ELIMINATION OF POROSITY IN STEEL CASTING: AN EXPERIMENTAL APPROACH

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Key Words

Alloy steel; Experimentation; Taguchi's method; Multilevel; Idle column; Pseudofactor.

Introduction

An alloy steel foundry with a monthly capacity of 20 tonnes of casting was facing a chronic problem of porosity in one particular type of casting. (The material of the casting was 13% chromium steel ASTM-A217-74C Grade-GA 15). Porosity was observed in about 60–70% of the castings, 20% of which could be salvaged by welding. These castings weighed 4.5 kg each and the cost of the machined casting was about Rs 500 (rupees). The foundry was producing twice the customer's casting requirement per month to meet the customer's delivery schedule. However, there were occasions when the customer's delivery schedule still could not be met. Several experiments carried out earlier involving varying one parameter at a time and keeping the others constant did not give a satisfactory result. This conventional approach to experimentation (vary one parameter and keep others constant) is uneconomical, time-consuming, and unreliable, especially when there are a large number of influencing parameters. Here, statistically designed factorial experiment, where all parameters vary simultaneously, is a useful technique for experimentation. An orthogonal array (OA) design developed by Taguchi was used to find a solution to this chronic problem.

Factors and Levels for the Experiment

Factors and their levels for the alloy steel casting porosity experiment were identified in a brainstorming session with the technical people concerned, including the chief executive of the plant. Factors and levels identified for the experiment are given in Table 1.

There are 14 factors, of which 7 are at 2 levels, 6 are at 3 levels, and 1 is at 4 levels. Here, G is a pseudofactor and is nested in F; i.e., factor G becomes G′ (machining allowance) for F_1 (horizontal molding) and becomes G″ (chill) for F_2 (vertical molding). A full factorial experiment will require $2^7 \times 3^6 \times 4^1 = 373{,}248$ trials. The experiment was designed as an L_{32} (2^{31}) OA layout using the linear graph technique developed by Taguchi. Four-level factors are assigned in (2^n) series by using the multilevel technique and three-level factors are assigned using the idle column method. The nested factor G is assigned using the pseudofactor design. Multilevel, idle column techniques, and pseudofactor design are discussed in the Appendix. Factors A, B, C, D, E, and K are melting parameters; the other factors are molding parameters. In order to reduce the number of heats from 32 to 16, the melting variables

Table 1. Factors and Levels

FACTORS		LEVELS 1	2	3	4
A	% Fresh charge	20	70	45	—
B	% Carbon in metal	>0.15	0.10–0.15	<0.10	—
C	% Chromium in metal	12.5–14	11–12.5	—	—
D	Superheating time (min)	60	30	—	—
E	Furnace temperature (°C)	1590	1710	1650	—
F	Directions of molding	Horizontal	Vertical	—	—
G	Pseudofactor nested in F				
G'	Machining allowance (mm)	40	5	15	—
G"	Chill	Full	Nil	Half	—
H	Core venting	Without	With	—	—
I	Core painting	With	Without	—	—
J	Choke area in gating system	Existing	80% of existing	—	—
K	Deoxidizer	K1	K2	K3	K4
L	Pouring rate	Slow	Standard	Quick	—
M	Grain size of molding sand (AFS No.)	30–60	60–100	—	—

A, B, C, D, E, and K are assigned to the first 15 columns (primary and secondary zones) of the L_{32} table. Assignment of the factors to the column are done with the help of a linear graph as shown in Figure 1. The layout of the experiment is given in Table 2.

The Experiment

Sixteen heats (molten metal) were prepared per the experimental combination. Two experimental trials for each heat were conducted. For instance, experimental trials 1 and 2 are the outcome of heat 1, and trials 3 and 4 are the outcome of heat 2, and so on. This was possible because factors associated with the molten metal preparation were assigned to the first 15 columns of the L_{32} (2^{31}) layout. Experimental conditions in the first 15 columns are the same for each pair of two experiments. Three castings were poured for each experimental combination. Castings were inspected for porosity after machining and classified into three categories:

Good—free from porosity—G
Salvageable—welding possible—R
Scrap—welding not possible—S

Scores of 5, 4, and 1 were assigned to these categories based on the value recovered. The total score for each experimental combination is given in Table 3.

