest to the desired relationship. Such a problem is called as a dynamic problem.

***4.6** S/N Ratio logic*

There are 3 Signal-to-Noise ratios of common interest for optimization of Static Problems

Smaller the Better

n = -10 Log10 [mean of sum of squares of measured data.

This is usually the chosen S/N ratio for all undesirable characteristics like defects etc.

a. *Larger the Better*

n = -10 Log10 [mean of sum squares of reciprocal of measured data]

b. *Nominal the Best*

n = 10 Log10 [square of mean/variance]

4.7 *Analysis of Varience (ANOVA)*

Analysis of variance (ANOVA) is a collection of statistical models used to analyse the differences between group means and their associated procedures. In its simplest form, ANOVA provides a statistical test of whether the means of several groups are equal. The ANOVA sequence is shown in fig 4. The ANOVA is dealt with the following information:

- Degrees of freedom
- The Sum of squares
- The Mean Square
- The F ratio

4.8 *Orthogonal Array*

With the use of Taguchi's method, the blend of experimental design together with optimum control parameters helps in obtaining the best results Orthogonal arrays (OA) gives a set of well poised experiments and signal-to noise ratios (S/N), which are log functions of output, commonly known as objective functions. Optimization of objective function under a set of the constraints helps in optimization of process parameters.

The standard orthogonal array shown in Table 2 based on process parameter (3) and the number of levels (3) has been chosen as L9 with the help of degrees of freedom. The number of degrees of freedom was 8 so the nearest array with respect to the given factor was L9.

Table 2. Orthogonal Array

POURING TEMP	PERMEABILITY	SAND MOISTURE
1	1	1
1	2	2
1	3	3
2	1	2
2	2	3
2	3	1
3	1	3
3	2	1
3	3	2

V. results and discussions

The Taguchi Method is used to optimize the results obtained from each trial. L9 orthogonal array is used for the trial purpose. The response of the S/N Ratio, contribution of different process parameters and relation between S/N ratio and the levels of different process parameters is studied and analysed to obtain optimum process parameters.

There are three categories of quality characteristics in the analysis of S/N ratio, i.e. smaller- the-better, larger-the-better, nominal-the-best.

The response table for Signal to Noise Ratios and response for the means is shown in fig 5. These values are computed by the Minitab17 software. As the main aim of the study was to reduce the casting defects for which the ideal value is zero, the S/N ratio for each level of process parameter has been computed by using a quality characteristic smaller-the- better. As the main aim of the study was to reduce the casting defects for which the ideal value is zero, the S/N ratio for each level of process parameter has been computed by using a quality characteristic smaller-the- better.

Response Table for Signal to Noise Ratios

Smaller is better

Level	pouring temp	permeability	sand moisture
1	-16.03	-16.69	-16.56
2	-16.86	-16.60	-16.60
3	-16.73	-16.34	-16.46
Delta	0.83	0.35	0.14
Rank	1	2	3

Response Table for Means

Level	pouring temp	permeability	sand moisture
1	6.333	6.833	6.733
2	6.967	6.767	6.767
3	6.867	6.567	6.667
Delta	0.633	0.267	0.100
Rank	1	2	3

Fig 5. Taguchi analysis res1 Vs Pouring temperature, Permeability, sand moisture.

The main effect plot for means based on the process parameters is shown in Fig.6. The trend curve clearly shows that pouring temperature seems to affect the rejection rate because the line is not horizontal. 1055deg C has a higher rejection rate mean than the rest of the temperature values. Permeability also affects the rejection rate. Permeability of 80(number) had a higher mean of means than the other two values. Similarly, the sand moisture also affects the rejection rate as the curve is not horizontal. However, there is no significant effect in rejection rate due to sand moisture. Among the three values of sand moisture, 3.4% has a higher mean of means than 3.3% and 3.5%.

The ANOVA decomposes the variance into the following components sums of squares.

