Validation of Taguchi optimization in sand casting process using process window approach based on theory of inventive problem solving method

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Abstract— **Optimization of sand casting process involves the adjustment of parameters as well as the improvement of optimization process procedures and measures. Analysis of various critical process parameters and the interaction among them is carried out with the help of Taguchi's method of experimental design. This paper proposes an innovative method, a process window approach (PWA) based on the Theory of Inventive Problem Solving (TRIZ) is to make the analysis more precise and validate the robustness of a casting process optimization. The successful validation of optimization demonstrates the feasibility of the proposed method. This article hopes to provide foundry personnel with innovative design ideas under practical applications.**

Keywords — ***TRIZ*, PWA, Taguchi, Sand Casting Process, Optimization, Parameters.**

INTRODUCTION

Optimization is a mathematical discipline and it comprises a wide variety of techniques which are used to improve business processes practically in all industries. In foundries, the commonly used process optimization methods, include trial and error, linear and non-linear methods, numerical simulation method, Taguchi design, grey scale and RSM method have been reported (Chi-Hui Chien[3]; Ghani[4]. However, all of these methods provide limited improvement of quality and economy for castings because they are only able to deal with sequential procedures, waste of substances and using of specified expensive software. In fact, the optimization of casting process involves not only the adjustment of parameters, but also the improvement of optimization procedures and measures. Therefore, the optimization procedures and measures must be taken to obtain adoptability in the optimization process by using theory of inventive problem solving method. The theory of inventive problem solving (TRIZ), one of the most important innovation theories, is capable of pointing out directions and approaches for solving technical problems. The Taguchi procedures has been shown to be an efficient and effective for achieving the optimum set of operating parameters for the particular product quality characteristic. Based on the report given in the literature, the Taguchi analysis for experiments is more expensive and it requires specialized software, knowledge workers and time. PWA is a simple statistical tool that quantifies the robustness of a manufacturing process which conform the process improvement with optimized parameters of manufacturing process, as reported by Jim Hall [10]. The idea of applying TRIZ is to improve the optimization process to cast a flywheel component which is realized by using this method. The success of the PWA optimization process for the sand casting process shows that the proposed method is of great potential for foundry..There is no a referred discussion or literature on implementing PWA using TRIZ application for the sand casting process optimization. This paper, introduces the TRIZ method (Altshuller [1], Li [13]) to assist the implementation process of PWA. Through case analysis, this paper wishes to establish a systematic PWA based on TRIZ application.

1. RESEARCH METHODOLOGY

This paper narrates the various critical process parameters and the interaction among them is carried out with the help of Taguchi’s method of experimental design and to optimize the results obtained. And also it is proposed the implementation of PWA based on TRIZ concept in order to optimize the variables of the sand casting process to minimize the casting defects developed in flywheel component. Eventually, the optimized parameters obtained by using Taguchi method is compared with PWA and validated in a foundry.

2. TAGUCHI’S ANALYSIS

2.1 *Orthogonal array*

Experience reveals that nonlinear behavior among the parameters of sand casting process can only be determined if more than two levels of parameters are used, and explained by Masters [15]. As per the study conducted to know the parameter interactions by Ross [17], it is inferred that there are significant interactions of moisture content with permeability and moisture content with loss on ignition. Therefore, based on the literature and the synthesized data of the foundry with the foundry man experience, moisture content variation with the permeability of the sand (A*B), and the moisture content variation with the loss on ignition of the sand (A*C), are taken to investigate the two factor interaction effect on casting rejection. The total degree of freedom (DOF) for nine parameters each at three levels and two second order interaction is 26 = (9 × (3 – 1) + 2(2 × 2)). Hence, the three levels Orthogonal Array (OA), with at least 26 degree of freedom has to be selected. The L27 OA having 26 degree of freedom is selected for the present work.

