Effect of Taguchi Counter Plot Function with Process Window Approach Validation in the Sand Casting Process

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Abstract - *This paper explains and illustrates the effect of the counterplot function with the Taguchi method to optimize the sand casting process operations using Process Window Approach (PWA) validation. The focus of this research is to minimize the defects in the sand casting process by analyzing the Taguchi method optimization with Process Window Approach. The Taguchi L27 orthogonal array (OA) with three-level is used for the study. The critical process parameters and the effect of counterplot interactions are analysed with the help of Taguchi's Method of experimental design. Subsequently, the significant parameters are determined by using ANOVA and the identified optimum levels of parameters are compared with PWA optimization validation to make the analysis more precise and cost cost-effective. The result shows that the identified process parameters significantly control and reduce the defects and improve the efficiency of the cast iron flywheel manufacturing process. The confirmation experiments at the optimal levels identified using Taguchi with counter plot analysis and Process Window Approach validation shows that the identified parameters can be significantly improved to achieve more desirable results in minimizing defects.*

Keywords; *Taguchi, Sand casting process, Process window approach, validation, optimisation, Process capability, orthogonal array*

Introduction

The green sand mould casting is a predictable process with several process parameters contributing to the various Casting Quality features of the product. The quality of green sand in the mould is a significant phenomenon in which parameters are technically controllable or not technically controllable based on responding nature. A large number of experimental

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investigations into the Sand Casting process and its Parameters with Casting Quality have been carried out by researchers over the past few decades (ASM International Committee, 1990). The principle of process improvement is to get better performance characteristics of the process related to customer needs and expectations. It can be achieved through optimal experimentation and the aim is to reduce variation in the process. The loss function quantifies the design factor that influences the average variation of performance of the process and properly adjusting the factors, the variations of the process are reduced, thereby the losses can be minimized (Taguchi.,1993). (Masters et al., 1999) introduced several new statistical tools and concepts in the quality improvement industry and variation in quality caused by uncontrollable process variables is minimized in the foundry (Ghani., 2002 and Osma et al., 2009). Whenever a defect occurs due to a single cause or a combination of causes in casting sand exact identification of the causes of the defect is difficult due to the involvement of various factors which include Technical Factors like Process Design, Process Flow, Pattern Shop, Sand Preparation, Core Making and Melting etc as well as Human Factors (Sushil Kumar et al., 2010). In the present competitive environment, the trial and error approach practices moved away to obtain optimal settings of Green Sand Casting Parameters by using the Taguchi Method (Guharaja et al., 2006 and kumaravadivel et al., 2012). (Jeyapaul et al., 2004 and Noorul haq et al., 2009) used the Taguchi concept to optimize the Sand Casting parameters and stated that control factors are the selected independent variables of the experiment, which have different effects on the response variables when adjusted to different levels. An experimental investigation of process parameter effects was presented to determine the optimum configuration of design parameters for performance, quality and cost. (Kumaravadivel et al., 2012) describes Taguchi’s design of experiments method in sand casting process parameters. (Kumaravadivel et al., 2013) analyzed several critical process parameters and their interactions with the help of Taguchi and use the process window approach more precise and cost-effective. (Xuejun Liu et al., 2020) analyzed the optimization problem is subsequently formulated using desirability and counter flow function-based optimization method, and the objective function is estimated using Taguchi. (Kinsman Malikongwa et al., 2021) analyzed Taguchi design of experiments (DoE) is employed to determine appropriate laser cladding (LC) parameters for optimizing microstructural and anti-wear properties of Tribology (T-800) coatings using co-efficient of friction and counter flow function analysis. The settings of parameters are determined by using the Taguchi experimental design method and the level of importance of the parameters on the casting defects is determined using the analysis of variance(ANOVA) and analysis of signal-to-noise (S/N) ratio. In this research, casting parameters are moisture content, permeability, vent holes and mould pressure have been considered to study. Investigation of

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several process parameters is carried out with the help of Taguchi's Method of counter flow experimental design. (Mohsen Lashgari et al.,2021) proposed a robust optimisation approach to solve a mathematical model integrating cell formation, group layout and operator assignment decisions under a dynamic situation. (Mukund Nilakantan Janardhanan et al., 2020) focuses on proposing a new model in RALs with the main objective of maximising production efficiency by minimising total defects and line cost. Hence Process Window Approach validation is used to make the analysis more precise and cost-effective by confirming the tests to improve predicted optimized parameters on responses of the Taguchi Method. Based on the works of literature regardless of the optimization process, this approach needs to address the point of considering Taguchi counter analysis for narrowing specific objectives to reduce defects and using the process window approach as a comprehensive effective approach to optimizing the process. Finally, the confirmation tests are conducted to attain the improvement in predicted optimized parameters recommended in a foundry to improve casting performance.

Process Methodologies

The focus of this article is on the robustness of the green sand casting process is analyzed to minimize the defects and validate with the following assumptions.

1. The most significant parameters that cause variations in the quality characteristics are moisture content; permeability, vent holes, pouring time, pouring temperature and mould pressure are selected.

The green sand casting defects are identified as its quality characteristics (shifts, sand inclusion, blow holes, sand drop, slag, etc.) and the objective is to achieve minimum casting defects through minimising the effect of uncontrollable parameters.

1. Taguchi's design of experiments optimizes casting process under the experimental conditions given by the chosen OA and parameter levels. The experimental conditions and data, pouring time and pouring, the temperature is most insignificant to the process and it is uncontrollable in the existing environment hence significant parameters are analyzed for optimization.
2. An ANOVA is calculated to determine the statistical significance of the parameters and response graphs are drawn to determine the desired levels for each parameter.
3. Based on the counterplot function, the selected parameters are analysed before the optimization for their feasibility and accuracy
4. The optimal values are obtained with predicted results using Taguchi.
5. The experiments are conducted for Taguchi predicted values and compare with error %.

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6. Using Taguchi analyses and its parameters, the process window optimization validation (kumaravadivel et al.,2013) is carried out and the results are compared with Taguchi.
7. The confirmation experiments are conducted to ensure the process is more precise and cost-effective.

Following casting, process parameters are selected to visualize and identify the casting defects of a cast-iron flywheel.

