Application of Six Sigma Method to Reduce Defects in Green Sand Casting Process: A Case Study

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Abstract: Six Sigma is statistical and scientific methods to reduce the defect rates and achieve improved quality. A case study carried out for a green sand casting manufacturing industry. Here Six Sigma methodology is used for the part: Transmission Case. DMAIC (Define–Measure–Analyse–Improve–Control) methodology along with Taguchi method is used to minimize the defects in the Transmission Case. The major tools used in this work are the project charter, process map and cause-and-effect diagram. Use of design of experiments (DOE) and analysis of variance (ANOVA) techniques are combined to determine statistically the correlation of defects with the mould hardness, green strength, and pouring rate also to find their optimum values needed to reduce/eliminate the defects. The experimental results were statistically analyzed and modelled through Taguchi analysis. Based on the findings, the optimized process parameters are taken for experiment and better performance obtained in the production process was confirmed. The comparison between the existing and the proposed process has been attempted in this paper and the results have been discussed in detail.

Keywords*: Six Sigma; DMAIC; Defect; DOE; Taguchi Analysis.*

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I. INTRODUCTION

Six Sigma is an organized & systematic method for strategic process improvement that relies on statistical & scientific methods to reduce the defect rates and achieve significant quality up- gradation [1]. Green sand casting gives enough green strength to get dimensional stability and provides excellent surface finish and better collapsibility during the knockout. Generally, the molding procedures of sand-casting processes are the same even though the materials used in the processes are different. Whenever a defect occurs in castings, various departments in the foundry normally blame each other for its occurrence due to the involvement of these departments. Defects may occur due to single cause or a combination of causes. Correct identification of the root causes of the defect is difficult because of 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 [2].

Six Sigma emphasizes an intelligent blending of the wisdom of an organization, with proven statistical tools, to improve both the efficiency and effectiveness of the organization for the whole-hearted satisfaction of the customer. The success of Six-Sigma program hinges on the sequence of many Six-Sigma elements of a model for implementation [3]. Six Sigma aims at reducing the defect levels in products and processes to a level of less than 3.4 defects per million opportunities (DPMO). Six-Sigma implementation is an important area because it contributes to the science and practice of the implementation to reduce the waste and create value. Six Sigma helps to identify hidden waste and costs, eliminate defects, increase profit margins, customer satisfaction, employees' satisfaction and level of commitment, and expand the business. In short, Six Sigma is about eliminating process defects and human defects [4–6].

There is research on how to optimize the green sand casting process and improve the quality of the castings. Taguchi method optimizes the mechanical properties of the casting process. Although there has been some research on optimizing the casting process using the Taguchi method as an experimental method, it is not effective for tracing root causes of defects. Another common approach to optimize casting parameters is the trial-and-error method, which is neither systematic nor efficient [7].

In this paper proposes to optimize the casting process in a metal casting industry by reducing the defects caused due to process variation. The Six Sigma define-measure- analyze-improve-control (DMAIC) methodology is used to identify the root causes of defects and optimum parameter settings for the process and to create a way to control the process to guarantee optimal performance. This paper is a case study of a metal casting industry that incurred major losses because of casting defects.

II. DMAIC METHODOLOGY

The study was performed on a casting part: Transmission Case from a green sand foundry industry, as shown in fig. 1. This project focuses on minimizing losses, improving the process, and reducing defects by using the Six Sigma DMAIC methodology.

Figure1. Transmission Case casting

A. *Define Phase*

The definition phase identifies goals of the improvement project in terms of customer requirements and develops a process that delivers those requirements. The project team members first listen to the "voice of the customer" and translate the customer language into setting to goal. Project Charter shown in Table 1. Includes, detailed project goals, roles and responsibilities, identifies the main stakeholders, and the level of authority of project team members.