2.2 *Taguchi’s design*

The Taguchi’s analysis is done with the help of MINITAP 15 and the control factors can be very easily determined from the casting defects and S/N ratio. The casting defects are “lower the better” type of quality characteristics.

2.3 *Raw Data Analysis of Experimental Results*

The parameter interaction is assigned to the particular column of the selected orthogonal array and the factors at different levels are assigned for each trial. The experiments are conducted thrice for the same set of parameters using single repetition randomization technique given by Ross [17]. The percentage of defect for each repetition and average casting defects are calculated for each trial condition. Taguchi method uses the signal-to-noise ratio instead of the average to convert the trial result data into a value for the characteristic in the optimum setting analysis. The S/N ratio replicates both the average and the variation of the quality characteristic.

For the case of minimizing the performance characteristic, S/N ratio can be calculated as given in Equation (1):

$$SN_i = -10 \log \left(\sum_{I=1}^{N_I} Y_i^2 \text{Log} \quad (\Sigma_{I=1}=Yi^2/Ni) N_I \right) \quad (1)$$

Where, Y_i - response value of observation in i^{th} test, N_i- number of trials in i^{th} test

For example, for trial no. 1, the S/N ratio is:

S/N ratio = -10 log [$(7.68^2+ 6.58^2+ 6.87^2)/ 3$)] = - 16.97.

The average values of the response at each parameter level are obtained by adding the results of all trail level conditions and then dividing by the number of data points added. Taguchi method cannot judge and determine the effect of individual parameter on the entire process. The ANOVA is used to analyze the results of the conducted experiments. Once an experiment is conducted then the optimum treatment condition within the experiment is determined.

The parameter *A*, the levels total of the response at A_1 and A_2 are calculated and it is given in the equation (2).

$$A_1 = [y_{11}+y_{12}+y_{13}]+[y_{21}+y_{22}+y_{23}]+[y_{31}+y_{32}+y_{33}]+[y_{41}+y_{42}+y_{43}]+ [y_{51}+y_{52}+y_{53}]+[y_{61}+y_{62}+y_{63}]+[y_{71}+y_{72}+y_{73}]+ [y_{81}+y_{82}+y_{83}]+ [y_{91}+y_{92}+y_{93}] \quad (2)$$

and similarly for A_2

The average values of the responses at A_1, and A_2 are given in the equation (3)

$$\bar{A}_1 = \frac{A_1}{27} \text{ and } \bar{A}_2 = \frac{A_2}{27} \quad (3)$$

The average values of *S/N* ratios for each parameter at different levels are plotted in Fig 1. The *S/N* ratio is also greater at the same level of the parameters. In order to study the significance of the parameters, three way ANOVA is performed for casting defects and *S/N* ratios and the results are calculated. It could be seen from the F-ratio value that result the significant factors are the control factors in the order of *B* (permeability), *E* (volatile content), A (moisture content), I (mould pressure), *H* (pouring temperature), *C* (loss on ignition), G (pouring time), *D* (pouring time), and *F*(vent holes).

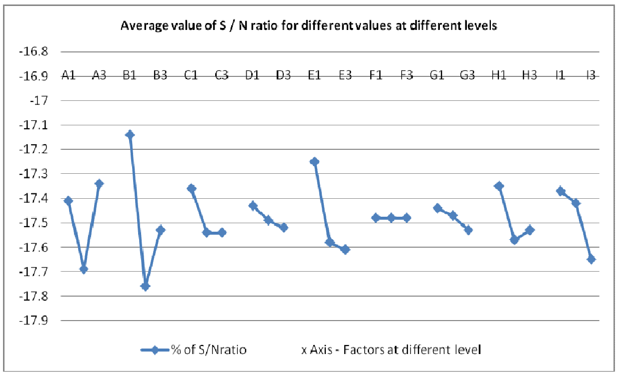

Figure.1 The average values of *S/N* ratios for each parameter at different levels

