TOTAL QUALITY MANAGEMENT, VOL. 9, NO. 7, 1998, 563–572

Determination of optimum sand mix for CO_2 core

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Summary *A foundry producing heavy casting (> 300 kg) using CO_2 core was facing two chronic problems on CO_2 core. 10–12% of core were breaking at the green stage due to low compression strength. 3–4% of castings developed cracks at the time of core removal due to low collapsible property of core. Several studies carried out on sand mix composition by varying one parameter at a time while keeping others constant did not yield satisfactory results. An exploratory study using statistical experimental design was conducted considering 8 variables to determine the optimum sand mix composition for manufacturing CO_2 core. All the variable turns out to be significant*

A fractional experiment using the OA layout developed by Taguchi has helped in identifying the critical core sand mix parameters and their best levels for improving the strength at the green stage and achieving high collapsibility at the knock out stage. Core breakage at the green stage is totally eliminated, as are cracks and breakages of the casting on account of hard core. The experimentation has been quite economical because the results were achieved by carrying out 32 trails only, whereas a full factorial experiment would have required 13 824 trials.

Introduction

Core, a solid block made out of sand and various additives, is placed inside the mould cavity. Casting is formed by pouring the liquid metal in between the space of the core and the mould. The main function of the core is to form the internal shape of the casting. After the metal solidifies, the solid core is removed by hitting the outer surface of the casting. Two problems were faced with the core, first at the green stage and second at the time of its removal from the casting. The problems were:

(1) Green core breaks during handling and storage due to softness (low compression strength).
(2) It is difficult to remove the baked core from the casting due to its hardness (high compression strength), which resulted in the castings developing cracks and breaking.

These problems are acute in foundries producing heavy castings (> 300 kg). For example, in a foundry producing medium and heavy castings the casting rejection was 3–4% and 10–12% of the cores were breaking at the green stage. The objective of the study was to determine a composition for the sand mix for manufacturing the CO_2 core which has the following properties:

- high compression strength at the green stage to prevent breakages during handling and storage;
- low retained strength or high collapsibility so the core crumbles at the knock-out stage.

Previous studies to investigate the effect of varying one parameter at a time while keeping others constant on the sand mix composition and its properties did not yield satisfactory results. An exploratory study using a statistical experimental design was thus planned to determine the optimum sand mix composition for manufacturing the CO_2 core with sufficiently high compression strength at the green stage and high collapsibility at the knock-out stage.

Identification of factors and levels for experimentation

The available literature on earlier work done on the CO_2 silicate process in India and abroad was reviewed. The literature survey highlighted factors and their levels to be studied. The factors and levels were finalized in a brainstorming session with the faculty from the foundry division of the Indian Institute of Science, Bangalore, and the foundry technical personnel. The factors and levels thus identified are given in Table 1. Factor H, i.e. temperature, is a noise factor here, and is included here to find out the best level of the other factors, although there is a variation in the temperature. Taguchi (1980) suggests keeping the noise factor in another array, but this increases the size of the experiment. Wu, C.F.J., on the other hand, suggest that it is not necessary to keep the noise factor in another array. Noise factors can also be included as part of the main experiment on control factors (Miller *et al.*, 1993/4).

Experimental design

Factors and levels

As can be seen from Table 1, factor D is nested in C. Factor C (collapsible agent) has got four levels, and these levels have subsequent factors as a percentage of material to be added

Table 1. *Factors and levels*

Factor		Level 1	Level 2	Level 3	Level 4
A	Sand (AFS no.)	30–35	60–65	50% of (30–35) + 50% of (60–65)	25% of (30–35) + 75% of (60–65)
B	Sodium silicate (%)	4	5	6	—
C	Collapsible agent	Silicol	Dextrine	Coal dust	Dexil
D	(C_1) Silicol (%)	1	2	—	—
D	(C_2) Dextrine (%)	0.5	1	—	—
D	(C_3) Coal dust (%)	2.0	3	—	—
D	(C_4) Dexil (%)	0.5	1	—	—
E	Moisture (%)	0	1	2	4
F	CO_2 gas passing time (s)	30	60	120	—
G	Shelf-life	0	24	48	96
H	Temperature	200/250	500/550	850/900	—

in the sand. The level of D for C_1 has no correspondence with the level of D for C_2, C_3 and C_4, so a separate study is needed to determine the effect of D for C_1, C_2, C_3 and C_4. The interaction of C and D can be obtained as follows:

Factorial effect	*Degrees of freedom*
C	3
D	1
C × D	3
Total	7

Since D is nested in C, a separate study for C_1, C_2, C_3 and C_4 is more meaningful. This results in the following decomposition:

Factorial effect	*Degrees of freedom*
C	3
D (C_1)	1
D (C_2)	1
D (C_3)	1
D (C_4)	1
Total	7

This decomposition shows that a design which permits estimability of interaction C × D should be used.

The experiment was designed with a L_{32} (2^{31}) orthogonal array (OA) layout (Taguchi, 1962), i.e. involving 32 experiments (only a main effect plan was considered), whereas a full factorial experiment would require 13 824 experimental trials. Three and four level factors were assigned in a 2^n series by using the multi-level and dummy-level technique (Anand, 1993/4). The associated linear graphs (Fig. 1) were obtained from a standard linear graph of the array OA (32, 31, 2) (Taguchi, 1962).

Three and four level factors are assigned in 2^n series by the method known as collapsing of the column. By collapsing the two columns, a column with a four level factor is generated. A three level factor is assigned to a four level column by assigning the most favourable level out of the three to the fourth level of the column. In other words, the most favourable level is repeated twice the number times compared to the other two levels. This technique of assignment is also known as the multi-level and dummy-level technique. The layout of the experiment is given in Table 2.

Response

The responses considered were the strength of the core at:

(1) Green stage—after passing CO_2 gas.
(2) Knock-out stage—after baking at different temperatures.

The actual condition at the knock-out stage is simulated by baking the core sample.

Method

The levels of various factors chosen in the experiment were randomized and trials were carried out in a random order.

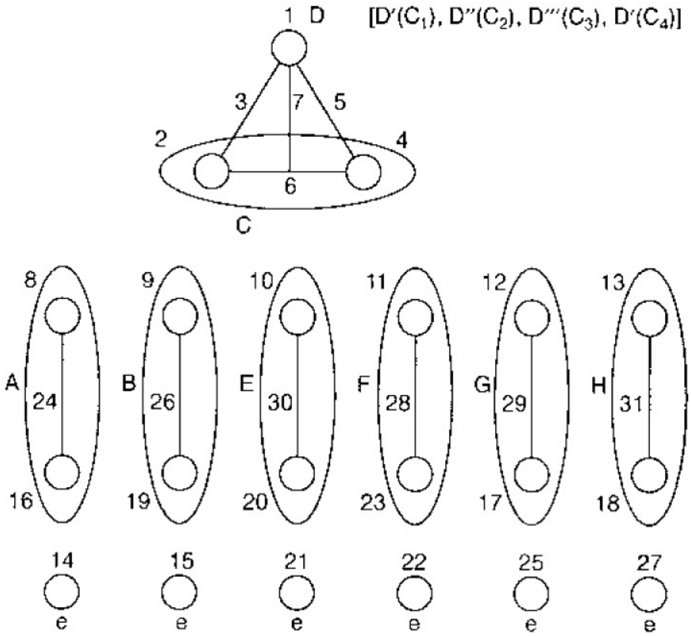

Figure 1. *Linear graph.*

Sand (2 kg) was prepared for each experimental combination. Six standard sample pieces of size 2″× 2″ were prepared for each experiment. The experiments were conducted at the foundry division of the Indian Institute of Science, Bangalore, due to its better facilities. Three sample pieces were tested for compression strength at the green stage and the remaining three sample pieces were tested after baking. The compression strength for each experimental combination is given in Appendix A.

