1. Introduction

Foundry industries in developing countries suffer from poor quality and productivity due to an involvement of a number of process parameters in the casting process. Even in a completely controlled process, defects in casting are observed and hence casting process is also known as a process of uncertainty which challenges explanation about the cause of casting defects. (Dabade and Bhedasgaonkar 2013) The production concerns must follow the quality control procedures correctly and perfectly to produce the quality casting. With the passage of time, the modified techniques based on the quality control research is becoming must to avoid defects in the products. (Vijayaram, Sulaiman et al. 2006)

Sand is used by means of different processes: green molding, shell, No-bake, hot box, cold box and others. Each one of them presents its own particularities and advantages in relation to the needs of the products. (Andrade, Cava et al. 2005) The difficulty with the green sand molding is that heated pattern plates and curing ovens are necessary; therefore it is mainly used for small castings. (Sarkar 1967) Some of the resin bonded sand systems used are furan, phenolic urethane and sodium silicate. Casting furan resin is a new type of casting self-hardening adhesive. (Liang and Tsay 2010) No-bake binder system does not require a baking cycle to generate mechanical strength, so the furan binder has been acknowledged as the first true no-bake binder. (Ireland, Chang et al. 2002) As the resin binders can be hardened by simply standing in the air have found very useful application in the production of large moulds in the steel foundry.

This means that stripping of cores and their consequent drying in stoves are eliminated resulting in a saving of labor and fuel cost. (Sarkar 1967) It also offers advantages such as hardening speed, strength, collapsibility framing,
high strength, high dimensional accuracy, fast hardening rate, high production efficiency and low labor intensity as well as an abundant source of raw materials and simple production process to improving the quality of the piece of metal produced. (Yuyan and Yingmin 2009) (Pathak, Bharati et al. 1998)

Furfuryl alcohol is the basic raw material for the furan family of acid-catalyzed no-bakes. It is produced from waste vegetable materials such as corn husks, rice hulls, etc. It is a simple two-part binder system made up of an acid catalyst and a reactive furan-type resin. The resin, which is dark colored thin liquid acts as the binder for sand particles and the catalyst or curing agent, is a solution of pure or mixture of organic, inorganic acids in varying concentration. The operating temperatures for this process range from 24 to 30 ºC. The sand, binder, and catalyst are continuously mixed and blown into the core box. The amount of furan no-bake binder used is usually 0.9-1.2%, based on sand weight. Catalyst levels generally are from 20-40% based on the weight of the binder. (Mancuso, Technical Data sheet, 2005)

After using the sand once, a lot of reacted products (binder and catalyst) are present in the sand, partly loose (Industrial Centre) and partly still attached to the sand grains. By re-using the sand, the “unburned” (organic) products will build up in the sand which is necessary to remove by reclamation process. Due to the cost of dumping or re-using the "used sand" the necessity of reclaiming is increased. A lot of heat and energy produces during reclamation of sand as a result exposure to high temperature occurs. (Bobrowski and Grabowska 2012)

For furan no-bake system, the temperature is a primary consideration because the catalyst component must work in combination with temperature to initiate and sustain the chemical curing reaction. Hence temperature must be monitored, controlled and, if possible, kept constant. The rate of cure increases as the temperature rises and slows as the temperature decreases. Catalyst adjustments can be made for temperature fluctuation, but it is better to control the sand temperature than to continually adjust the amount of catalyst. (Canada)

As per (Sarkar 1967) in furan molding process silica sand should be used with approximately 2 % binder and a catalyst addition of between 30 and 40 % by weight of the binder. The setting time of the cores is governed by the amount of catalyst and the sand temperature. Sarkar concluded that the amount of catalyst is increased, higher strengths are achieved at the early stages, but the ultimate strengths are lower with a higher amount of catalyst addition. Whether a faster curing rate and hence increased production or a higher ultimate strength is required or not, will be decided by the requirements of the individual foundry. As per him, the rate of curing and hence stripping time will also be controlled by the sand temperature as it would vary between seasons.

The quality of the casting may be given by compressive strength of the mould and rejection rate/ casting defect. The temperature of the sand is depending on many parameters like storage location of sand hoppers, amount of catalyst which is responsible for reaction, Seasonal variation of temperature and humidity.

### 2. Methodology used in the present work

The main objective of this study is to evaluate furan no-bake system in context with the strength and quality of the product. Experiments were performed at private company in India making motor body casting. The company started in 1985, initially using single part binder and gradually adopted FNB binder system for improving process efficiency and quality of casting. The methodology to study the influence of process parameters and to establish non-linear input-output relationships of a furan no-bake based resin bonded sand core system has been explained in the following steps. The analysis is performed in design expert software by using response surface methodology for face-centered central composite design.