$$\mu = T + [A_3 - T] + [B_1 - T] + [C_1 - T] + [D_1 - T] + [E_1 - T] +$$

$$[F_3 - T] + [G_1 - T] + [H_1 - T] + [I_1 - T] \quad (4)$$

$$\mu = A_3 + B_1 + C_1 + D_1 + E_1 + F_3 + G_1 + H_1 + I_1 - 8T$$

μ=7.354+7.175+7.357+7.430+7.259+7.461+7.435 +7.337+7.361– 8 × 7.464

μ = 6.457 %

where, **μ is the casting defects at the optimal casting parameters**; T the average casting defects of all control factors; A_3 the lower value of average casting defect when factor A (moisture content) is at level 3, B_1 the lower value of average casting defect when factor B (permeability) is at level 1, C_1 the lower value of average casting defect when factor C (loss on ignition) is at level 1, D_1 the lower value of average casting defect when factor D (compressive strength) is at level 1, E_1 the lower value of average casting defect when factor E (volatile content) is at level 1, F_3 the lower value of average casting defect when factor F (vent holes) is at level 3, G_1 the lower value of average casting defect when factor G (pouring time) is at level 1, H_1 the lower value of average casting defect when factor H (pouring temperature) is at level 1, and I_1 the lower value of average casting defect when factor I (mould pressure) is at level 1.

3. THE TRIZ INNOVATIVE DESIGN METHOD

3.1 *TRIZ objective*

The Taguchi method points out clearly the technical and physical contradictions and thus helps TRIZ in the sense of identification of the problem becomes easy. TRIZ tools can be applied to resolve the contradictions.

3.2 *TRIZ contradiction matrix*

In solving engineering problems, the engineers usually encounter the system's contradiction, i.e., when a system improves one certain engineering feature, another engineering feature worsens. They are featured into **39 engineering parameters and 40 inventive principles** to establish a contradictive matrix and provide solutions for technical contradiction (Kim [11] and Marsh [14]). First of all, the technical personnel propose the encountered technical problem or conflict. The designer then introduces the TRIZ and transfers it into a TRIZ problem. The TRIZ problem solving process can be divided into the following steps:

Step 1: Confirm and clarify the encountered technical problem and difficulty that needs to be solved.

Step 2: The technical problem goes through TRIZ's 39 engineering parameters and becomes a TRIZ problem.

Step 3: Confirm whether technical contradiction or physics contradiction exists in the TRIZ engineering problem.

Step 4: Different parameter technical contradictions exist, then directly enter the TRIZ contradictive matrix to locate the corresponding principle. If a single improving or worsening parameter can be located only, or no conflict existed among parameters then refer step_6.

Step 5: Through a TRIZ contradictive matrix (improving parameter is set as Y-axis, while worsening parameter is set as X-axis), the conflict problem can obtain inventive suggested principle (refer to step 8). If a corresponding position is an empty matrix then refer step 6.

Step 6: Set parameter is introduced into single engineering inventive principle (SEIP) method to obtain inventive suggested principles (refer to step 8).

Step 7: The TRIZ separation principle is used to obtain suggested principle through separation of time, space, and substance.

Step 8: The Obtained TRIZ suggested principle conducts proper selection to obtain the TRIZ solution.

Step 9: The TRIZ solution transfers to inventive design reference for solving an actual engineering problem to produce a final solution.

Step 10: When obtained suggested principle cannot satisfy final demand, the engineering parameter can be redefined and go through steps 1 to 9 once again and obtain new suggested inventive principle (refer step 3).

Worsening feature Improving feature		# 23 Waste of substance
#35	Adaptability	15-Dynamics 10-Preliminary action 02- Taking out 13-The other way round

3.3 TRIZ *matrix formation*

Regarding the modification motive, the contradiction matrix engineer parameters are not convenient for use due to its rather big size. In addition, not all the engineering parameters are involved in the problems. The engineering parameter closest to the problem is selected according to different directions of demands. Taking into consideration these two points, the present study made slight modification on the selection of engineering parameters and contradiction matrix. Several engineering parameters closest to the modification problems are selected and the matrix is formed.