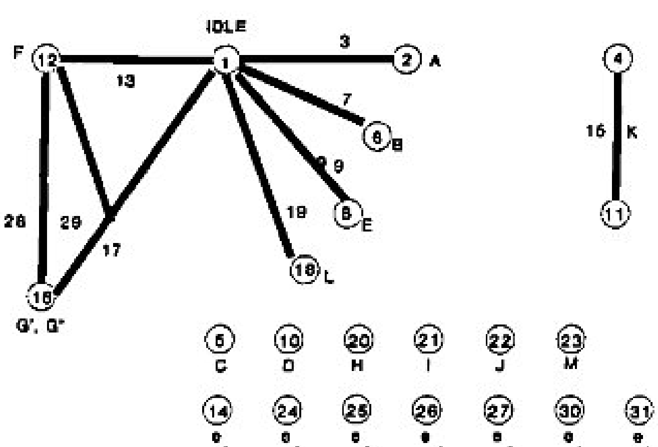

Figure 1. Linear graph. Experimental layout from the linear graph is given in Table 2.

Analysis and Results

An analysis of variance (ANOVA) was carried out on the score data. The results are given in Table 4. Here, e_1 represents the experimental error arising out of unused columns in the L_{32} layout and e_2 is the replication error, because three castings were made for each experimental combination. e_1 is tested against e_2 and found to be insignificant. Therefore, e_1 and e_2 are pooled, and an overall estimate of e is obtained. Effects of other factors are tested against e. It is seen that 9 factors are significant out of a total of 14 considered. Significant factors are A, B, C, E, G, I, J, K, and L. Here, the idle column 1 is significant,

Table 2. Layout of the Experiment: L_{32} (2^{31})

EXP. NO.	IDLE (1)	A (2,3)	B (6,7)	C (5)	E (8,9)	D (10)	K (4,11,15)	F (12)	G′/G″ (16,17)	L (18,19)	H (20)	I (21)	J (22)	M (23)
1	1	1	1	1	1	1	1	1	G′ 1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	2	2	2	2	2	2
3	1	1	1	1	2	2	2	2	G″ 1	1	1	1	1	1
4	1	1	1	1	2	2	2	2	2	2	2	2	2	2
5	1	1	2	2	1	1	3	2	1	1	2	2	2	2
6	1	1	2	2	1	1	3	2	2	2	1	1	1	1
7	1	1	2	2	2	2	4	1	G′ 1	1	2	2	2	2
8	1	1	2	2	2	2	4	1	2	2	1	1	1	1
9	1	2	2	1	1	2	2	1	1	2	1	1	2	2
10	1	2	2	1	1	2	2	1	2	1	2	2	1	1
11	1	2	2	1	2	1	1	2	G″ 1	2	1	1	2	2
12	1	2	2	1	2	1	1	2	2	1	2	2	1	1
13	1	2	1	2	1	2	4	2	1	2	2	2	1	1
14	1	2	1	2	1	2	4	2	2	1	1	1	2	2
15	1	2	1	2	2	1	3	1	G′ 1	2	2	2	1	1
16	1	2	1	2	2	1	3	1	2	1	1	1	2	2
17	2	3	3	2	3	1	2	1	3	3	1	2	1	2
18	2	3	3	2	3	1	2	1	2	2	2	1	2	1
19	2	3	3	2	1	2	1	2	G″ 3	3	1	2	1	2
20	2	3	3	2	1	2	1	2	1	2	2	1	2	1
21	2	3	2	1	3	1	4	2	3	3	2	1	2	1
22	2	3	2	1	3	1	4	2	1	2	1	2	1	2
23	2	3	2	1	1	2	3	1	G′ 3	3	2	1	2	1
24	2	3	2	1	1	2	3	1	2	2	1	2	1	2
25	2	1	2	2	3	2	1	1	3	2	1	2	2	1
26	2	1	2	2	3	2	1	1	2	3	2	1	1	2
27	2	1	2	2	1	1	2	2	G″ 3	2	1	2	2	1
28	2	1	2	2	1	1	2	2	1	3	2	1	1	2
29	2	1	3	1	3	2	3	2	3	2	2	1	1	2
30	2	1	3	1	3	2	3	2	1	3	1	2	2	1
31	2	1	3	1	1	1	4	1	G′ 3	2	2	1	1	2
32	2	1	3	1	1	1	4	1	2	3	1	2	2	1

meaning that the block effect of the first 16 experiments to the last 16 experiments is significant. It is mainly due to the confounding of some of the effect with the idle column. The last column in the ANOVA table gives the ρ percentage (degrees of contribution) for critical factors. Of the total variation, 69.9% is explained by the critical factors. The average response for different levels of significant factors were computed and are given in Table 5.