#### 2.1 Identification of Important Process Parameters and Their Levels:

The moulding/core sand mixture used consists of three ingredients, namely sand, resin – furfuryl alcohol and the hardener or catalyst – phosphoric acid.

Temperature, the percentage of resin and percentage of the catalyst has been considered as independently controllable process parameters with the significant contribution on mould/core properties. The working ranges of the
input parameters are determined by consulting the experts from foundry and literature. Table 1 shows the ranges of the input process parameters used for conducting the experiments.

| Parameter                             | Levels      | Parameter | Levels      |
|---------------------------------------|-------------|-----------|-------------|
| Sand temperature in °C                | Low (-1)    | Medium (0) | High (+1)   |
| Resin in g                            | 28          | 34        | 40          |
| Catalyst in g                         | 7.5         | 8         | 8.5         |
| Sand temperature in °C                | 4.4         | 4.6       | 4.8         |

Moreover, the compressive strength at 4th hour and scratch hardness at 4th hour are considered as responses for the current experiment. The block diagram showing the input-output relationships of the furan no-bake system is shown in Figure 1.

![Fig.1 Input-output model of the furan no-bake binder system](image)

2.2 Development of design matrix

In design matrix in Design Expert software for three input parameters consist of 17 sets of experiments. The 17 experimental runs allowed the estimation of linear, square, cubic and two-way interaction effects of the input parameters.

| Std | Run | Block  | Temp.(A) °C | Resin (B) g | Catalyst (C) g | Compressive Strength kg/cm² | Scratch Hardness |
|-----|-----|--------|-------------|-------------|----------------|-------------------------------|------------------|
| 4   | 1   | Block 1| 1           | 1           | 1              | 16.97                        | 76               |
| 10  | 2   | Block 1| 0           | 0           | 0              | 21.29                        | 65               |
| 12  | 3   | Block 1| 1           | 1           | -1             | 18.13                        | 75               |
| 13  | 4   | Block 1| 1           | 0           | 1              | 22.1                         | 65               |
| 17  | 5   | Block 1| 1           | -1          | 1              | 15.1                         | 73               |
| 9   | 6   | Block 1| -1          | 1           | -1             | 26.36                        | 60               |
| 5   | 7   | Block 1| 0           | 1           | 0              | 28.37                        | 68               |
| 7   | 8   | Block 1| -1          | 0           | 0              | 26.32                        | 65               |
| 6   | 9   | Block 1| -1          | 1           | 1              | 24.21                        | 59               |
| 1   | 10  | Block 1| -1          | -1          | 1              | 23.17                        | 59               |
| 8   | 11  | Block 1| -1          | 0           | -1             | 27.01                        | 70               |
| 11  | 12  | Block 1| 1           | -1          | -1             | 17.29                        | 73               |
| 3   | 13  | Block 1| 0           | 0           | -1             | 26.32                        | 70               |
| 2   | 14  | Block 1| 1           | 1           | 0              | 22.97                        | 66               |
| 14  | 15  | Block 1| 1           | 0           | 0              | 21.44                        | 65               |
| 15  | 16  | Block 1| 1           | 0           | 0              | 19.25                        | 69               |
| 16  | 17  | Block 1| -1          | -1          | -1             | 28.06                        | 58               |
2.3 Conducting Experiments

Experiments have been conducted to test the properties of furan no-bake binder system. The cores are prepared with the help of sand, resin and hardener. The type of resin and hardener used in the present study is furfuryl alcohol and phosphoric acid respectively. The set of experiments are performed in the dry season (winter season in India i.e. in January), so the effect of atmospheric humidity can be neglected. The grain fineness number (GFN) of the sand that was obtained from the sieve analysis test has been found to be equal to 48.25 (As per IS standard it should be below 50, hence our sand is of good quality). (IS) 1966 Standard procedure has been used to prepare the test specimens for compressive strength as well as scratch hardness test piece as shown in figures 2 and 3 above. The compressive strength (CS) is measured using compressive strength testing equipment as shown in figure 2 and scratch hardness (SH) is measured using standard baked core hardness tester as shown in figure 3.

2.4 Determining the Adequacy of the developed model

The non-linear regression model will be developed using the data collected as per design matrix. The effect of individual parameters and their interaction terms are examined by conducting a significance test. Contour plots are used to understand the relationships of process parameters and their interaction with responses. Further, they are utilized to study the contribution of process parameters. Design expert software is used for the said purpose. The prediction accuracy of the models has been tested by passing seventeen experimental test cases.