TABLE 1. PROJECT CHARTER

Project Title:	Application of Six Sigma Method to Reduce Defects in Green Sand Casting Process: A Case Study
Aim of Project:	At present the rejection level is observed to be 9.58%. We are aiming to bring down the level of rejection to 5.5%.
Project Champion:	General Manager
Team Members:	Production Manager, Production Engineer, Quality Control Engineer, Supervisor Production, Operators.
Expected Benefits:	-Cost saving due to the defects reduction/wastage -Improved Quality of Products
Expected customer benefits:	Customer is happy to get high quality products at low price and with more confidence of defect-free product
Schedule:	Define: Two week Measure: Three week Analyse: Three week Improve: Four week Control: Three week

A critical to quality (CTQ) is the flowchart process of finding out quality features or characteristics of the customer with the perspective to identity the problems. The rejection value was 9.58% and component rejection was mainly due to Sand inclusion, Shrinkage, Gas Trap and Swelling shown in Fig. 2. After discussing the problem with the project members in the company, we proposed the CTQ's of process is selected.

Figure 2. Sand Inclusion defect in Transmission Case casting

B. *Measure Phase*

The find out Sigma level by evaluate and understand the current state of the process is purpose of the Measure step. In this phase includes collecting data on measures of quality. From Pareto diagram it was found that the most significant defects in this work to be considered are Sand inclusion, Shrinkage, Gas Trap and Swelling as shown in Fig. 3. Sand inclusion, Shrinkage, Gas Trap and Swelling were responsible for 74.9, 12.9, 6.9 and 5.3% defect percentage in total percentage. One major defect Sand inclusion which creates major changes were taken into account. The Sand Inclusion defect contribution is 74.9% in total defect parentage for this reason we select this one defect for next analysis. Sigma Level was calculated before implementing DMAIC model and the value was 2.97 at that DPMO (Defect per Million Opportunity) of 71757 gives in Table 2.

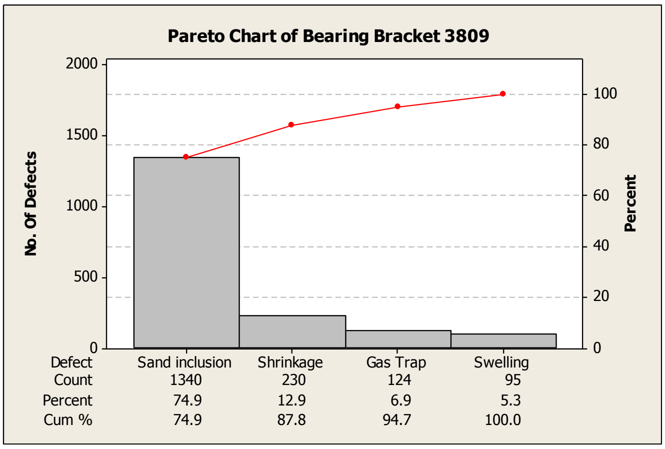

Figure 3. Pareto analysis for Transmission Case defects

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TABLE 2. BASELINE STATUS

Part Name	Average %	DPMO	Sigma Level
Transmission Case	9.58	71757	2.97

C. *Analyse Phase*

The this phase most important to finding the causes of mostly changing the process, the removing an minimum affect the process cause usually involves minimizing specific problem. In this phase, the significant factors that affect Sand Inclusion defects are find out using a fishbone