Optimum Combination

The best levels of significant factors are found by comparing the level response by average score. The level with the highest score is the best level. Thus, the optimum combination arrived at is

$$A_2,\ B_2,\ C_1,\ E_2,\ F_1,\ G_1',\ J_2,\ I_2,\ K_4,\ L_2.$$

Confirmatory Trial

A trial batch of 30 castings was made with the optimum combination. Castings were machined and inspected for porosity. The results were as follows:

Good castings	28
Salvageable	1
Reject	1

Table 3. Experimental Data

EXP. NO.	RESPONSE G	S	R	SCORE (REP.) 1	2	3	TOTAL SCORE
1	0	0	3	1	1	1	3
2	0	0	3	1	1	1	3
3	0	1	2	4	1	1	6
4	2	1	0	5	5	4	14
5	0	0	3	1	1	1	3
6	0	0	3	1	1	1	3
7	2	1	0	5	5	4	14
8	0	0	3	1	1	1	3
9	3	0	0	5	5	5	15
10	3	0	0	5	5	5	15
11	3	0	0	5	5	5	15
12	2	1	0	5	5	4	14
13	2	1	0	5	5	4	14
14	3	0	0	5	5	5	15
15	2	1	0	5	5	4	14
16	0	2	1	4	4	1	9
17	0	0	3	1	1	1	3
18	0	2	1	4	4	1	9
19	0	0	3	1	1	1	3
20	0	1	2	4	1	1	6
21	2	1	0	5	5	4	14
22	3	0	0	5	5	5	15
23	0	1	2	4	1	1	6
24	1	2	0	5	4	4	13
25	0	3	0	4	4	4	12
26	0	0	3	1	1	1	3
27	2	1	0	5	5	4	14
28	0	2	1	4	4	1	9
29	0	0	3	1	1	1	3
30	0	1	2	4	1	1	6
31	1	1	1	5	4	1	10
32	1	2	0	5	4	4	13
Total	32	25	39	116	101	82	299

n other words, the optimum combination resulted in 9 .3% usable castings. The optimum combination was mplemented on a permanent basis by modifying and releasing the method sheet. Implementation of the optimum combination gave, on average, 90% porosity-free castings against the earlier level of 30–40%.

Conclusion

It is thus seen that fractional factorial experiments using the orthogonal array layout adopted by Taguchi has helped in identifying as many as nine critical material and process parameters and their best levels for eliminating the porosity in an alloy steel casting. The porosity was reduced to less than 10%, as compared to 59–70% earlier. The experimentation was quite economical as the results were achieved involving only 32 trials, whereas a full factorial experiment would have required 373,248 trials—an impossible number to be tried in an investigation. The experiment has been highly successful, as about 70% of the total variation is explained by the critical factors. The company has saved about Rs 0.10 million per annum.

Table 4. ANOVA on Porosity

SOURCE	d.f.	S.S.	M.S.	F	ρ (%)
Idle 1	1	4.59	4.59	4.73*	
Idle 13	1	0.51	0.51	0.53	
C	1	10.01	10.01	10.32**	2.9
D	1	0.09	0.09	0.09	
F	1	0.84	0.84	0.87	
H	1	0.09	0.09	0.09	
I	1	17.51	17.51	18.05**	5.4
J	1	14.26	14.26	14.70**	4.3
M	1	0.26	0.26	0.268	
A_1-A_2	1	80.08	80.08	85.26**	25.7
A_1-A_3	1	0.02	0.02	0.02	
B_1-B_2	1	0.33	0.33	0.34	
B_2-B_3	1	22.69	22.69	23.39**	7.1
E_1-E_2	1	6.75	6.75	6.99*	1.9
E_1-E_3	1	1.69	1.69	1.74	
G_1'-G_2'	1	10.67	10.67	11.00**	3.3
G_2'-G_3'	1	2.04	2.04	2.10	
G_1''-G_2''	1	2.67	2.67	2.75	
G_3''-G_1''	1	0.17	0.17	0.18	
L_1-L_2	1	0.08	0.08	0.08	
L_2-L_3	1	13.02	13.02	13.42**	3.9
K	3	50.36	16.79	17.39**	15.4
e_1	7	12.34	1.76	1.99	
ST_1	31	251.07			
e_2	64	56.67	0.88		
ST_2	95	307.74			
Pooled error	71	69.01	0.97		