In this work, the engineering parameters “#35-Adaptability” as an improving feature and “#23-waste of substance” as a worsening feature are selected. The engineering characteristics are selected to improve the parameters and are incorporated with the contradiction matrix of modification for crossover to obtain the recommended number of the 40 innovation methods are 15- dynamics, 10- preliminary action, 02- taking out, and 13- the other way round.

Use of TRIZ contradictive matrix is shown in Table.1. The corresponding matrix obtains suggested inventive principles as 15,10,2 and 13. Through a TRIZ contradictive matrix, the improving parameter is set as adaptability to validate the Taguchi optimization process and this PWA is to find the optimal parameter level which supplements the other optimization process (improving parameter is set as Y-axis), as explained by Hsieh [7].The undesirable secondary effect i.e. worsening parameter is selected initially as convenient for use, area of non moving object, durability of non moving object and waste of substances.

Table.1 several engineering parameters closest to the modification problems are selected and the matrix is formed.

3.4 *TRIZ selection of inventive principles*

Based on the inventive principles for the corresponding X and Y axis parameters, the number of repeated inventive principles are identified and from the analysis the X axis parameter is confirmed and its related inventive principles are listed according to the rank given in the Table 2 . The definition for the inventive principles of segmentation and partial and excessive actions will not satisfy the specific problem solution of PWA which includes mathematical and analytical research for continuity. Hence, the preliminary action and the other way round principles are taken in addition with the principles 'taking out' and 'dynamics' principles.

Inventive Principle Number	***No of times occurrences***	***Name of the principles***
1	6	Segmentation
2	6	Taking out
7	1	Nested doll
10	2	Preliminary action
13	3	The other way round
14	1	Curvature
15	7	Dynamics
16	5	Partial or excessive actions
29	1	Pneumatics and hydraulics
32	1	Color changes
34	1	Discarding and recovering
35	1	Parameter changes

Table.2 The number of repeated inventive principles are identified and from the analysis the X axis parameter is confirmed and its related inventive principles are listed according to the rank

The selected most combination inventive principles for the respective parameters for validating and optimizing sand casting parameters are given in Table.3.

Principle 15- Dynamics: Allow a system or object to change to achieve optimal operation under different conditions. Split an object or system into parts capable of moving relatively to each other. If an object or system is rigid or inflexible, make it movable or adaptable. Increase the amount of free motion.

Principle 10- Preliminary action: It can be performed before it is needed the required change of an object (either fully or partially). Pre-arrange objects such that they can come into action from the most convenient place and without losing time for their delivery.

Principle 2- Taking out: Where a system provides several functions of which one or more is not required (and may be harmful) at certain conditions, design the system in such a way as they can be taken out.

Principle 13- The other way round: Use an opposite action(s) used to solve the problem; make moveable objects fixed, and the fixed objects movable; Turn the object, system or process upside-down.

1.1 *proposed model-Process Window Approach*

Inventive Principles (X axis)	***Inventive Principles (Y axis)***	***Principles***
Convenience of use	Adaptability	15, 16,1,34
Area of non moving object	Adaptability	15, 16
Durability of non moving object	Adaptability	2, 16
Waste of substance	**Adaptability**	**15,10,2,13-selected**
Adaptability	waste of substance	15,10,2

Table.3 The selected most combination inventive principles for the respective parameters for validating and optimizing sand casting parameters

(PWA)

Optimal solution arrived from the Taguchi analysis, the set of parameters are again analyzed to its significance on the defects. In this approach the most significant parameters moisture content, permeability, volatile content and mold pressure is selected and other parameters are kept as it is. These parameters are more critical to the overall process or more likely to cause defects. The PWA considers all interactive parameters separately and gives the optimal result for the individual parameter by selecting sweet spot through process window.