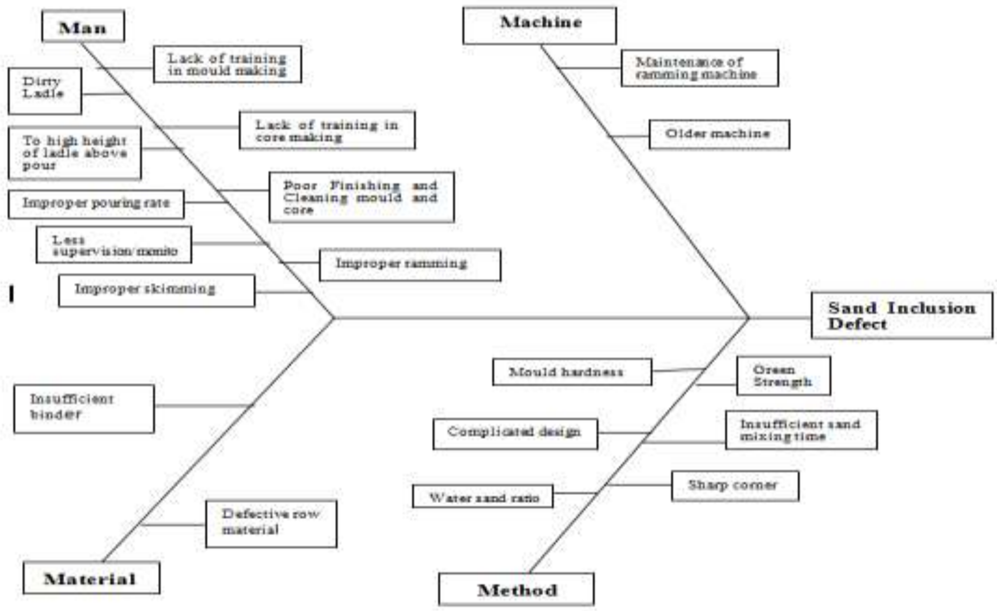

Figure 4. Fish bone diagram for Sand inclusion Defects

diagram. A cause-and-effect diagram was drawn based on these causes. All potential factors affecting Sand Inclusion in castings were identified; all of these factors are summarized in the fishbone diagram in Fig. 4.

The important control factors were chosen to score from all considerable factors shown in the fishbone diagram for skilled operators. Table 3 shows an XY matrix for identifying control factors; the output variables are Y (product quality and easy to control), and process variables are X. The Most weighted score variables are choose for validated causes shows in Table 3.

TABLE 3. XY MATRIX FOR IDENTIFYING CONTROL FACTORS

	Output parameter Y		
Process variables (X)	Product quality	Easy to control	Weighted score
Weightage of Y	10	7	--
Lack of training in mould making	5	4	78
Dirty Ladle	4	7	89
Lack of training in core making	5	6	92
Poor Finishing and Cleaning mould and core	3	7	79
Less supervision/monitoring	4	5	75
Improper skimming	5	6	92
Green strength	**7**	**8**	**126**
Improper ramming	4	5	75
Pouring rate	**9**	**8**	**146**
Improper handling of mould box	3	7	79
To high height of ladle above pour	3	8	86
Insufficient sand mixing time	4	6	82
Sharp corner	3	4	58
Water sand ratio	4	7	89
Mould hardness	**9**	**8**	**146**
Complicated design	4	4	68
Maintenance of ramming machine	3	4	58
Insufficient binder	5	4	78
Defective raw material	5	6	92
Older machine	4	6	82

The process variable scores are from 1 (the factor has small relevance to the output variables) to 10 (the factor has a big relevance to the output variables). The scores were then defined. The higher the weighted score, the more important the factors were in determining the quality of the final product. The team had a detailed discussion in this regard with the engineers and the operators and supervisors of the score gives to causes. Based on this discussion, a plan was prepared with details of data on each cause and the type of validation required. Green strength, mould hardness, and pouring rate were identified as the top three factors affecting quality according to the weighted score in Table 3.

D. Improve Phase

This phase statistically reviews the variations in the process and determines what factors significantly contribute to the output. The main goal of this Improve phase is develop optimal solutions of the problems. The optimization process involves the large number of key process input variables to determine the greatest impact few variables of process. Taguchi is a statistics method that aims to understand variation instead of conducting many experiments and is used to provide experiment runs.

1. Experimental Design

The Taguchi-based experimental design used in this study was an L9 orthogonal array and is shown in Table 4 the controllable factors for orthogonal array design. These control factors were classified low, medium, or high. The control factors are mainly divided in three levels as show in Table 4.

