CONTROL FACTOR DESIGN OF INVESTMENT SHELL MOULD FROM COAL FLYASH BY TAGUCHI METHOD

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In the present work an attempt has been made to arrive at the optimum values of control factors, which govern the quality of investment shell moulds. The effect of control factors and subsequent optimization have been carried by Taguchi's design method. The predicted optimum value of hot bending strength, hot permeability and %thermal expansion of shells are respectively 2.42 N/mm^2, 7.94 and 0.24.

NOTATION

α	risk
C.I	confidence interval
e	error
e_p	pooled error
F	ratio of variances
N	total number of observations
n_{eff}	effective number of observations
P	percent contribution
ss	sum of squares
T	sum of square due to total variation
$\overline{T}$	grand mean of all observations
υ	degrees of variance
V	variance
V_e	degree of freedom for pooled error
V_{ep}	pooled error variance

INTRODUCTION

In the manufacture of investment shell moulds by the lost-wax process, a multi-layered shell is built-up by repeatedly dipping a wax pattern into slurry and stuccoing with coarse sand. Each individual coat is air-hardened prior to applying the next coat. On achievement of the required thickness of the shell, the wax pattern is removed from the set-up, the shell is fired, and poured [1].

The investment for shell making is a mixture of refractory filler and liquid binder. Selection of any refractory filler material for shell making is dependent on a wide variety of factors, which can affect the properties of investment slurry, shell and casting and also the economy of the process [2,3].

The objective of the present investigation was the control design investment shell moulds from coal flyash by Taguchi method. The design strategy was to select the proper levels of factors which would affect both average and variation of ceramic shell properties [4].

The coal flyash is a residue of coal combustion in the coal fired power generations. Microanalysis of coal flyash shows that it consists of primarily spherical particles of impure alumino silicate glass [5]. The particle size varies from sub-micro meters to 100μm.

EXPERIMENTAL PLANNING AND TESTING

Raw Materials Used

Binder - Colloidal silica
Refractory filler - Coal flyash
Coating powder - Zirconia (40 μm)
Stucoo sand - (i) Primary stucco of AFS 120
- (ii) Secondary stucco of AFS 50

Planning

The important control factors by which the properties of the ceramic shell could be affected are as follow:

- Concentration level of SiO_2 in the liquid binder
- Particle size of filler
- Filler/Binder ratio
- Standing time of dip-coating slurries
- Type of coating
- Air-drying time of coats
- Sintering temperature of shells

The individual and interaction contributions of the above-said control factors were investigated by Taguchi method to optimize hot bending strength, hot permeability and %thermal expansion characteristics of the investment shells. The selected levels of the chosen control factors are summarized in Table-1. Each of seven control factors was studied at two levels. There seems the possibility of 8 interactions among the control factors. The assignment of control factors and interactions along with the OA matrix is given in Table-2.

Manufacturing of Shells and Testing

Investment shells were made by applying a series of ceramic coatings to the wax patterns. The pattern was first dipped into the dip-coating slurry bath. The pattern was then withdrawn from the slurry and manipulated to drain off excess slurry and to produce a uniform layer. The wet layer was immediately stuccoed with coarse silica sand. Each coating was allowed to dry in the open air. The operations of coating, stuccoing, and drying were repeated six times. The seventh coat was left unstuccoed to avoid the occurrence of loose particles on the shell surface. The first two coats were stuccoed with sand of AFS fineness number 120 and the next four coats were with sand of AFS fineness number 50. As per the design of experiments the two first coats on some of the patterns were also given by dipping them in the slurry prepared from zircon powder. The zircon coating was to improve the surface finish of the castings and the refractoriness of the shells. After all coats, the shells were air dried for 24 hours. Two shells of each treatment were made.