The data are available from the set of runs; the lowest probability can be confirmed by calculating the process capability index (Cpk) as Equation (6):

$$C_{pk} = (USL - \bar{X}) \div 3\sigma \; OR \; (\bar{X} - LSL) \div 3\sigma 3\sigma \quad (6)$$

(Whichever is less?)

If the mean value is centered between the LSL and the USL, then both (USL –Mean) and (Mean –LSL) are equal to [(USL+LSL) / 2], and both equations yield the same value of Cpk. If the mean value is not centered, then one of these differences will be less than [(USL+LSL) / 2], resulting in a lower Cpk. However, this relationship would most certainly be very product- specific, so no general guidelines can be given. If such data is available for a specific product, then the process setup should be adjusted to move the mean closer to this sweet spot to produce fewer defects. The Cpk is calculated for percentage of defects as derived in Table.4. The overall Cpk value provides an excellent metric for qualitatively evaluating processing parameter adjustments. If relationship between the Cpk and quality (defects) is clearly understood, an acceptable maximum Cpk value can be established for the PWA.

3.6 *TRIZ model calculation*

First step, the Cpk, Average Cpk for the respective runs and the row-column average Cpk are calculated to identify and confirms deviation of process from the optimal setting. Second step to identify and draw the window for the selected parameters. The higher values of average Cpk value for the corresponding X, Y parameters with respective column and row wise average Cpk values which determines and confirms the performance of the process for the given run. The third step is to evaluate, select the intersecting point of optimum parameter which produce less defects based on the higher values in the matrix derived. In the row average Cpk column the highest value has been selected first, similarly in the column average Cpk. The first line indicates where the permeability at 120 and Moisture Content of 3% has the sweet spot when it intersects with the optimal setting of parameters to produce minimum defects. This is the optimized value given by the Taguchi which confirm the PWA test result (P1). The next higher value in the selected interaction line for sweet spot (P1) will be noted as sweet spots (P2s), where also the casting defect is very less.

Moisture content	Runs	Cpk	Avg Cpk	Cpk	Avg Cpk	Cpk	Avg Cpk	Row Avg Cpk
3	1	0.81	0.92	0.58	0.78	0.87	0.8	0.83
	2	0.96		0.82		0.81		
	3	0.99		0.94		0.73		
3.3	1	0.96	0.84	0.90	0.8	0.72	0.73	0.79
	2	0.98		0.79		0.89		
	3	0.58		0.73		0.58		
3.6	1	0.77	0.83	0.65	0.78	0.63	0.72	0.78
	2	0.98		0.70		0.67		
	3	0.76		1.0		0.88		
Permeability		120		155		190		
Column Avg Cpk			0.86		0.79		0.75	

3.7 *Confirmation of Experimental Results*

Optimal conditions predicted are verified experimentally and compared with the calculated data to validate the fitness of the model. A small variation is observed in experimental results. Verification tests are conducted for the three selected tests conditions of defects predicted by the model at desirability level 1. The experimental results show the accuracy to the predicted level and the average of percentage of error in the production is **6.64.**

4. RESULTS AND DISCUSSIONS.

This work is started by optimizing sand casting process using the Taguchi method in a foundry. This work facilitates an innovative approach in new way in validating and optimizing casting process by preventing and eliminating the occurrence of typical steps in the optimization process. The inventive principles confirm the selected worsening (waste of substances) and improving (adaptability) parameters for the contradiction matrix. The Taguchi method of experimental design is applied to analyze the optimum levels of individual process parameters. The interaction effects between permeability, moisture content, volatile content and mold pressure are also quite significant and must be taken into account when designing further experiments as shown in Table.6. The results of each interaction parameters are more closer to each other and the occurrences in the selection of principle with respect to parameters is based on the TRIZ method which validates the optimal process requirements.

This study proves that the proposed TRIZ based PWA is capable of validating and optimizing sand casting process parameters. General solution for the specific problem and to the specific solution is identified by using the TRIZ engineering and innovative principles.