TABLE 4. CONTROLLABLE FACTORS FOR ORTHOGONAL ARRAY DESIGN

Level	A	B	C
1	40	1200	9
2	50	1275	5
3	60	1350	3

A-Mould hardness (number), B- Green strength (g/cm^2), C- Pouring rate (Sec). Slow: 9 seconds, medium: 5 seconds, and fast: 3 seconds.

This basic design uses up to three control factors, each with three levels. A total of nine runs, using a combination of levels for each control factor (A through C), are indicated. Response variance (Y) is the percentage of sand inclusion defects. The percentage of sand inclusion defect is designated as (β). An orthogonal array in Table 5 was created using a Taguchi L9 design. The basic array with the control factors are shown as the inner control factor array. The study found that there is required repetition for each run. There were 9 runs in this experiment. This study was conducted using Transmission Case made from C.I. and green sand for making the mold.

TABLE 5. EXPERIMENTAL L9 ARRAY FOR TRANSMISSION CASE

Run	A	B	C
1	40	1200	9
2	40	1275	5
3	40	1350	3
4	50	1200	9
5	50	1275	5
6	50	1350	3
7	60	1200	9
8	60	1275	5
9	60	1350	3

A-Mould hardness (number), B- Green strength (g/cm^2), and C- Pouring rate (Sec).

2. Experiment Setup and Measurement of sand inclusion Defect

Once the parameters and parameter interactions are assigned to a particular column of the selected orthogonal array, the factors at different levels are assigned for each trial. The casting of the part in focus was made with the trial conditions given in Table 5. Fifty test specimens were made from the same set of parameters using a single repetition, and the casting defects that occurred in each trial were measured in Table 6. The outcomes of each combination were inspected by the foundry supervisor to determine whether the part was good or bad. In this work, casting defects that were considered occurred due to sand inclusion. The sand inclusion defect was determined in each trial and is recorded in Table 6.

3. Analysis of Orthogonal Array

The results of the percentage of sand inclusion defect for each sample are shown in Table 6. These effects were only based on visual interpretation of the orthogonal array, and a simple statistical test would provide a more valid analysis of this variance.

$$H = -10 \log [1/n(\sum y_i^2)]$$

where H is the S/N ratio, "yi" is the individual defects percentage in columns, and n is the number of noise factors (in this case, n = 1).

TABLE 6. THE AVERAGE PERCENTAGE OF DEFECTS AND S/N RATIO

RUN	**Average percentage of defects (*β*)**	**S/N Ratio *H***
1	6	-15.5630
2	12	-21.5836
3	8	-18.0618
4	6	-15.5630
5	10	-20.0000
6	4	-12.0412
7	12	-21.5836
8	8	-18.0618
9	6	-15.5630

Added to this array are mean of the sand inclusion defect percentage, which are used to verify the performance of the calculated S/N ratio. By using Mini Tab software the result obtain in Taguchi analysis is shows in Tables 7 and 8 indicate that the optimal parameter settings are A2 (50 no mould hardness), B3 (1350 g/cm^2-green strength) and C1 (9 sec pouring rate).

The S/N effect table under the array in Table 8 indicates the mean of S/N values for each level of each control factor. The average defect percentage is as small as possible; the ideal S/N effects should always be as large as possible. This can be shown graphically as well. Fig. 5 shows the main effects plots of the average defect percentage and parameter levels in Tables 7. The Fig. 6 shows the S/N ratio effects plots of the defect percentage and parameter levels in Tables 8, the ideal parameter levels are identified and underlined.

TABLE 7. MEAN DEFECT PERCENTAGE

Response Table For Mean			
Level	***A***	***B***	***C***
1	8.667	8.000	**6.000**
2	**6.667**	10.000	10.000
3	8.667	**6.000**	8.000
Underlined and dark entries are ideal parameter levels.			