The hot bending strength and hot permeability of shells were conducted on an universal sand strength machine and standard permeability meter with an attached electrical oven respectively [6]. The length, width and thickness of shells were measured using vernier calipers before and after sintering in the electrical oven. The %thermal expansion was computed using the following formula:

$$\%\text{Thermal expansion} = \left[\frac{\left(\begin{matrix}\text{volume of shell}\\ \text{after sintering}\end{matrix}\right) - \left(\begin{matrix}\text{volume of shell}\\ \text{before sintering}\end{matrix}\right)}{\text{volume of shell before sintering}} \right] \times 100$$

ANALYSIS AND DISCUSSION

The experimental values of hot bending strength and hot permeability and %thermal expansion of shells are given in Appendix-A.

Effect of Control Factors on the Hot Bending Strength of Shell

The pooled ANOVA summary for hot bending strength of shell is shown in Table-3. The percent contribution indicates the factor F, sintering temperature, all by itself contributes most towards the variation observed in the bending strength of shells: almost 45%. The factor B, filler particle size contributes over a fourth of the total variation observed and others factors have a weak effect or no measurable effect. Fine particles of coal flyash exhibit greater strength of shells. This is owing to the large surface area per unit volume which is exposed to the silicon radicals in the binder for electrostatic, bonding. As the temperature of sintering increases the shell strength decreases. This is due to the crystallographic change of silica content in the coal flyash. Coal flyash consists of approximately 62% of SiO_2.

Effect of Control Factors on the Hot Permeability of Shells

The pooled ANOVA summary is given in Table-4. According to the analysis of variance, there are two strong factors, which influence the hot permeability of shells. The percent contributions of factor G (Zircon coating) and the factors A (%SiO2 in the binder) are respectively 40% and 16%. The zircon coating on the shells and large number of silica colloidal particles in the binder reduce the permeability of shells. These are respectively due to i) fine particle size of zircon, and ii) sealing of voids between filler particles by very fine colloidal silica particles from the binder. The effects of other factors are less important. The uncoated shells have shown high permeability owing to round particle shape of flyash. The scanning electron micrograph for one of the fraction of flyash (74 μm) indicates that it consists largely of solid or hollow spherical particles of variable size as shown in fig.1.

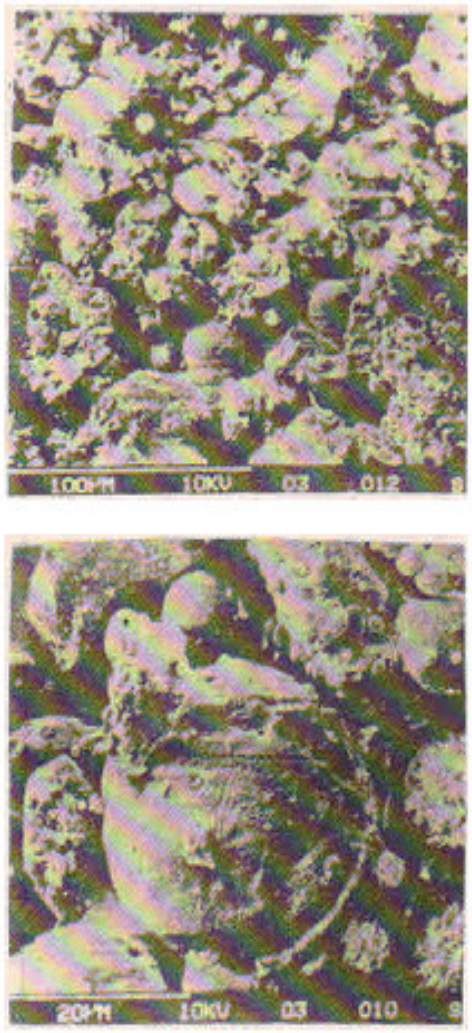

Fig.1: SEM photomicrograaoh of flyash sample (74 µm) (a) 500X, 100µm, 10kV (b) 2000X, 20µm, 10kV. Dark areas are organic matter, light areas are mineral matter.

Effect of Control Factors on the Thermal Expansion of Shells

The pooled ANOVA summary is given in Table-5. The ANOVA calculations indicate that there is only one factor (sintering temperature), which influence the thermal expansion of ceramic shells. All other factors are relatively weak. The thermal expansion of shell increases with increase of temperature. The uneven expansions of various constituents of coal flyash have resulted cracks in the ceramic shells. The shell cracks (Fig.2) were associated with thermal shocks when the shells were heated to 600^0C. The cracks were found on the internal surface of flyash shells.