Mould pressure (a) The range of moisture content is taken as 2.8–3.2%, (b) the range of permeability 140–180, (c) the range of vent holes 9–13, (g) the range of pouring time 40–44 s, (h) the range of pouring temperature 1400–1440C, and (i) the range of mould pressure 5–7 kg/cm2. For each control factor, three levels are selected, out of which, one level is usually the starting level. The selection of parameter levels for the process should cover a wide experimental region. Each parameter is analyzed at different levels based on the behaviour of the process parameters. From the selected parameters, the significant interaction between them is also considered. Based on the ANOVA contribution results, the insignificant parameters are neglected for the further process since it is not impacted technically on the process. The selected casting process parameters along with their values are shown in Table 1. Selection of an OA Experience reveals that non-linear behaviour among the parameters of a sand casting process can only be determined if more than two levels of parameters. To know the parameter interactions, it is inferred that there are significant interactions of moisture content with permeability, vent holes and mould pressure. Based on the literature synthesized data of the foundry, with the foundry man's experience, the most significant parameter variations are taken to investigate the effects on casting rejection. The total degree of freedom (DOF) for six, each in three levels with at least 26 DOFs, L27 OA are selected for this study.

Table 1 Process parameters with their ranges and values

Parameter designation	Process parameters	Range	Level 1	Level 2	Level 3
A	Moisture content (%)	2.8-3.2	2.8	3	3.2
B	Permeability	140-180	140	160	180
C	Vent holes	9-13	9	11	13
D	Mold Pressure (kg/cm^2)	5-7	5	6	7

Experimental procedure

This Taguchi Method uses the Signal-to-Noise replicates of both the average and the variation of the quality characteristics. The parameters are assigned to a particular column of the selected OA. Tests are conducted thrice for the same set of parameters using a single repetition given by Ross (1988) and Montgomery(2001). The percentage of defects for each repetition is calculated and average casting defects are calculated for each trial condition. Since the optimal parameter is minimum casting defect, the lower the better characteristics are selected and the S/N ratios are calculated. The average casting defect value and S/N ratios, as shown in Table 2.

Table 2 Average Casting defects a n d S/N ratio against trail numbers

S.No	Trial 1	Trail 2	Trail 3	Average(mean)	S/N Ratios
1	9.68	8.38	7.87	8.64	-18.76
2	9.12	9.42	9.68	9.41	-19.47
3	7.26	7.28	7.78	7.44	-17.43
4	9.61	8.25	7.21	8.36	-18.49
5	7.81	9.31	6.24	7.79	-17.91
6	8.52	7.38	8.74	8.21	-18.31
7	8.12	8.36	8.24	8.24	-18.32
8	6.28	7.61	7.76	7.22	-17.19
9	8.96	9.77	6.21	8.31	-18.50
10	7.24	8.34	6.36	7.31	-17.32
11	7.54	9.1	6.12	7.59	-17.68
12	8.86	6.54	7.76	7.72	-17.80
13	7.34	8.24	7.66	7.75	-17.79
14	9.65	9.25	7.12	8.67	-18.82
15	9.68	8.24	6.76	8.23	-18.37
16	8.26	7.31	8.46	8.01	-18.09
17	6.62	6.32	8.24	7.06	-17.02
18	7.34	9.24	7.66	8.08	-18.18
19	8.24	9.36	8.24	8.61	-18.72
20	7.12	6.21	6.64	6.66	-16.48
21	6.52	6.12	8.13	6.92	-16.86
22	6.64	6.48	7.24	6.79	-16.64
23	6.94	9.24	7.12	7.77	-17.86
24	8.12	8.26	8.74	8.37	-18.46
25	8.24	8.12	6.76	7.71	-17.76
26	7.28	7.61	7.26	7.38	-17.37
27	7.74	7.84	7.78	7.79	-17.83

The mean response refers to the average value of the performance characteristics for each parameter at different levels and the calculated values as shown in Table 2. From the response graph, the optimum levels of parameters are found and the average values of S/N ratios and mean

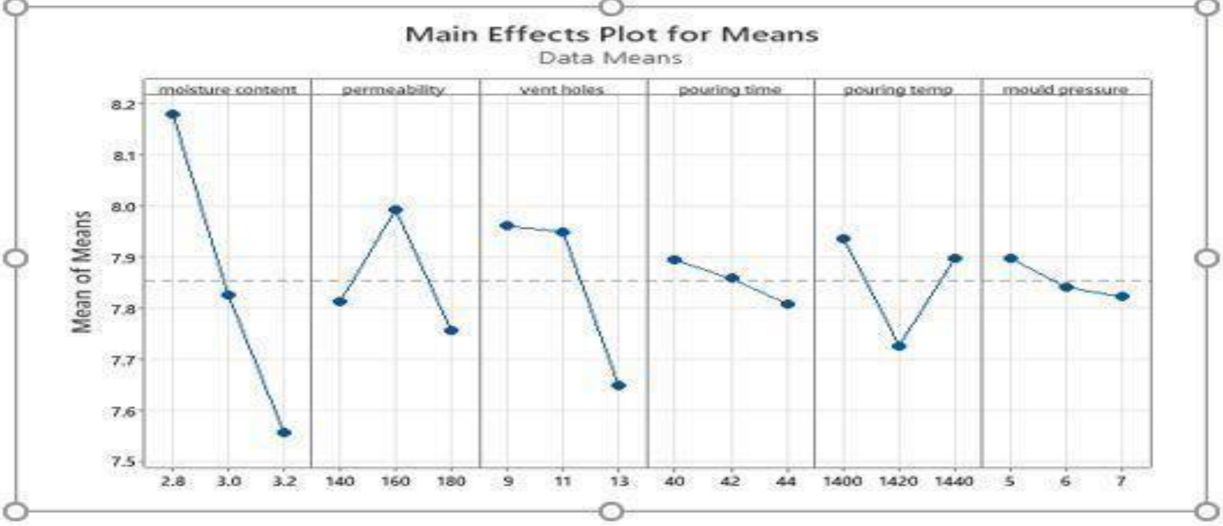

Figure 1 Effects plots for S/N ratio

for each parameter at different levels are shown in Figure 1 and Figure 2 respectively.

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ANOVA analysis is carried out to set up the relative significance of the individual factors. In ANOVA, the *F* ratio (*a*– 95% confidence interval) determines whether an effect is insignificant.