Note: Total contribution of ρ (%) = 69.9.
*Significant at 5% level.
**Significant at 1% level.

Appendix: Multilevel, Idle Column, and Axial Factor Techniques

Multilevel Technique

This technique is useful in designing fractional experiments when the number of levels of different factors are not the same. For such an experiment, a multilevel arrangement is applied; that is, to arrange a 4- or 8-level column in 2-level series orthogonal tables, or to arrange a 9- or 27-level in 3-level series orthogonal tables. Let us consider the problem of accommodating a 4-level factor in the 2-level orthogonal array series. In the linear graph, the representation of a 4-level factor is made by the two nodes and the edge joining them. In other words, we use three columns of the array for a 4-level factor. The two columns corresponding to the two nodes give four possible level combinations: (1, 1), (1, 2), (2, 1), and (2, 2). We use the following one-to-one correspondence to obtain the corresponding levels of the 4-level factor.

$$(1, 1) \to 1, \qquad (2, 1) \to 3,$$

$$(1, 2) \to 2, \qquad (2, 2) \to 4.$$

This assignment using the multilevel technique is explained as follows: Let us assume that A has four levels and B, C, D, and E have two levels each. The assignment using the linear graph is shown in Figure 2. Table 6 gives the assignment to an orthogonal array.

Idle Column Method

This method is used to accommodate 3-level factors in 2-level orthogonal series. Let A be a factor at two levels A_1 and A_2, and let B be a factor at three levels B_1, B_2, B_3.

Table 5. Average Response (Score)

FACTOR	AVERAGE SCORE	FACTOR	AVERAGE SCORE
A_1	2.48	I_1	2.69
A_2	4.62	I_2	3.54
A_3	2.88	J_1	2.73
B_1	3.25	J_2	3.50
B_2	3.50	L_1	3.29
B_3	3.25	L_2	3.40
C_1	3.44	L_3	2.38
C_2	2.79	K_1	2.46
E_1	3.02	K_2	2.54
E_2	3.71	K_3	2.38
E_3	2.71	K_4	4.08
G_1'	3.83		
G_2'	2.83		
G_3'	2.58		

B is treated as pseudofactor at two levels. If it is assigned in a 2-level series table, part of B forms B_1 and B_2 when A is A_1, and forms B_2 and B_3 when A is A_2. The column $A \times B$, which is the interaction of factor A and pseudofactor B in the orthogonal table, must be erased. The distribution of the degrees of freedom is presented in Table

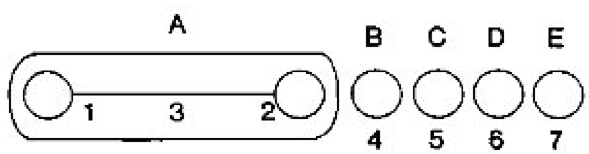

Figure 2. Linear graph for 4×2^4 design.

Table 7. Distribution of Degree of Freedom for Idle Column Method

FACTORIAL EFFECTS	DEGREE OF FREEDOM
A	1
B_1 vs. B_2 (from A_1)	1
B_2 vs. B_3 (from A_2)	1
Total	3

7. Such a layout results in the confounding of the comparison between B_1 and B_3 (precisely half the effect between B_1 and B_3) with the effect between A_1 and A_2. However, the effect due to factor A can be calculated after making corrections due to the effect of factor B. Because such a correction is not desirable, the column where A is assigned is kept empty. The column of interaction between the empty column and column B is erased from the orthogonal table as it is used up. The empty column is called an "idle column."