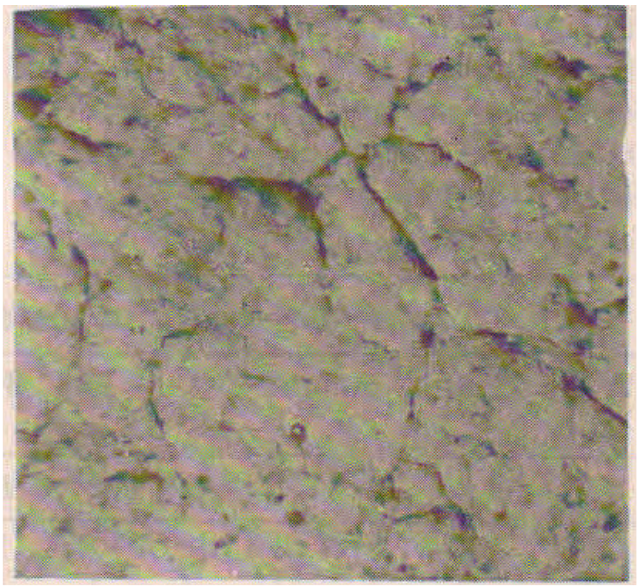

Fig.2: Optical photograph showing cracks in the flyash shell heated to 6000C. Magnification: 10X.

Optimum Levels of Control Factors

The confirmation test was carried out (appendix-B) to validate the conclusions drawn during the analysis phase. The predicted values of hot bending strength, hot permeability and %thermal expansion are respectively 2.42 N/mm^2, 7.94 and 0.24, which are approximately equal to the average values of treatment No.10. Hence, all the control factors with the levels of treatment No.10 are chosen for the manufacturing of investment shells.

Conclusion

The sintering temperature of all itself contributes the most towards the variation in the hot bending strength of investment shells: almost 45%. The filler particle size contributes over a fourth of the total variation in the hot bending strength of shells. The zircon coating on the shells and large number of colloidal silica particles in the binder reduce the permeability of shells. The only one factor, which influences % themal expansion of shells, is sintering temperature. The predicted values of hot bending strength, hot permeability and %thermal expansion of shells are respectively 2.42 N/mm^2, 7.94 and 0.24.

Table-1: Control Factors and Levels

Factor	Symbol	Level – 1	Level – 2
% SiO_2 in binder	A	25	30
Filler Particle Size, μm	B	45	74
Filler / Binder ratio, cc/ml	C	0.60	0.70
Standing time of slurry, hr	D	0	4
Drying time of shells, hr	E	2	4
Sintering temperature, °C	F	400	600
Coating on shells	G	No	Yes (Zirconia)

Table-2: Orthogonal Array (OA16) (Control Factors and Interaction assignment)

Treat No.	A	B	CD	C	BD	BC	D	E	BF	CG	F	CE/BG	e	G	CF
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2
3	1	1	1	2	2	2	2	1	1	1	1	2	2	2	2
4	1	1	1	2	2	2	2	2	2	2	2	1	1	1	1
5	1	2	2	1	1	2	2	1	1	2	2	1	1	2	2
6	1	2	2	1	1	2	2	2	2	1	1	2	2	1	1
7	1	2	2	2	2	1	1	1	1	2	2	2	2	1	1
8	1	2	2	2	2	1	1	2	2	1	1	1	1	2	2
9	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
10	2	1	2	1	2	1	2	2	1	2	1	2	1	2	1
11	2	1	2	2	1	2	1	1	2	1	2	2	1	2	1
12	2	1	2	2	1	2	1	2	1	2	1	1	2	1	2
13	2	2	1	1	2	2	1	1	2	2	1	1	2	2	1
14	2	2	1	1	2	2	1	2	1	1	2	2	1	1	2
15	2	2	1	2	1	1	2	1	2	2	2	2	1	1	2
16	2	2	1	2	1	1	2	2	1	1	1	1	2	2	1