The optimum parameter values are then applied to the process and sample production data that is gathered from the foundry over a period of time. It illustrates the improved state and there is a considerable amount of reduction in percentage of defects is 6.44 in average and it is validated and confirmed by the TRIZ based PWA. The optimal parameter level for the interaction parameters are determined by the result of occurrences with respect to the individual parameter setup as given in Table.5.

Parameter designation	*Process parametes and its range*	*Mean of casting defects % contribution*	*S/N ratio of casting defects %*	*Optimum parameter value*	
				Taguchi (optimal)	*RSM (optimal range)*
A	Moisture content (%)- 3, 3.3,3.6	7.35 (>F value)	8.76	3.6	3.0 to 3.3
B	Permeability 120, 155, 190	24.40 (>F value)	25.39	120	120 to 155
C	Loss on Ignition (%) 3.5, 4.25,5	2.95	3.02	3.5	Insignificant
D	Comp strength (kg/cm^2),1 1.1.35,1.7	0.50	0.52	1	Insignificant
E	Volatile content (%) 2.1, 2.8, 3.5	10.83 (>F value)	10.07	2.1	2.12 to 3.5
F	Vent holes (No's) 8,9,10	-	–	10	Insignificant
G	Pouring Time (sec) 45,46.5,48	0.62	0.59	45	Insignificant
H	Pouring temp ($^\circ$ C) 1400,1420 ,1440	4.29	3.60	1400	Insignificant
I	Mould pressure (kg/cm^2) 5,6,7	6.33 (>F value)	6.13	5	5.8 to 6.85
% defects calculated from analysis				**6.457**	**5.73**
Average % defects confirmed				**7.32**	**6.44**
Average Error %				**11.8**	**6.64**

Table.5. calculation of average defects and average error %

1. CONCLUSIONS

Using the response surface methodology and by the Taguchi approach, a significant reduction in casting defects is obtained and it is validated and confirmed through the optimization process parameters by the TRIZ based PWA.

Based on the experimental and analytical results, the following conclusions are drawn.

1. The TRIZ based PWA is an innovative validation and optimization method for casting process parameters. In the PWA, all the individual parameters are interacting with each other to optimize parameter level and it is only interactive method to identify the impact of parameters on casting defects. It can be applied for various process parameters optimization.

2. In the Proposed Process, with the Taguchi and response surface analysis values for the range of average defect percentage is decreased from **7.32 to 6.44** and the **average error percentage is decreased from 11.8 to 6.64** as derived in Table.5.

3. Under a different parameter combination, the TRIZ tool can acquire different innovative principles and provide an improvement in optimization and concept to avoid much unnecessary trial and error work. The results revealed that minimal casting rejection percentage could be arrived significantly for casting operations.

4. In the TRIZ method, designer thinking is not limited by a single professional experience and the solution is equipped with innovation and diversification. The procedure has shown that it is an efficient and

effective way for achieving the optimum set of operating parameters for a particular product quality.

5. In terms of PWA, conflict problems (technical) encountered in the process can be provided by the alternative thinking principles of TRIZ. Thus, innovation replaces conventional compromise to avoid reduction of process quality and waste of substance.

Parameter Matrix	Parameters			
	Moisture Content %	Permeability	Volatile Content %	Mold Pressure kg/cm^2
Moisture content and Permeability	3,3,3.3	120,120,190		
Moisture content and Volatile Content	3,3.3,3		3.5,2.1, 2.1	
Moisture content and Mold Pressure	3,3,3.3			6,7,7
Permeability and Volatile Content		120,120,155	2.1,2.1, 2.8	
Permeability and Mold Pressure		120,120,190		6,7,7
Volatile Content and Mold Pressure			3.5,2.1, 2.1	6,7,7
Parameter selected based on the number of occurrences	**3**	**120**	**2.1**	**Range 6-7**

Table.6 The optimal parameter level for the interaction parameters

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