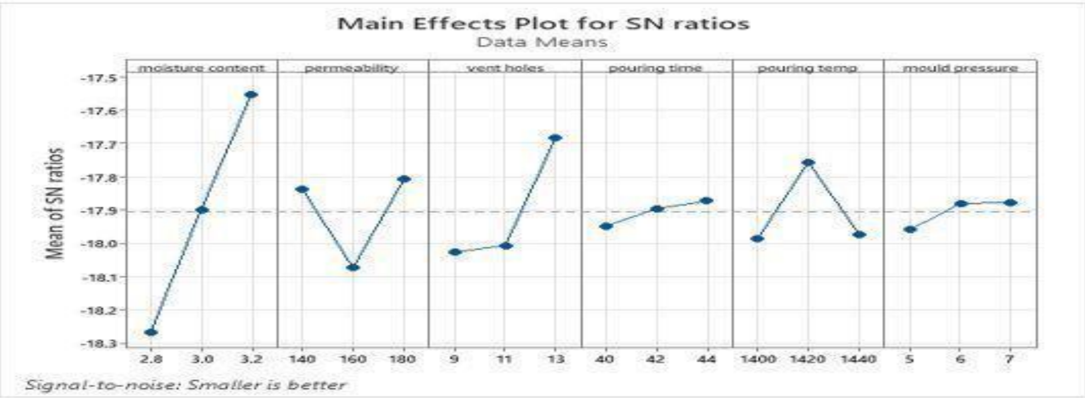

Figure 2 Effects plots for Mean values

Table 3 illustrates the percentage contributions of the various interaction effects. The Sand Casting defects are minimum at the third level of moisture content, the third level of permeability, the third level of vent holes, and the third level of mould pressure. The S/N ratio is also high at the same levels in the parameters. The *F* –ratio value is the mean square of a factor to the variance of error and it can be seen from the F -ratio value that results permeability, moisture content, vent holes and mould pressure are the most significant parameters in the Green Sad Casting Process since they contribute a greater percentage than all other control factors as shown in Table 3.

Table 3 ANOVA analysis illustrating the significance level of various factors against casting defects response

Factors	Degrees of freedom DF	Sum of SqSres SDS	R-Sq	P-value	F value	P value
Moisture content	2	0.61	16.34%	1.77	2.34	0.12
Permeability	2	0.66	2.55%	0.28	0.31	0.73
Vent holes	2	0.65	5.19	0.57	0.66	0.53
Mold pressure	2	0.67	0.26%	0.03	0.03	0.97

Determination of optimum Sand Casting Process parameters

Optimal casting parameters in terms of these control factors are determined from the casting defects and S/N Ratio. The interaction plot for means (response graph) clearly shows the

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optimum Sand Casting parameters obtained at S/N Ratios and are mean defects given in Figure 3 and Figure 4 respectively.

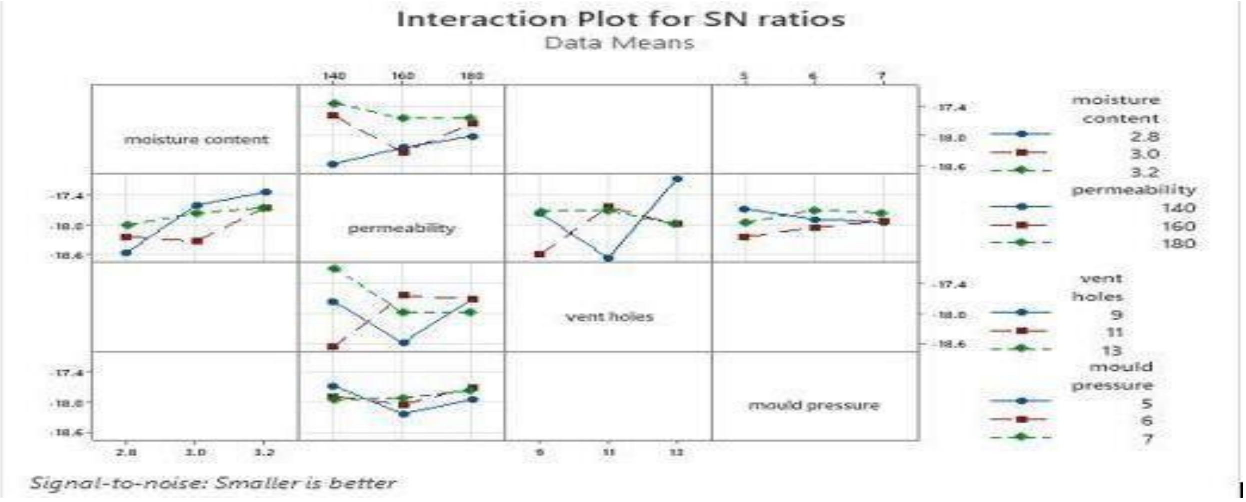

Figure 3 Process parameters interaction plot for S/N ratios

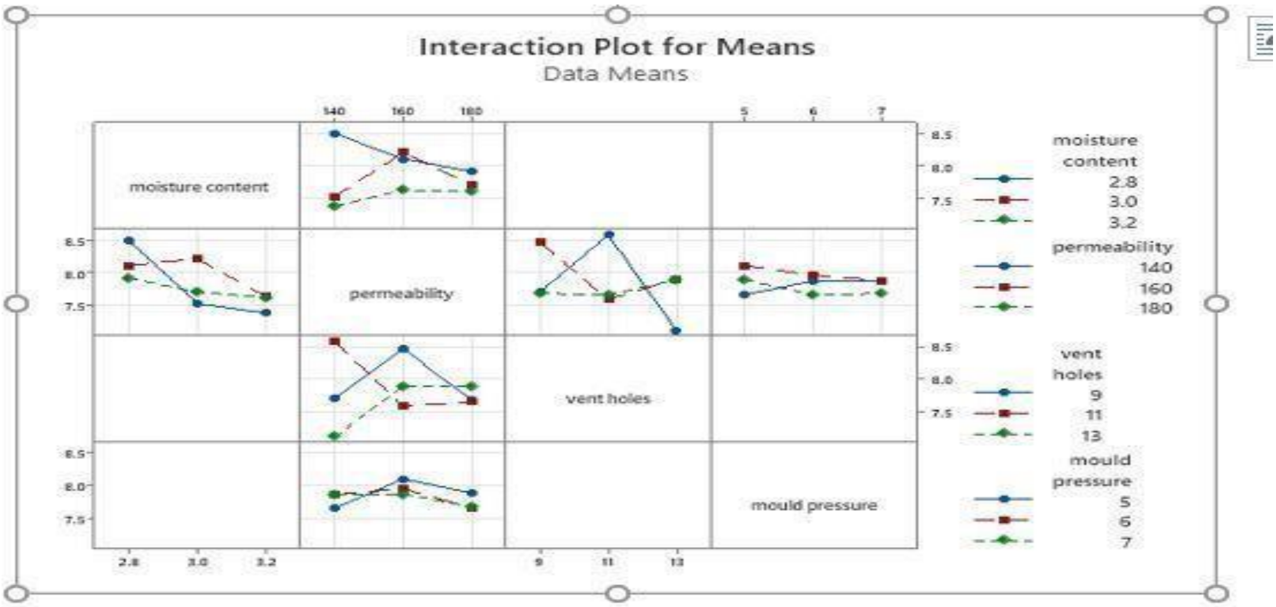

Figure 4 Process parameters interaction plot for means

The estimation of the mean for casting defects is achieved for the respective process standard deviation to all control factors. a lower value of average casting defect (moisture content) is at level 3 (3.2), the lower value of average casting defect (permeability) is at level 3 (180), lower value of average casting defect (vent holes) is at level 3 (13), lower value of average casting defect (mould pressure) is at level 3 (7) are shown table 4. From the results obtained through Taguchi's experimental design, the average % casting defects is 7.85, as shown in Table 5.