Analysis of data

Significant factors

It was decided to carry out more than one analysis to extract the maximum information on the behaviour of different factors on the two responses, i.e. the compression strength at the green stage and the compression strength after baking. Separate analyses were carried out on each of the two responses to arrive at the best combination for the sand mix composition (Table 3).

The various sums of squares required in the different analyses for preparing the analysis of variance (ANOVA) table were obtained with the help of a computer program. F-Ratios were computed for each ANOVA and the test of significance was carried out (Chakravarti *et al.*, 1985). The significant factors were identified as revealed by each analysis. Table 4 gives the significant factors arising from the different analyses and Table 5 gives the average responses for significant factors.

The best level of the significant factors on the two responses, i.e. the compression strength at the green stage and the compression strength at the bake-out stage based on the average responses are summarized in Table 6.

Table 2. *Experimental layout L_{32} (2^{31})*

	Levels of variables							
Exp. no.	A 8, 16, 24	B 9, 19, 26	C 2, 4, 6	D 1	E 10, 20, 30	F 11, 23, 28	G 12, 17, 29	H 13, 18, 31
1	1	1	1	1	1	1	1	1
2	2	2	1	1	2	2	2	2
3	4	1′	1	1	4	1′	4	3′
4	3	3	1	1	3	3	3	3
5	1	1	2	1	2	2	4	3′
6	2	2	2	1	1	1	3	3
7	4	1′	2	1	3	3	1	1
8	3	3	2	1	4	1′	2	2
9	1	2	4	1	4	3	1	2
10	2	1	4	1	3	1′	2	1
11	4	3	4	1	1	2	4	3
12	3	1′	4	1	2	1	3	3′
13	1	2	3	1	3	1′	4	3
14	2	1	3	1	4	3	3	3′
15	4	3	3	1	2	1	1	2
16	3	1′	3	1	1	2	2	1
17	1	3	1	2	1	3	2	3′
18	2	1′	1	2	2	1′	1	3
19	4	2	1	2	4	2	3	1
20	3	1	1	2	3	1	4	2
21	1	3	2	2	2	1′	3	1
22	2	1′	2	2	1	3	4	2
23	4	2	2	2	3	1	2	3′
24	3	1	2	2	4	2	1	3
25	1	1′	4	2	4	1	2	3
26	2	3	4	2	3	2	1	3′
27	4	1	4	2	1	1′	3	2
28	3	2	4	2	2	3	4	1
29	1	1′	3	2	3	2	3	2
30	2	3	3	2	4	1	4	1
31	4	1	3	2	2	3	2	3
32	3	2	3	2	1	1′	1	3′

Optimum combination

An examination of the best level of the significant factors in the foregoing analysis reveals three areas of conflict. The first level of factor A (sand mix composition) is found to be better for compression strength at the bake-out stage, whereas either the second or third level of factor A is better for compression strength at the green stage. Similarly, the first and third level of factor C (collapsible agent) is found to be better for compression strength at the green stage whereas the fourth level of factor C is better for compression strength after bake-out. Bad smell was observed during the usage of Dexil (C_4) as the collapsible agent in the

Table 3. *Summary of analyses*

No.	Response	Description
1	Compression strength at green stage	(a) ANOVA on mean response (b) ANOVA on variance (c) Concurrent measure (i.e. S/N ratio (Taguchi *et al*., 1980) as suggested by Taguchi)
2	Compression strength	(a) ANOVA on mean response (b) ANOVA on variance (c) Concurrent measure (i.e. S/N ratio)

Table 4. *Significant factors*

	Green stage			Bake-out stage		
Factor	Mean	Variance	S/N Ratio	Mean	Variance	S/N Ratio
A	✓		✓	✓		✓
B	✓		✓	✓		
C	✓		✓			
D^{IV} (C_4)				✓		
E	✓					
F	✓	✓	✓	✓		
G	✓		✓	✓		