Table-3: Pooled ANOVA summary–Bending strength

Source	**ss**	**v**	**V**	**F**	**P**
A	0.077	1	0.077	13.27^{+}	1.47
B	1.228	1	1.228	154.30^{+}	25.33
C	0.212	1	0.212	36.55^{+}	4.27
BXC	0.591	1	0.591	101.89^{+}	12.13
D	0.393	1	0.393	49.38^{+}	8.02
F	2.178	1	2.178	375.51^{+}	45.02
e_P	0.145	25	0.006	-	3.76
T	4.824	31	-	-	100.00

+ at least 99% confidence

Table-4: Pooled ANOVA summary –Permeability

Source	**ss**	**v**	**V**	**F**	**P**
A	12.103	1	12.103	16.91^{+}	15.50
B	5.088	1	5.088	$7.11^{\#}$	5.95
CXD	4.263	1	4.263	$5.98^{\#}$	4.82
CXE/BXG	3.264	1	3.264	$4.50^{\#}$	3.46
G	30.147	1	30.147	42.13^{+}	40.06
e_P	18.601	26	18.601	-	30.21
T	73.466	31	73.466	-	100.00

+ at least 99% confidence
# at least 95% confidence

Table-4: Pooled ANOVA summary – %Thermal Expansion

Source	ss	v	V	F	P
A	0.010	1	0.010	13.56^{+}	0.32
B	0.069	1	0.069	87.17^{+}	2.23
C	0.004	1	0.004	$6.02^{\#}$	0.13
BXF	0.008	1	0.008	11.05^{+}	0.26
F	2.958	1	2.958	3715.99^{+}	96.52
e_P	0.020	26	0.001	-	0.54
T	3.064	31	-	-	100.00

+ at least 99% confidence and # at least 95% confidence

Appendix: A Experimental Results

Treat.	Hot Bending Strength N/mm^2		Hot Permeability		% Thermal Expansion	
No	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2
1	2.00	2.14	10.00	10.08	0.21	0.23
2	1.44	1.50	07.92	07.80	0.80	0.78
3	1.90	2.00	06.80	06.92	0.25	0.28
4	1.30	1.28	08.24	08.30	0.83	0.80
5	1.10	1.06	08.06	08.00	0.90	0.94
6	1.64	1.58	12.25	12.16	0.28	0.25
7	1.05	1.10	11.56	11.70	0.92	0.90
8	1.53	1.50	07.25	07.30	0.30	0.32
9	1.89	1.82	07.68	07.92	0.82	0.82
10	2.45	2.52	07.44	07.50	0.23	0.23
11	1.24	1.30	07.27	07.20	0.85	0.87
12	1.60	1.66	08.51	08.54	0.27	0.25
13	1.52	1.48	07.69	07.60	0.30	0.34
14	1.00	1.07	08.05	07.96	0.95	0.99
15	1.76	1.80	08.60	08.48	0.31	0.35
16	1.30	1.20	07.08	07.14	1.00	0.98

Appendix –B:

The optimum value of hot bending strength of shells was predicted at the selected levels of significant factors. The significant factors are $\%SiO_2$ in the binder at level 2 (A_2), standing time of slurry at level 2 (D_2), the sintering temperature at level 1 (F_1) and the interaction B_1xC_1.

The estimated mean of hot bending strength $= \overline{A}_2 + \overline{B_1XC_1} + \overline{D}_2 + \overline{F}_1 - 3\overline{T}$

$= 1.61 + 1.97 + 1.67 + 1.82 - 3 \text{ X } 1.55$

where grand mean, $\overline{T} = 1.55$

$$n_{eff} = \frac{N}{1 + [\text{Total degrees of freedom associated in the estimate of mean}]}$$

$$= \frac{32}{1+4} = 6.4$$

$F_{\alpha,1,ve} = F_{5,1,25} = 4.24$

Confidence Interval, CI = $\sqrt{\frac{F_{\alpha,1,ve} V_{ep}}{n_{eff}}} = \sqrt{\frac{4.24 \times 0.006}{6.4}} = 0.063$

The predicted range of hot bending strength is $2.375 \leq 2.42 \leq 2.483$

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