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Table 4 ANOVA analysis illustrating the selected mean defects including percent contribution

Moisture content	Mean (Avg.Defects	StDev	95% CI
2.8	8.180	0.652	(7.757, 8.602)
3.0	7.824	0.487	(7.402, 8.246)
3.2	7.555	0.683	(7.133, 7.977)
Permeability	Mean	StDev	95% CI
140	7.811	0.898	(7.356, 8.267)
160	7.992	0.554	(7.536, 8.448)
180	7.755	0.452	(7.299, 8.211)
Vent holes	Mean	StDev	95% CI
9	7.960	0.655	(7.511, 8.410)
11	7.949	0.765	(7.500, 8.399)
13	7.649	0.515	(7.200, 8.099)
Mold pressure	Mean	StDev	95% CI
5	7.897	0.600	(7.436, 8.358)
6	7.840	0.732	(7.379, 8.301)
7	7.821	0.672	(7.360, 8.283)
Taguchi optimized parameters based on average defects are- moisture content (3.2%),permeability(180),vent holes(13),mould presuure(7-kg/cm2)			

Counter Plot Function Analysis

After the Taguchi confirmation tests to make the analysis more precise and cost-effective and improve the results using DOE counter plot analysis with the following assumptions.

1. Estimating a functional relationship between one or more responses and several independent variables that influence the responses are analyzed for better performance.

2. Searching and exploring the best (data) optimum setting conditions for these two dominant factors with the use of the plot graph.

3. The best value of centre point average (average mean, Cpk), the values are taken for optimization of two dominant factors individually and then compared with the determined Taguchi results.

Table 5 Taguchi average % of defects with Cpk

% defects run 1	% defects run 2	% defects run 3	Avg %defects	sigma	Process capability Index Cpk	Moisture content	Permea bility	Vent holes	Mold pressure
9.68	8.38	7.87	8.64	0.76	0.33	2.8	140	9	5
9.12	9.42	9.68	9.41	0.23	0.40	2.8	140	11	6
7.26	7.28	7.78	7.44	0.24	0.25	2.8	140	13	7
9.61	8.25	7.21	8.36	0.98	0.39	2.8	160	9	5
7.81	9.31	6.24	7.79	1.25	0.41	2.8	160	11	6
8.52	7.38	8.74	8.21	0.60	0.29	2.8	160	13	7
8.12	8.36	8.24	8.24	0.10	0.41	2.8	180	9	5
6.28	7.61	7.76	7.22	0.67	0.27	2.8	180	11	6
8.96	9.77	6.21	8.31	1.52	0.32	2.8	180	13	7
7.24	8.34	6.36	7.31	0.81	0.39	3	140	13	7
7.54	9.1	6.12	7.59	1.22	0.40	3	140	9	5-
8.86	6.54	7.76	7.72	0.95	0.40	3	140	11	5

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7.34	8.24	7.66	7.75	0.37	0.36	3	160	13	6
9.65	9.25	7.12	8.67	1.11	0.29	3	160	9	7
9.68	8.24	6.76	8.23	1.19	0.41	3	160	11	5
8.26	7.31	8.46	8.01	0.50	0.30	3	180	13	6
6.62	6.32	8.24	7.06	0.84	0.29	3	180	9	7
7.34	9.24	7.66	8.08	0.83	0.30	3	180	11	5
8.24	9.36	8.24	8.61	0.53	0.24	3.2	140	11	7
7.12	6.21	6.64	6.66	0.37	0.40	3.2	140	13	7
6.52	6.12	8.13	6.92	0.87	0.31	3.2	140	9	6
6.64	6.48	7.24	6.79	0.33	0.31	3.2	160	11	7
6.94	9.24	7.12	7.77	1.04	0.26	3.2	160	13	5
8.12	8.26	8.74	8.37	0.27	0.32	3.2	160	9	6
8.24	8.12	6.76	7.71	0.67	0.26	3.2	180	11	7
7.28	7.61	7.26	7.38	0.16	0.26	3.2	180	13	5
7.74	7.84	7.78	7.79	0.04	0.38	3.2	180	9	6
Average			7.85%						

4. Based on Taguchi's analysis, the F-ratio shows the significant factors are the control factors in the order of permeability, volatile content, moisture content and mould pressure in The Green Sand Casting Process, since it contributes a greater percentage than all other control factors. Hence these four significant process parameters are taken for counter plot analysis to optimize the parameter setting to be more accurate.

The DOE contour plot is generated for two factors. Typically, these would be the two most important factors as determined by Taguchi analyses (e.g., through the use of the DOE mean plots and analysis of variance), as shown in Figure 5a-5f.