A single idle column can be used for more than one factor with three levels. We should use a design which permits the estimation of the interaction between the idle column and the pseudofactor, representing a 3-level factor. Those columns should be erased from the orthogonal table, as they are already used up.

Example: A $3^2 \times 2^2$ Experiment in Eight Trials

Let A and B be factors with three levels and C and D be factors with two levels. Using any one of the linear graphs associated with the array (3, 7, 2, 2), the following arrangement can be obtained. The assignment using the

Table 6. Assignment of $4^1 \times 2^4$ Design in L_8 (2^7) Using Multilevel Technique

EXPERIMENT NO.	1	2	3	A 1 2 3	B 4	C 5	D 6	E 7
1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2
3	1	2	2	2	1	1	2	2
4	1	2	2	2	2	2	1	1
5	2	1	2	3	1	2	1	2
6	2	1	2	3	2	1	2	1
7	2	2	1	4	1	2	2	1
8	2	2	1	4	2	1	1	2

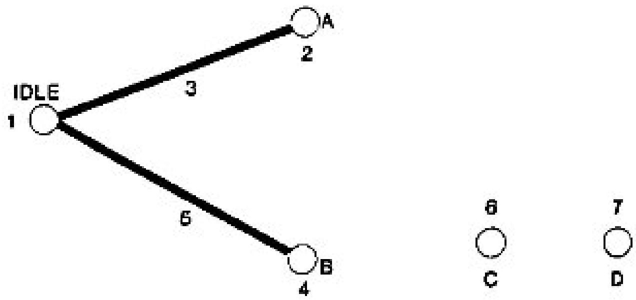

Figure 3. Linear graph. Experimental layout from the linear graph is given in Table 8.

idle column method is shown in Figure 3 and Table 8. The breakdown of degrees of freedom is shown in Table 9.

Axial-Factor (Nested-Factor) Method

The concept is illustrated with the help of an example. At the manufacturing stage of alloy steel casting, two methods of molding are considered:

A_1: Horizontal molding
A_2: Vertical molding

The optimum conditions of horizontal and vertical molding are not known. To find optimum operating conditions for horizontal molding, the machining allowance is considered:

B′: Machining allowance—3-level

to find optimum operating conditions for vertical molding, the factor chill is considered:

B″: Chill—3-level

Table 8. Layout of $3^2 \times 2^3$ Experiment Using Idle Column Method

EXP. NO.	IDLE 1	A 2 3	B 4 5	C 6	D 7
1	1	1	1	1	1
2	1	1	2	2	2
3	1	2	1	2	2
4	1	2	2	1	1
5	2	2	2	1	2
6	2	2	3	2	1
7	2	3	2	2	1
8	2	3	3	1	2

Table 9. Distribution of Degrees of Freedom

FACTORIAL EFFECTS	DEGREE OF FREEDOM
Idle	1
A_1 vs. A_2	1
A_2 vs. A_3	1
B_1 vs. B_2	1
B_2 vs. B_3	1
C	1
D	1
Total	7

Therefore, the problem is to design an experiment so as to obtain the main effects B′ under condition A_1 and the main effects B″ under condition A_2, and then compare the optimum condition of A_1 and A_2. When factors under A_1 and A_2 are not the same as shown above, it is assigned as follows. Ordinarily, the interaction of A and B is obtained by the composition shown in Table 10. In our example, B is nested in A. The levels of the factor B for A_1 have no correspondence with the level of B for A_2. In this situation, a more meaningful thing is to study the effect of factor B for A_1 and A_2 separately. This results in the breakdown presented in Table 11.

In this way, the decomposition is perfect no matter how effect B varies from A_1 to A_2. This leads to the assumption that factor B could be different factors for A_1 and A_2.

Table 10. Decomposition

FACTORIAL EFFECT	DEGREE OF FREEDOM
A	1
B	1
A × B	1
Total	3

Table 11. Breakdown

FACTORIAL EFFECT	DEGREE OF FREEDOM
A	1
B′ (Under condition A_1)	1
B″ (Under condition A_2)	1
Total	3

Thus, factor B which becomes B′ for A_1 and becomes B″ for A_2 is called an axial factor.

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