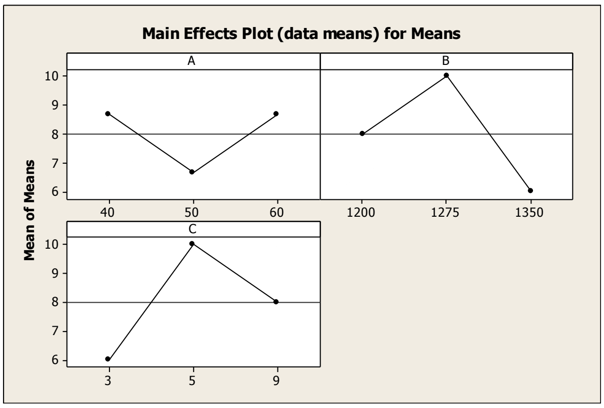

Figure 5. Main Effects Plot for Means

TABLE 8. S/N RATION

Response Table for Signal to Noise Ratios			
Level	***A***	***B***	***C***
1	-18.40	-17.57	**-15.22**
2	**-15.87**	-19.88	-19.88
3	-18.40	**-15.22**	-17.57
Underlined and dark entries are ideal parameter levels.			

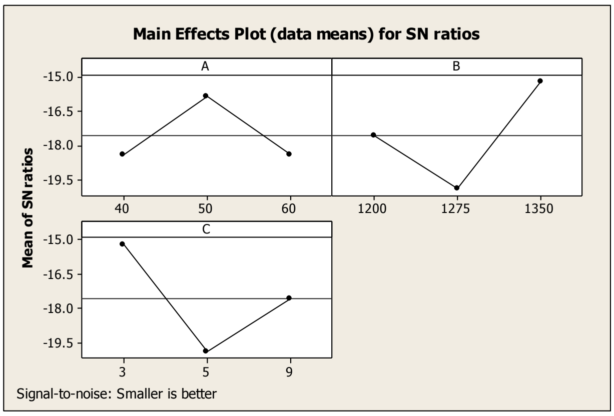

Figure 6. Main Effects Plot for SN ratios

4. Analysis of variation (ANOVA)

ANOVA is a statistical method to determine if the control factors have any significant impact on the sand inclusion defect. Taguchi method cannot judge and determine the effect of individual parameter on entire process. There were three control factors in this experiment: mould hardness (A), green strength (B) and pouring rate(C). Each has three levels, and ANOVAs of these three factors was conducted in Minitab. ANOVAs of the three control factors are shown in Table 9.

TABLE 9. RESULTS OF ANOVA FOR RESPONCE FUNCTION OF DEFECT

Factor	DF	SS	MS	F	P
A	2	8.00	4.00	0.43	0.670
B	2	38.00	19.00	3.21	0.046*
C	2	24.00	12.00	1.80	0.244
C×A	4	47.86	11.96	4.86	0.028*
C×B	4	21.52	5.38	0.56	0.594

*Significant at 5 per cent level of significance

The result is shown in Table 9. A "P" value less than 0.05 indicates that the respective factor is significant to the defect percentage at a 95% confidence interval. Table 9 shows that interaction between "Mould Hardness with Pouring Rate", and Green Strength value of 'P' is less than 0.05; this means that all interaction factors are significant to the defect percentage in the experiments.

5. Final setting and conformation run

Final settings of the significant input process parameter are given in Table 10. To validate the result of the decision on Taguchi method and ANOVA based process setting, the foundry management has takes trial confirmation run for setting the significant input process parameter. The final setting is done by the range of the closer to optimal process parameter gives to Taguchi analysis.

TABLE 10. FINAL SETTING OF SIGNIFICANT PROCESS PARAMETER

Sl. No.	**Significant Parameter**	**Final Setting (calculated range which is very closer to optimal setting parameters)**
1	Mould Hardness	48-52Number
2	Green Strength	1335-1360 g/cm^2
3	Pouring Rate	8-9 Sec

This newly derived parameter setting was used in the production process, and a total of 500 parts were produced in 10 Trial are conducted at the optimum setting of process; only 28 parts were scrapped due to sand inclusion defect is show in Table 11. The average of the responds casting defects in each experiment is found to be 5.6%.