3 Results and discussion

This section discusses the non-linear regression models developed for furan no-bake binder system using design expert software.
3.1 Mathematical model and statistical analysis

The experimental data obtained from furan resin bonded sand core has been used to develop non-linear regression models. Further, the analysis of the models is contour plots for the responses – compressive strength (CS) and scratch hardness (SH).

3.1.1 Response – Compressive Strength

Equation (1) shows the non-linear model expressed as a function of input process parameters (in coded form), that represents the compressive strength of the furan resin bonded sand core system in kg/cm$^2$. By considering all the significant factors the response surface equation for compressive strength with the optimized number of digits- 4 points after decimal points very little/no change in the end result is as shown below:

$$CS=85.9989-1.1310*A+4.4787*B-13.0959*C+0.4239*A*B+1.1573*A*C-4.2117*B*C-0.1208*A^2$$

(1)

Table 3 shows that the model is significant and sand temperature (A), resin (B) and catalyst (C) are the significant factors (terms) in the model. The lack-of-fit is insignificant thereby indicates that the model fits well with the experimental data. (Lalwani, Mehta et al. 2008) Sand temperature is the dominant contributor to the compressive strength compared to other parameters resin and catalyst. A negative sign indicates that temperature and compressive strength having an inverse relationship.

The various $R^2$ statistics (i.e. $R^2$, adjusted $R^2$ ($R^2$ Adj) and predicted $R^2$ ($R^2$ Pred)) of the compressive strength are given in Table.2. The value of $R^2 = 0.8148$ for compressive strength indicates that 81.5% of the total variations are explained by the model. The value of the $R^2$ Adj = 0.6708 indicates that 67% of the total variability is explained by the model after considering the significant factors. (Montgomery and Wiley 2001) ‘C.V.’ stands for the coefficient of variation of the model and it is the error expressed as a percentage of the mean ((S.D./Mean)×100). The lower value of the coefficient of variation (C.V. = 11.30%) indicates improved precision and reliability of the conducted experiments.

| Source          | Sum of Squares | df | Mean Square | F Value | p-value Prob > F | % Contribution |
|-----------------|----------------|----|-------------|---------|-----------------|----------------|
| Model           | 248.94         | 7  | 35.56       | 5.66    | 0.01            | 27.21          |
| A-A- Sand       | 145.01         | 1  | 145.01      | 23.07   | 0.00            | -2.01          |
| Temperature     |                |    |             |         |                 |                |
| B-B- Resin      | 0.58           | 1  | 0.58        | 0.09    | 0.77            | 1.55           |
| C-C- CAT        | 22.14          | 1  | 22.14       | 3.52    | 0.09            | 0.31           |
| AB              | 13.75          | 1  | 13.75       | 2.19    | 0.17            | 3.22           |
| AC              | 16.40          | 1  | 16.40       | 2.61    | 0.14            | 3.33           |
| BC              | 1.51           | 1  | 1.51        | 0.24    | 0.64            | 1.52           |
| A^2             | 49.56          | 1  | 49.56       | 7.89    | 0.02            | -0.85          |
| Residual        | 56.56          | 9  | 6.28        |         |                 |                |
| Cor Total       | 305.50         | 16 |             |         |                 |                |
| Std. Dev.       | 2.51           |    | R-Squared   | 0.81    |                 |                |
| Mean            | 22.18          |    | Adj R-Squared | 0.67 |                 |                |
| C.V. %          | 11.30          |    | Pred R-Squared | 0.02 |                 |                |
| PRESS           | 299.23         |    | Adeq Precision | 7.52 |                 |                |

The normal probability plot of the residuals (i.e. error = predicted value from model–actual value) for compressive strength is shown in figure 4 which reveal that the residuals lie reasonably close to a straight line, giving support that terms mentioned in the model are the only significant (Montgomery and Wiley 2001). Figure 5 shows the graph of predicted values of compressive strength from response surface equations to the actual (experimental) values.
The compressive strength is expressed in kg/cm$^2$ as per instruments reading scale and as per Bureau of Indian Standard, IS: 1966. The SI unit is converted into N/mm$^2$ by the multiplication factor of 0.0980665.