- Total sum of squares. The degrees of freedom for this entry is the number of observations minus one.
- Sum of squares for each of the factors. The degrees of freedom for these entries are the number of levels for the factor minus one. The mean square is the sum of squares divided by the number of degrees of freedom.
- Residual sum of squares. The degrees of freedom are the total degrees of freedom minus the sum of the factor degrees of freedom. The mean square is the sum of squares divided by the number of degrees of freedom.

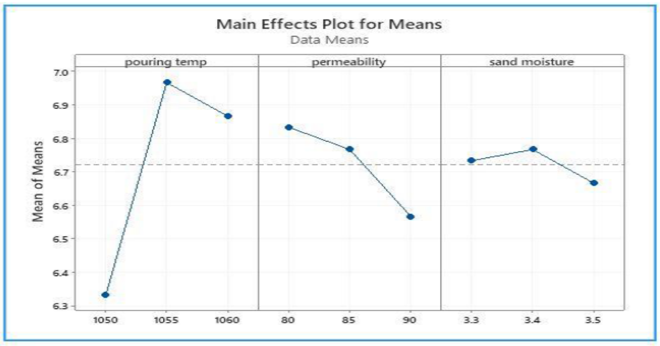

Fig 6. Main effects plot for means

The Fig 7 shows the Anova calculations and results for finding out the R value. The analysis of variance summarizes how much of the variance in the data (total sum of squares) is accounted for by the factor effects (factor sum of squares) and how much is due to random error (residual sum of squares). Ideally most of the variance to be explained by the factor effects. The ANOVA table provides a formal *F* test for the factor effects. To test the overall effect for this work, the following hypotheses is used.

Method

Factor coding	(-1, 0, +1)

Factor Information

Factor	Type	Levels	Values
pouring temp	Fixed	3	1050, 1055, 1060
permeability	Fixed	3	80, 85, 90
sand moisture	Fixed	3	3.3, 3.4, 3.5

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
pouring temp	2	0.695556	0.347778	78.25	0.013
permeability	2	0.115556	0.057778	13.00	0.071
sand moisture	2	0.015556	0.007778	1.75	0.364
Error	2	0.008889	0.004444		
Total	8	0.835556			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0666667	98.94%	95.74%	78.46%

Fig 7. Anova results

H_0: All individual batch means are equal.
H_a: At least one batch mean is not equal to the others.

The *F* statistic is the mean square for the factor divided by the residual mean square. This statistic follows a F distribution with (*k*-1) and (*N*-*k*) degrees of freedom where *k* is the number of levels for the given factor. Here, it is observed that the "Pouring temperature " effect dominates the rate of rejection. For our calculations the critical *F* value (upper tail) for $\alpha = 0.05$, $(k-1) = 1$, and $(N-k) = 475$ is 3.86111. Thus, "permeability" and "sand moisture" are significant at the 5 % level.

A. *Co-efficent factors from Anova*

The coefficient factors are computed in Anova tool using Minitab17. The calculation outputs are shown in Fig 8. Very high or a very low (negative) Z scores, associated with very small p-values, are found in the tails of the normal distribution. When it is performed for a feature pattern analysis and it yields small p-values and either a very high or a very low (negative) Z score, this indicates it is very unlikely that the observed pattern is some version of the theoretical spatial random pattern represented by your null hypothesis.

In order to reject the null hypothesis, a subjective judgment is made with regard to the degree of risk. This degree of risk is often given in terms of critical values and/or confidence levels.

The critical Z score values when using a 95% confidence level are -1.96 and +1.96 standard deviations. The p-value associated with a 95% confidence level is 0.05. If the Z score is between -1.96 and +1.96, the p-value was larger than 0.05, this was null hypothesis. A key idea here is that the values in the middle of the normal distribution scores represent the expected outcome.