TABLE 11. RESULTS OF THE CONFORMATION RUN

Trial No.	**A**	**B**	**C**	**Number of defect occur**	**Experimental result (defect%)**
1	48-52	1335-1360	8-9	3	6
2	48-52	1335-1360	8-9	2	4
3	48-52	1335-1360	8-9	3	6
4	48-52	1335-1360	8-9	4	8
5	48-52	1335-1360	8-9	2	4
6	48-52	1335-1360	8-9	2	4
7	48-52	1335-1360	8-9	4	8
8	48-52	1335-1360	8-9	2	4
9	48-52	1335-1360	8-9	3	6
10	48-52	1335-1360	8-9	3	6
Total				28	5.6

A-Mould hardness (number), B-Green strength (g/cm^2), C-Pouring rate (Sec).

E. Control Phase

The control stage is the last and final stage and its sole purpose is to preserve the optimized response obtained from the experiments. The main part of this phase includes standardization and documentation of the improved process and creating a plan for monitoring the process. In control phase the project team are to make a fully documentation of the process and what improvement changes is done.

A process flowchart was displayed at the working section with details of process specification. Check sheets were prepared for data recording for controlling the process. The control charts were made to monitor the process so that the operator can take timely action before the critical process parameters and performance characteristics go out of limits. These charts are very useful in understanding of process data recording and process is going on right or wrong direction. The major defects of Sand inclusion were analyzed and corrective action was taken. The rejection percentage declined to 5.6 from 9.58.

III. RESULTS AND DISCUSSION

In this case study, DMAIC based Six Sigma approach is implemented to optimize the process parameters of foundry. For the conformation of experiment, 500 (total of ten tests) components were produced and only 28 components were defective. It can be seen from the verification test results that the rejection percentage of defects of the casting process was greatly reduced by the optimal setting of process parameters. From the above results, it is proved that the casting parameters were optimized and minimum percentage of casting defect values was obtained. The stability of the casting process is also increased. Before the application of Taguchi and ANOVA, the parameters of the casting process were more arbitrary and difficult to control and hence the product quality suffered instability problems. Taguchi and ANOVA yielded optimized control factors, resulting in superior product quality and stability. A higher product yield is possible because prior to the application of the Taguchi and ANOVA, the casting defects of the molding process were 9.58 % of the Transmission Case castings produced, and, after the application of Taguchi and ANOVA, the casting defects of the molding process declined to 5.6 %.

To test the feasibility of the proposed process, experimental study was carried out to know the true picture by projecting a proposed process on production volume at this existing level. The Sigma level of the company increased to a higher level than under the existing process and the rejection percentage declined is shown in Table 12.

TABLE 12. RESULTS: BEFORE & AFTER

Part Name	Result	Average %	DPMO	Sigma Level
Transmission Case	Before	9.58	71757	2.97
	After	5.6	56000	3.12

IV. CONCLUSIONS

This study presented application of a six sigma DMAIC methodology to identify the problems in a casting process and solve the problem by determining the optimal operation parameters for reducing Sand inclusion defect. The problem was refined in the define phase to create a feasible project. The current condition of the company was inspected in the measure phase, and significant parameters were identified in the analyze phase. In the improve phase, a Taguchi method was applied to the set of parameters. In the control phase, we determined an optimal parameter setting for reducing the Sand inclusion defects.

The effect of casting parameters on the casting defect was evaluated, with the help of Taguchi analysis and optimal casting parameter conditions were determined to minimize the percentage of defects. The specific application of the ANOVA find out the mould hardness, green strength and pouring rate all the three parameter effect on percentage of defect compared with other parameters. The optimal parameter setting was identified from the mean Sand inclusion defects percentage effect table and the S/N ratio effects table. It can be concluded that use of the Six Sigma DMAIC approach was successful in identifying the problem, improving the process, and controlling the defects.

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