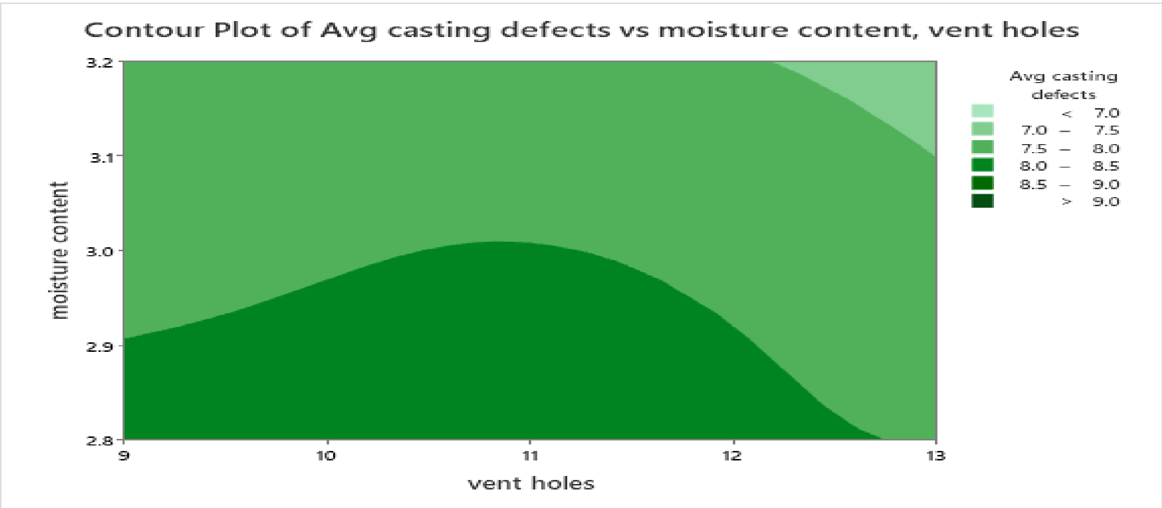

Figure 5a Counterplot of Avg casting defects vs moisture content, vent holes

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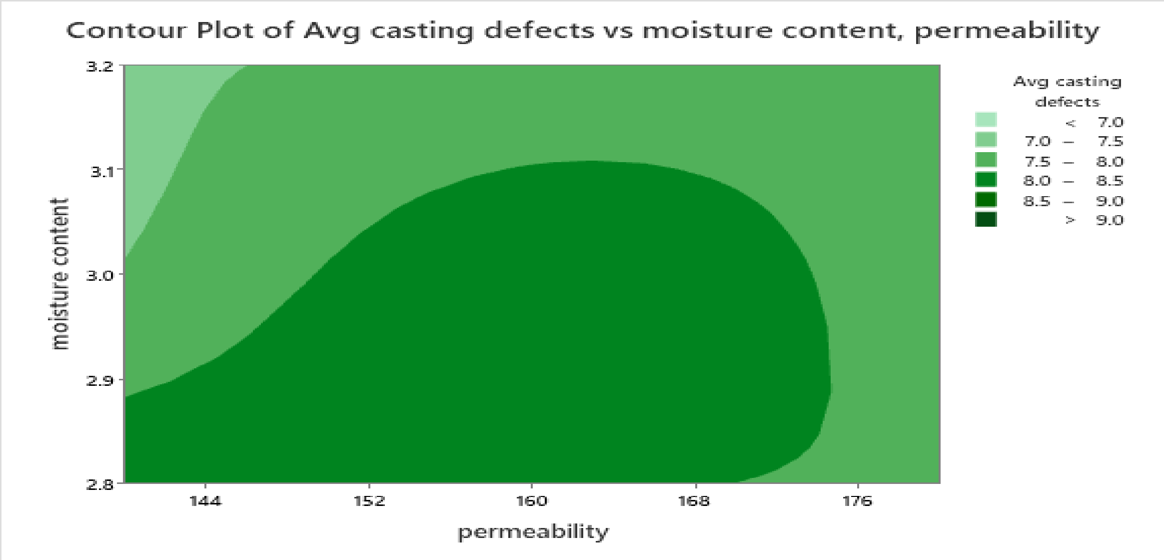