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	6.7222	0.0222	302.50	0.000	
pouring temp					
1050	-0.3889	0.0314	-12.37	0.006	1.33
1055	0.2444	0.0314	7.78	0.016	1.33
permeability					
80	0.1111	0.0314	3.54	0.072	1.33
85	0.0444	0.0314	1.41	0.293	1.33
sand moisture					
3.3	0.0111	0.0314	0.35	0.757	1.33
3.4	0.0444	0.0314	1.41	0.293	1.33

Regression Equation

res-1 = 6.7222 - 0.3889 pouring temp_1050 + 0.2444 pouring temp_1055
+ 0.1444 pouring temp_1060 + 0.1111 permeability_80 + 0.0444 permeability_85
- 0.1556 permeability_90 + 0.0111 sand moisture_3.3 + 0.0444 sand moisture_3.4
- 0.0556 sand moisture_3.5

Factor Information

Factor	Type	Levels	Values
pouring temp	Random	3	1050, 1055, 1060
permeability	Random	3	80, 85, 90
sand moisture	Random	3	3.3, 3.4, 3.5
SNRA1	Random	7	-17.0252, -16.9020, -16.7770, -16.6502, -16.2583, -16.1236, -15.7066
MEAN1_1	Random	7	6.1, 6.4, 6.5, 6.8, 6.9, 7.0, 7.1

Variance Components

Source	Var	% of Total	SE Var	Z-Value	P-Value
pouring temp	0.114078	82.03%	0.115957	0.983796	0.163
permeability	0.018993	13.66%	0.021307	0.891411	0.186
sand moisture	0.000914	0.66%	0.003172	0.288022	0.387
SNRA1	0.002774	1.99%	0.010343	0.268244	0.394
MEAN1_1	0.000000	0.00%	*	*	*
Error	0.002312	1.66%	0.007411	0.312013	0.378
Total	0.139072				

-2 Log likelihood = -3.533822

Model Summary

S	R-sq	R-sq(adj)	AICc	BIC
0.0480856	99.49%	99.49%	92.47	8.94

Coefficients

Term	Coef	SE Coef	DF	T-Value	P-Value
Constant	6.724354	0.213682	2.66	31.468993	0.000

Fig 8. Coefficient factors from Anova output

A main effects plot is a plot of the mean response values at each level of a design parameter or process variable. This can be used to plot to compare the relative strength of the effects of various factors. The sign and magnitude of a main effect is given below.

- The sign of a main effect indicates the direction of the effect, that is, whether the average response value increases or decreases.
- The magnitude indicates the strength of the effect.

If the effect of a design or process parameter is positive, it implies that the average response is higher at a high level rather than a low level of the parameter setting. In contrast, if the effect is negative, it means that the average response at the low-level setting of the parameter is more than at the high level. Fig 9 illustrates the main effect of pouring temperature, permeability and sand moisture on the airholes blow holes defect on the castings.

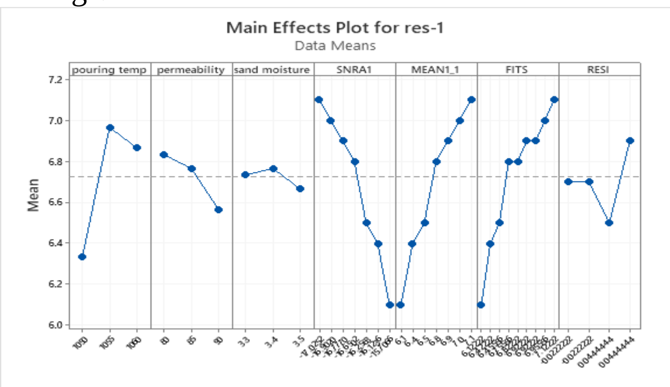

Fig 9. Main effects Plot for res-1

The effect of a process or design parameter (or factor) can be mathematically calculated. An interactions plot is a powerful graphical tool which plots the mean response of two factors at all possible combinations of their settings. If the lines are parallel, this indicates that there is an interaction between the factors. Non-parallel lines are an indication of the presence of interaction between the factors. S/N ratio is used as measurable value instead of standard deviation since, as the mean decreases, the standard deviation also deceases and vice versa. In other words, the standard deviation cannot be minimized first and the mean brought to the target. In practice, the target mean value may change during the process development.

a. Verification of Taguchi method

After conducting the initial nine experiments (each in triplicate trial is 9X3=27), liner regression models are developed for “Segment holder 8”in order to predict the optimized parameters for Pouring temperature, Permeability and sand moisture. To verify the accuracy of such prediction of process parameter values, the experimental trials were conducted. The trial results with S/N ratio is shown in Table 3. A combination of experimental values is made with predicted values it is observed that regression model based on initial nine experiments are not very well but reasonably well. Based on these experimental results, the optimized process parameters were recommended during regular production.