Table 5. *Average response table for significant factors*

	Green stage			Bake-out stage		
Factor level	Mean	Variance	S/N Ratio	Mean	Variance	S/N Ratio
A_1	4.36		10.49	28.77		− 25.54
A_2	12.16		20.31	43.69		− 31.54
A_3	12.17		20.45	54.92		− 33.57
A_4	8.44		17.34	42.46		− 30.98
B_1	10.43			39.19		
B_2	7.00			52.37		
B_3	9.27			39.10		
C_1	11.35					
C_2	7.94					
C_3	9.77					
C_4	8.07					
E_1	7.69					
E_2	8.46					
E_3	11.45					
E_4	9.52					
F_1	9.09	0.67	17.50	45.82		
F_2	4.58	0.74	11.55	42.15		
F_3	14.37	2.55	22.03	36.05		
G_1	7.10		15.60	44.16		
G_2	8.32		16.70	36.00		
G_3	9.51		16.28	61.89		
G_4	12.19		20.01	27.78		
D_1^{IV} (C_4)				57.50		
D_2^{IV} (C_4)				28.75		

Table 6. *Best level of critical factors*

Response	Best level of critical factors
Compression strength	
(1) Green stage	
(a) Mean	$A_{2,3}$, $B_{1,3}$, $C_{1,3}$, E_3, F_3, G_4
(b) Variance	F_1 or F_2
(c) S/N ratio	$A_{2,3}$, F_3, G_4
(2) Bake-out stage	
(a) Mean	A_1, $B_{1,3}$, F_3, G_4, C_4, D_4^{IV}
(b) S/N ratio	A_1

sand and the use of such material is not recommended on a permanent basis. Therefore, factor C can be chosen at the first level or third level, i.e. C_1 or C_3.

The level of factor D (percentage content) is determined by comparing the average compression strength at the green and baked stages. Factor D at the second level was found to be better for factor C at C_1 while factor D at the first level was found to be better for C at C_3.

The third area of conflict is with factor F. The third level of factor F is found to be better in all the analyses except the variance analysis at the green stage. At the green stage, a higher compression strength is needed to avoid breakage of the core. Choosing F at either the first or second level will result in lower compression strength. The compression strength at the green stage drops down by about 10 units when F is at the second level and it increases the mean strength after baking by 6 units (see Table 5). The objective of high compression strength at the green stage and low compression strength at bake-out will not be met if we choose F other than at the third level. Therefore, F is chosen at the third level only. An optimum combination had to be found among the six alternative possibilities:

(a) $A_1\ B_1\ C_3\ D_1\ E_3\ F_3\ G_4$ (d) $A_1\ B_1\ C_1\ D_2\ E_3\ F_3\ G_4$
(b) $A_2\ B_1\ C_3\ D_1\ E_3\ F_3\ G_4$ (e) $A_2\ B_1\ C_1\ D_2\ E_3\ F_3\ G_4$
(c) $A_3\ B_1\ C_3\ D_1\ E_3\ F_3\ G_4$ (f) $A_3\ B_1\ C_1\ D_2\ E_3\ F_3\ G_4$

The expected results with regard to compression strength at the green stage and bake-out stage were estimated for the six combinations and are shown in Table 7.

The second possibility was considered because the compression strength is quite low at the bake-out stage, i.e. good enough to prevent breakage during the green stage. A compression strength of 3.81 will not pose any problem during the removal of the core at the knock-out stage. Thus, the second combination was selected as an overall optimum combination: $A_2\ B_1\ C_3\ D_1\ E_3\ F_3\ G_4$.