Figure 5b Counterplot of Avg casting defects vs moisture content, permeability

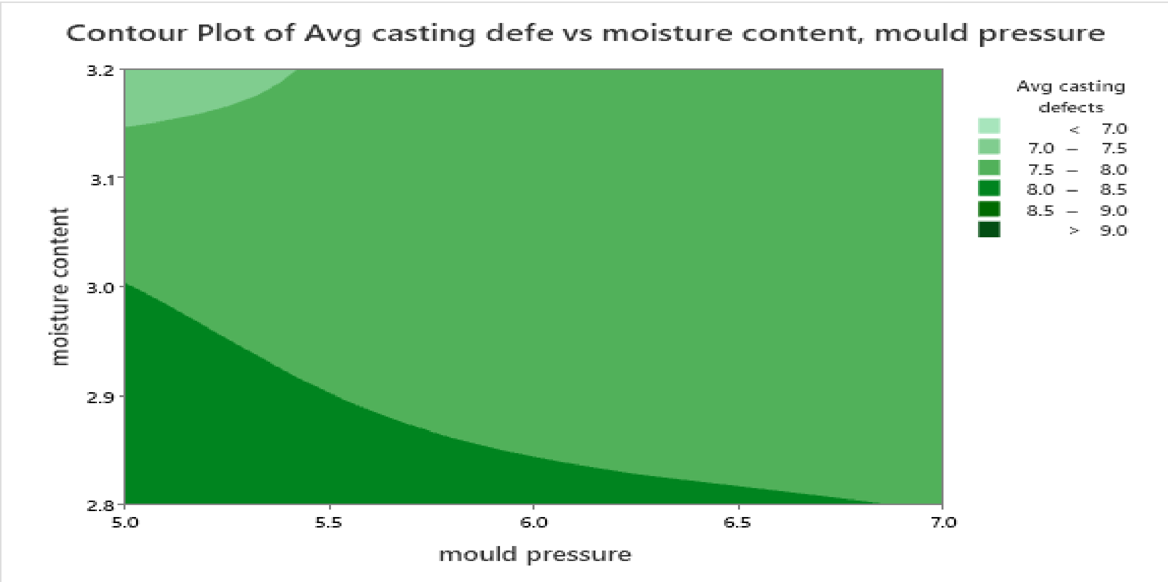

Figure 5c Counterplot of Avg casting defects vs moisture content, mold pressure

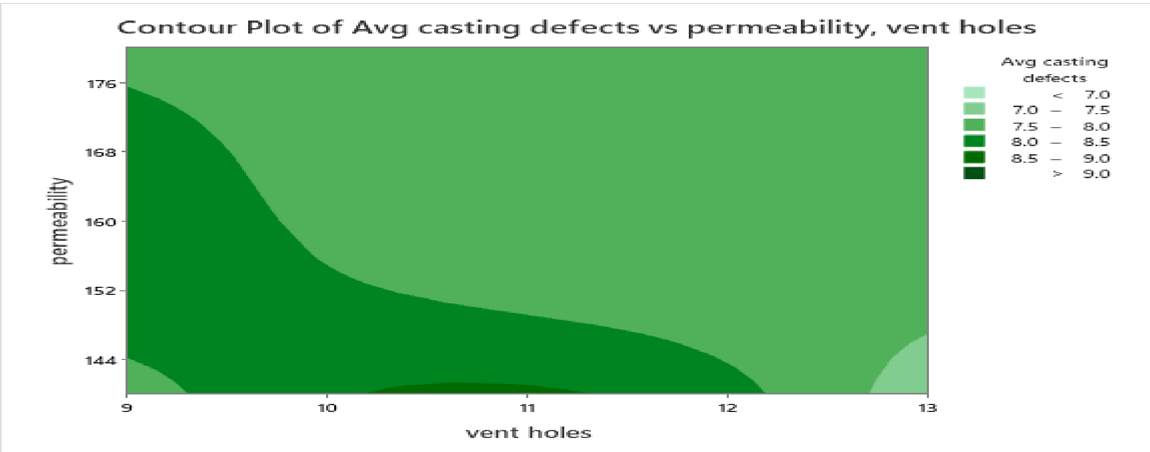

Figure 5d Counterplot of Avg casting defects vs permeability, vent holes

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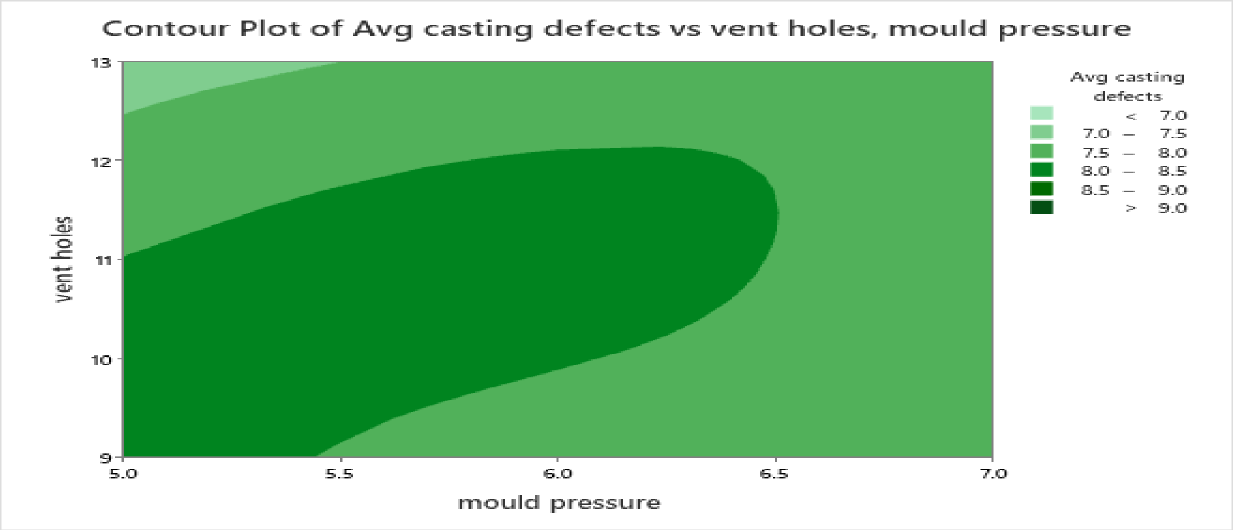

Figure 5e Counterplot of Avg casting defects vs vent holes,mold pressure

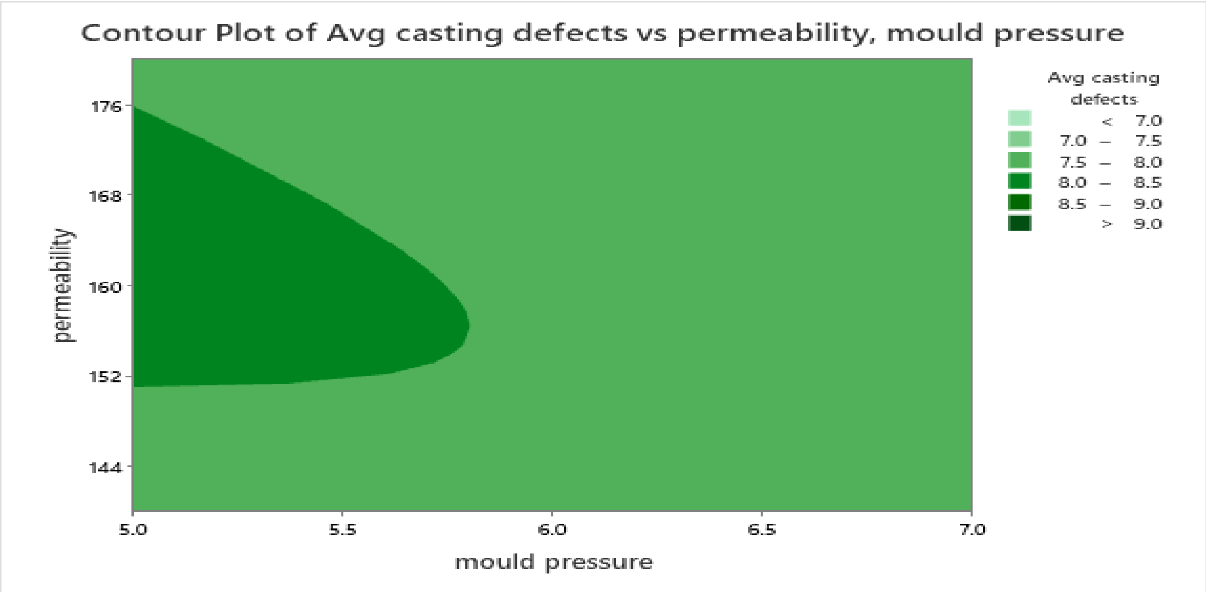

Figure 5f Counterplot of Avg casting defects vs permeability, mould pressure

These designs have a low level, coded as "2.8 and 9", and a high level, coded as "3,2 and 13" for each factor and centre points are at the mid-point between the low and high level for each factor and are coded as"11", as shown in Figure 5a. The typical application of the DOE contour plot in determining settings that will minimize the defects is the response variable. It can also help determine settings that result in the response variable hitting a pre-determined target value. The DOE contour plot plays a useful role in determining the settings for the next iteration of the experiment. The following are the primary steps in the construction of the DOE contour plot. The

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Vent holes (x) and moisture content (y) axes of the plot represent the values of the two factors (independent) variables.

Concerning the centre points, a point is drawn at (3,11) and the average of the response values at the centre points is printed. In the plot, the optimal value of both parameters lies in the top right corner of the plot (Dull green colour variation) shown to identify where the average casting defects is very less and the interaction of two parameters of moisture content optimum level 3.2 with average defects % of 7.55 and vent holes optimum level 13with average defects % 7.649. Interaction Significance noted the appearance of the contour plot curves has considerable curvature. Similarly, the other two factors' interaction is analyzed on par with the counterplot and the optimal setting is designed for the conformation test.