Table 3. Trials results with S/N ratio

Trial	Percentage of defects in experiment				S/N ratio	Average
	1	2	3	Total		
1	6.5	7.3	6.9	18.7	-17.9	6.23
2	7.5	3.8	7.3	14.6	-13.8	4.87
3	7.3	7.6	7.6	20.5	-16.7	6.83
4	3.5	4.2	4	11.7	-11.8	3.9
5	6.3	4.9	7.1	18.4	-17.7	6.12
6	7.4	6.7	6	20.1	-16.5	6.7
7	7.1	7	7.8	17.9	-17.5	7.96
8	3.3	7.3	4.5	17.2	-14.1	7.05
9	3.5	7.6	1.5	10.6	-11.2	3.54

b. Final results and comparision

With the results of verifications and experimental trial results the foundry industry has implemented maintaining of optimized process parameters and the results are provided in the above Table 4 with the comparison of previous data. The segment holder 8” part average rejection rate (with the data analysis for 6 months) was 6.41%. After implementation of optimized process parameters three months data were taken and the average rejection was 4.99%. Thus, there was a reduction in rejection of 1.41%.

With respect to the quantity, the average rejection before the study was 895 and after the implementation of optimized parameters the average rejection reduced to 611. Thus, as an average there are 284 parts are saved from rejection every month.

With regard to the weight, before the study the average weight of rejected parts was 984.5 kg and after the new optimized process the weight of rejected parts reduced to 672.1 kg.

Table 4. Trls results with S/N ratio

S. No	Part name	Wt. in kg	BEFORE EXPERIMENT					AFTER EXPERIMENT				
			Month	Produced Qty	Rej.Qty	Rej.Wt in Kg	% Rej	Month	Produced Qty	Rej.Qty	Rej.Wt in Kg	% Rej
1	"Segment holder 8	1.1	Jan-19	8909	825	907.5	9.26	Dec-20	12325	679	746.9	5.51
			Feb-19	20302	1578	1735.8	7.97	Jan-20	14656	706	776.6	4.82
			Mar-19	18550	639	703.9	3.44	Feb-20	9748	447	491.7	4.59
			Apr-19	10632	722	794.2	6.79					
			May-19	12460	920	1012	7.38					
			Jun-19	13062	686	754.6	5.25					
			Average	13986	895	984.5	**6.4**	Average	12243	611	335.9	**4.99**

VI. CONCLUSIONS

Application of DoE techniques in foundry industry creates new chances for achieving a better quality castings and higher production effectiveness. By means of DoE customization of parameters depending on pouring temperature, sand permeability and sand moisture the rejections can be minimized.

Taguchi's method for optimization is simple and effective in terms of time and cost of overall manufacturing operation performed. It improves the overall quality of product and helps in development at all stages of product life cycle starting from design to finishing of product therefore it helps in reducing the cost at a larger extent with the help of smaller resources.

The analysis proves that by improving the quality by Taguchi's method of parameter design at lowest possible cost, it is possible to identify the optimum levels of signal factors at which the noise factors effect on the response parameter is less.

The proximity of the results of predictions based on calculated S/N ratios and experimental value show that the Taguchi's method can be used successfully for both optimization and prediction in cast iron sand casting.

Analysis of variance (ANOVA) is used to verify if the means of all the three process parameters that are significantly different from each other. It was verified with ANOVA that the impact of one or more factors by comparing the means of different samples.

The rate of rejection is gradually reduced when the pouring temperature is getting low and permeability is increased inversely.

It was evident that the rejection rate of Segmental holder 8" reduced from 6.41%. to 4.99% after implementation of optimized process parameters. Foundry has a saving of 1.41%. of their production through process parameters optimization.

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