Table 7. *Expected responses for the six possibilities*

	Compression strength	
Possible combination	Green stage	Bake-out stage
(a) $A_1\ B_1\ C_3\ D_1\ E_3\ F_3\ G_4$	16.61	0
(b) $A_2\ B_1\ C_3\ D_1\ E_3\ F_3\ G_4$	24.41	3.81
(c) $A_3\ B_1\ C_3\ D_1\ E_3\ F_3\ G_4$	24.42	15.05
(d) $A_1\ B_1\ C_1\ D_2\ E_3\ F_3\ G_4$	20.99	0.41
(e) $A_2\ B_1\ C_1\ D_2\ E_3\ F_3\ G_4$	28.79	15.33
(f) $A_3\ B_1\ C_1\ D_2\ E_3\ F_3\ G_4$	28.80	26.57

Confirmatory trial

Sand (300 kg) was prepared with the optimum combination and 10 large cores were made. Castings were made after 4 days of core shelf-life and core removal was observed at the knock-out stage. Core sand came out with minimum effort in 2–3 minutes; previously, it had taken 8–10 minutes. Hard hitting of casting for removal of the core was not necessary. The process was implemented on a permanent basis and a new process standard was released.

Conclusions

It has been shown that a fractional factorial experiment using the OA layout developed by Taguchi has helped in identifying the critical core sand mix parameters and their best levels for improving the strength at the green stage and achieving high collapsibility at the knock-out stage. Core breakage at the green stage is totally eliminated, as are cracks and breakages of the casting on account of hard core.

The experimentation has been quite economical because the results were achieved by carrying out 32 trials only, whereas a full factorial experiment would have required 13 824 trials.

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Appendix A: *Response of the experiment*

Exp. no.	Trial no.	Compression strength at green stage (kg cm)^2	Compression strength after baking (kg cm)^2
29	1	0.8	6.4
		0.7	4.0
		0.9	5.0
6	2	9.0	76.0
		8.2	70.0
		8.6	68.0
25	3	3.5	16.0
		4.0	18.0
		1.9	24.0
4	4	24.0	74.0
		20.0	80.0
		21.0	90.0
23	5	3.8	56.0
		3.5	43.0
		3.3	50.0
8	6	7.5	19.0
		9.0	16.0
		8.5	17.0
30	7	18.0	36.0
		16.0	56.0
		17.0	48.0
26	8	3.4	37.0
		5.0	34.0
		3.0	40.0
27	9	7.1	20.0
		6.5	21.0
		8.1	20.0
32	10	7.0	88.0
		6.0	90.0
		6.4	86.0
22	11	16.0	9.3
		14.0	9.2
		14.0	8.5
19	12	7.2	124.0
		5.2	96.0
		4.3	99.0
14	13	18.0	36.0
		20.0	46.0
		22.0	56.0
2	14	4.1	30.0
		4.5	40.0
		5.0	39.0
28	15	18.0	37.0
		16.0	38.0
		13.0	40.0
12	16	8.0	90.0
		9.5	96.0
		8.8	100.0
5	17	2.0	19.0
		4.0	25.0
		3.0	32.0
24	18	8.2	34.2
		7.0	20.0
		6.5	40.0

Appendix A: —*Continued*

Exp. no.	Trial no.	Compression strength at green stage (kg cm)^2	Compression strength after baking (kg cm)^2
20	19	22.0	36.0
		24.0	34.0
		23.0	28.0
31	20	14.0	28.0
		16.0	28.0
		15.0	32.0
21	21	3.5	83.0
		3.5	63.0
		3.5	62.0
18	22	12.0	27.0
		12.5	24.5
		12.0	33.0
11	23	5.5	48.0
		5.4	42.0
		5.6	32.0
17	24	10.0	6.6
		10.0	4.7
		8.0	6.9
1	25	3.2	76.0
		3.8	78.0
		3.5	74.0
9	26	2.5	17.0
		4.2	21.0
		5.1	19.0
15	27	5.1	15.0
		4.8	14.4
		5.2	13.7
7	28	14.0	40.0
		15.0	100.0
		15.0	38.0
3	29	10.0	21.0
		11.0	20.0
		12.0	18.0
13	30	9.0	10.0
		8.0	11.0
		6.0	8.8
10	31	17.5	76.0
		15.0	64.0
		17.0	85.0
16	32	5.6	54.0
		7.1	54.0
		5.9	57.0