Concerning the centre points, a point is drawn at (3,160) and the average of the response values at the centre points is printed. In the plot the optimal value of both parameters lies in the top left corner in the plot (Dull green colour variation) shown to identify where the average casting defects is very less and the interaction of two parameters of moisture content optimum level 3.2 with average defects % of 7.55 and permeability holes optimum level 140 with average defects % 7.75. Interaction Significance noted the appearance of the contour plot curves has considerable curvature is given in the Figure 5b.

Concerning the centre points, a point is drawn at (3,6) and the average of the response values at the centre points is printed. In the plot, the optimal value of both parameters lies in the top left corner of the plot (Dull green colour variation continued in the vertex area) shown to identify where the average casting defects is very less and the interaction of two parameters of moisture content optimum level 3.2 with average defects % of 7.55 and mould pressure optimum level 7 with average defects % 7.82. In this plot for mould pressure, the curve spreads between 5 to 7, but in the repetition approach the optimal level is settled at 7 and interaction significance noted the appearance of the contour plot curves has considerable curvature is given in Figure 5c.

Concerning the centre points, a point is drawn at (160,11) and the average of the response values at the centre points is printed. In the plot, the optimal value of both parameters lies in the bottom right corner of the plot (Dull green colour variation) shown to identify where the average casting defects is very less and the interaction of two parameters of permeability optimum level 180 with average defects % of 7.55 and vent holes optimum level 13 with average defects % 7.65. In this plot for permeability, the curve spreads between 140 to 180, but with the repetition approach the optimal level is settled at 180 and interaction significance noted the appearance of the contour plot curves has considerable curvature is given in the Figure 5d.

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Concerning the centre points, a point is drawn at (11,6) and the average of the response values at the centre points is printed. In the plot the optimal value of both parameters lies in the top left corner in the plot (Dull green colour variation) shown to identify where the average casting defects is very less and the interaction of two parameters of moisture content optimum level 13 with average defects % of 7.65 and mould pressure optimum level 7 with average defects % 7.82. In this plot for mould pressure curve spreads between 5 to 7, but in the repetition approach the optimal level is settled at 7 and interaction significance noted the appearance of the contour plot curves has considerable curvature is given in Figure 5e.

Concerning the centre points, a point is drawn at (160,6) and the average of the response values at the centre points is printed. In the plot, the optimal value of both parameters might lie in the top right corner in the plot (Dull green colour variation) shown to identify where the average casting defects is very less and the interaction of two parameters of permeability optimum level 180 with average defects % of 7.55 and mould pressure optimum level 7 with average defects % 7.82. In this plot mould pressure and permeability, the curve might spread between the higher value of the parameters, but the repetition approach the optimal level is settled at 180,7 and interaction significance noted the appearance of the contour plot curves has considerable curvature is given in the Figure 5f.

To determine the best factor settings for the Taguchi experiments and with the counterplot function analysis first define what "best" means. For the sand casting operation data set used to generate this DOE contour plot, "best" means to minimise the casting defects as the response. Hence from the contour plot, determine the best settings for the two dominant factors by simply scanning the four vertices and choosing the vertex with the smaller value (average defects).

Thou the two approaches have given the optimized results, the counterplot analysis marked its technical accuracy with the counter vertex area of optimization which is given in the counterplot analyses are just varying with nearest optimal values a little bit. But it needs repetitive experiment analysis and is time-consuming for getting optimal values following values given in the Taguchi analysis. Hence Process Window Approach optimization is used to have the very close optimal value and make the optimization more precise and cost-effective.

Validation of experiments-Process Window Approach (PWA)

Process Window Approach is a statistical method that statistically proves the robustness of a manufacturing process with optimized process parameters (Jim Hall and Phil Zarrow, 2002). PWA indicates and ensures how well a Sand Casting Process fits into a higher capability level of the process limit known as the Specification Limit which is optimized in the DOE. The Specification Limit is the tolerance allowed for the process obtained in the casting production in

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terms of Cpk and it is statistically determined. Using PWA values, Casting Process performance can be accurately measured, analyzed and compared. In the process, the lowest average defects could exist at some value or sweet spot within the range but not at its centre. If such data are available for a specific product, then the process parameter set-up should be adjusted to move the mean closer to this sweet spot to produce fewer defects (A.Kumaravadivel).

After the Optimal Solution has arrived from the Taguchi Analysis, the most significant parameters are identified as permeability, moisture content, vent holes and mould pressure. These parameters are more critical to the overall process or more likely to cause defects. The Cpk is calculated for % of defects as given by Taguchi Calculation. There are three sets of calculations for the three variables of selected parameters as shown in Figure 6a-6f.

As shown in Figure 6a, permeability and moisture content are the selected parameters for Process Window Approach in which X-Axis represents permeability number and Y-Axis moisture content in %.

Y-axis Moisture content (3 levels)		Average Cpk		Row avg Cpk
2.8	0.33	0.36	0.33	0.34
3	0.40	0.35	0.30	0.35
3.2	0.32	0.30	0.30	0.31
Column avg Cpk	0.35	0.31	0.31	
X axis-Permeability (3 levels)	140	160	180	minimum selected

Figure 6a Process window approach of Avg Cpk vs moisture content, permeability

Y-axis Moisture content (3 levels)		Average Cpk			Row avgCpk
2.8	0.38	0.36	0.29		0.34
3	0.33	0.37	0.35		0.35
3.2	0.34	0.27	0.31	sweet	0.31
Column avgCpk	0.35	0.33	0.32	spot 1	
X axis-Vent holes (3 levels)	9	11	13		

Figure 6b Process window approach of Avg Cpk vs moisture content, vent holes

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Y-axis Moisture content (3 levels)	Average Cpk			Row avg Cpk
2.8	0.38	0.36	0.29	0.34
3	0.37	0.35	0.33	0.35
3.2	0.31	0.34	0.27	0.31
Column avg Cpk	0.35	0.35	0.30	
X axis-Mold pressure(3 levels)	5	6	7	

Figure 6c Process window approach of Avg Cpk vs moisture content, mold pressure

Y-axis Permeability (3 levels)	Average Cpk			Row avgCpk
140	0.35	0.35	0.35	0.35
160	0.30	0.36	0.30	0.35
180	0.36	0.28	0.32	0.32
Column avgCpk	0.34	0.33	0.32	
X axis-Vent holes (3 levels)	9	11	13	

sweet spot 2

sweet spot 1

Figure 6d Process window approach of Avg Cpk vs permeability, vent holes

Y-axis permeability (3 levels)	Average Cpk			Row avg Cpk
140	0.38	0.37	0.30	0.35
160	0.35	0.36	0.30	0.34
180	0.32	0.32	0.30	0.30
Column avg Cpk	0.35	0.35	0.30	
X axis-mold pressure (3 levels)	5	6	7	

Figure 6e Process window approach of Avg Cpk vs permeability, mold pressure

Y-axis vent holes (3 levels)	Average Cpk			Row avg Cpk
9	0.38	0.34	0.25	0.32
11	0.37	0.36	0.27	0.33
13	0.29	0.35	0.29	0.31
Column avg Cpk	0.35	0.35	0.27	
X axis-mold pressure (3 levels)	5	6	7	

Figure 6f Process window approach of Avg Cpk vs vent holes, mold pressure

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In the first step, the Average Cpk for the respective runs and the row-column average Cpk is calculated to identify and confirm the deviation of the process from the optimal setting.

The second step is to identify and draw the window for the selected parameters. The higher values of average Cpk value for corresponding X, and Y parameters with respective column and row-wise average Cpk values, determine and confirm the performance of the process for the given runs. Figure 6a shows the 3*3 matrix of the average Cpk with the right extreme and bottom of the matrix noted by its corresponding Cpk values. The matrix may vary according to the design level of analysis like 3*4, 4*4 etc. In this given matrix, a window is made to identify the lowest values. The shape of the window will be a square or rectangular (sweet spot) in which most of the lower values can be located.

The third step is to evaluate and select the intersecting point of the optimum parameter which produces fewer defects based on the lowest values in the matrix. In the row average of the Cpk column, the lowest value is selected first and similarly in the column average Cpk. The first line indicates the permeability at 180 and moisture content of 3.2 % has the sweet spot of intersecting in which the optimal set of parameters produces fewer defects. This is the optimized value given by the Taguchi Analysis and it confirms the test result.

Table 6 Taguchi and PWA selected parameters for conformation test

Parameters	PWA figure Numbers	Parameter levels-Most selected-repetitive	Cpk	Selected for conformation test from PWA	Selected for conformation test from Taguchi
Permeability	6a	180,180,160	0.3,0.3	180-most repetitive	Taguchi optimized parameters based on average defects are-moisture content (3.2%),permeability(180), vent holes(13),mould presuure(7-kg/cm2)
Moisture content		3,3.2		3.2-most repetitive	
Moisture content	6b	3.2,2.8,3.2	0.31,0.29,0.34	3.2	
Vent holes		13,11		13- Based on Cpk	
Moisture content	6c	3.2,2.8	0.27,0.29,0.34	3.2	
Mould pressure		5,7		7- Based on Cpk	
Permeability	6d	180,160	0.32,0.30,0.28	180	
Vent holes		11,13		13	
Permeability	6e	160,180	0.3,0.3,0.32	180	
Mould pressure		7,6		7	
Vent holes	6f	13,11	0.29,0.25,0.34, 0.35	13	
Mould pressure		6,7		7	

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In the second line, the second lowest row average Cpk value is selected and it intersects with the column average Cpk in the first line, the sweet spot in which the permeability level at 160 and moisture content of 3 % produced fewer defects. This is the optimized value of the selected parameter by the Taguchi analysis, which conform to the test result (point 2). The row average Cpk and column average Cpk selection is purely based on the lower values and it is satisfied. However, points 3 and 4 in the window have a corresponding value which is less than of column Cpk value but it has the potential to conform to the performance capability by altering the setting parameter. Similarly, PWA is carried out for other interactions which are shown in Figure 6b-6f. This is the robust process parameter set up to produce less % of casting defects and PWA is a powerful approach for validating the Taguchi optimisation.

After the validation of Taguchi analysis with the process window approach, there is no deviation in the optimisation process and Taguchi conforms its robustness in process optimization, as shown in Table 6. Hence Taguchi optimized process parameters are recommended for the conformation test.

Confirmatory Experiments

A confirmatory experiment is carried out after the optimal control factor setting is determined and the results are shown in Table 7. The response of casting defects is found to be 7.34% and the average % of casting defects declined from 7.85%. The positive error range is (0.51%) after a confirmation test with Taguchi-designed parameters very small and valuable improvements in experimental results within the Taguchi confidence interval of the casting defects. The results are compared with Taguchi's predicted vale response results are very close to the experimental results (7.34-7.22%) and the error % is 0.12. Optimal conditions predicted are verified experimentally with the PWA to validate the Fitness of the Model. Test numbers 1, 2, and 3 show the comparison of experimental results. Verification tests are conducted for the three selected test conditions with few varying-parameter levels to achieve the predicted results, as shown in Table 6.

Table 7 Result of confirmation experiments- Taguchi

Day/Trail	% of casting defects			Experimental Average % casting defects	Taguchi Predicted design casting defects %	Error %
	Trail 1	Trail 2	Trail 3			
Day 1	7.45	7.61	7.79	7.62	7.22 (S/N Ratio -17.2041)	0.12
Day 2	6.74	7.71	7.22	7.22		
Day 3	6.90	7.41	7.23	7.18		
Total Average				7.34		

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Results and Discussion

In this study, the Taguchi counterplot function experimental design is applied to analyze the optimum levels process parameters of a sand casting process. Table 7 shows the results obtained from the Taguchi counter plot design and provides a technical view to the process parameters and the % of casting defects fixed at 7.85. Further, the processes are validated with the process window approach to make the analysis more robust and it has no process deviation with Taguchi. The confirmation results show the average % of defects to be 7.34. Thus, from the ANOVA analysis, it can be concluded that moisture content, vent holes, permeability and mould pressure are the most crucial, significant and influential parameter and the interaction effects between permeability, moisture content, vent holes, and mould pressure are also quite significant and must be taken into account while designing further experiments.

Conclusion

This paper has explained the fact that the efficiency and performance level of the sand casting Process can be improved by using a Taguchi design of experiments with counter plot module analysis to produce good quality products. Based on the experimental and analytical results, the following conclusion has been drawn.

In the proposed process, the counterplot function with the Taguchi the values for the range of average defects percentage came down from 7.85 to 7.34 and just closer to the predicted value of 7.22%. The results valuable improvement revealed that a minimal casting rejection percentage could be arrived at significantly for casting operations while using Taguchi. This is the robust process parameter set up to produce less % of casting defects and it is validated with the process window approach.

The procedure is efficient and effective for achieving the optimum set of operating parameters for a particular product quality characteristic. Many industrial experiments have been carried out to validate the results which indicate that the cost of the experimentation will be more than paid back by the increased efficiency and quality of the process.

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