Fig. 4 Normal probability plot of residual compressive strength

Fig. 5 Actual v/s predicted a value of compressive strength

The overall remarks from the response surface contours are narrated in table 4, which is actually from figures 6, 7 and 8.

| Graph AB | Resin vs. Temp. | Conclusive Remark |
|----------|-----------------|-------------------|
| Parameter C Catalyst Level | 4.6 g (Middle) | Maximum Resin 8.5g Temp Range 28-34 °C Comp. Strength 24.63 kg/cm$^2$ |
| | 4.8 g (Higher) | Maximum Resin 8.1g Temp Range 28-35 °C Comp. Strength 23.22 kg/cm$^2$ |
4.4 g (Lower) | Maximum Resin 8.5 g  
| Temp Range 28-34 °C  
| Comp. Strength 26.24 kg/cm²

Graph BC | Resin vs. Catalyst | Conclusive Remark
---|---|---
34 °C (Middle) | Resin Max. 8.5 g  
| Catalyst Range 4.4 to 4.7 g  
| Comp. Strength 25.13 kg/cm²

Parameter A | Sand Temp.  
Level
---|---
28 °C (Lower) | Resin Max. 8.5 g  
| Catalyst Range 4.5 to 4.65 g  
| Comp. Strength 25.23 kg/cm²

40 °C (Higher) | Resin Max. 7.6 g  
| Catalyst Range 4 to 4.7 g  
| Comp. Strength 15.7 g

Graph AC | Temp. vs. Catalyst | Conclusive Remark
---|---|---
8.0 g (Middle) | Catalyst 4.4 to 4.6 g  
| Temp 28 to 34 °C  
| Comp. Strength 25.89 kg/cm²

Parameter B | Resin Level
---|---
7.5 g (Lower) | Catalyst 4.4 to 4.6 g  
| Temp 28 to 34 °C  
| Comp. Strength 26.24 kg/cm²

8.5 g (Higher) | Catalyst 4.4 to 4.5 g  
| Temp 28 to 35 °C  
| Comp. Strength 25.58 kg/cm²

---

Fig.6 Response surface contour in sand temperature direction and resin at 4.8 g catalyst (●, Design points)
Fig. 7 Response surface contour in sand temperature direction and catalyst at 8 g resin (●, Design points)

Fig. 8 Response surface contour in resin direction and catalyst at temperature 34 °C (●, Design points)

3.1.2 Response – Scratch Hardness

Equation (2) shows the non-linear model expressed as a function of input process parameters (in coded form), that represents the scratch hardness of the furan resin bonded sand core system. By considering all the significant factors - the response surface equation for scratch hardness is as shown below:

\[
SH = -2569.9132 + 150.93793A + 314.8703B + 1.25C - 18.1884AB - 2.1366A^2 + 0.2592A^2B
\]  

(2)

In Table 5 below resin and catalyst are the equal dominant contributors to the scratch hardness. Whereas sand temperature having a very negligible contribution in scratch hardness.

Table 5 Analysis of Variance, or ANOVA partial sum of square for scratch hardness

| Source          | Sum of Squares | df | Mean Square | F Value | p-value | % Contribution |
|-----------------|----------------|----|-------------|---------|---------|----------------|
| Model           | 596.45         | 6  | 99.41       | 3.33    | 0.05    | 72.41          |
| A-A- Sand       | 497.02         | 1  | 497.02      | 16.64   | 0.00    | 10.9           |
| Temperature     |                |    |             |         |         |                |
| B-B- RESIN      | 4.07           | 1  | 4.07        | 0.14    | 0.72    | 9.65           |
| C-C- CATALYST   | 0.62           | 1  | 0.62        | 0.021   | 0.89    | 4.1            |
| AB              | 23.89          | 1  | 23.89       | 0.8     | 0.39    | 2.5            |

95% CI
The normal probability plot of the residuals (i.e. error = predicted value from model−actual value) for scratch hardness is shown in figure 9, which reveal that the residuals lie reasonably close to a straight line, giving support that terms mentioned in the model are the only significant. (Montgomery and Wiley 2001) Figure 10 shows the predicted values of scratch hardness from response surface equations and the actual (experimental) values also.

![Normal Plot of Residuals](image)

**Fig.9 Normal probability plot of residual compressive strength**

![Actual vs. Predicted Scratch Hardness](image)

**Fig.10 Actual vs. predicted values of scratch hardness**
As shown in figure 11, at 4.60 g catalyst as the temperature increase scratch hardness increase and reach nearly equal to 70 at the temperature range of 37 to 40 °C and at resin level 8.25 to 8.5 g. At the temperature range of 31 to 34 °C, the value of scratch hardness is varying from 63 to 65 which are reasonably good. At combination of low temperature i.e. 28 °C and low resin level i.e. 7.50, scratch hardness is lie near 50 which is not allowable as the handling of mould and wear due to the turbulence of molten metal are concerned. All low, medium and a higher level of catalyst favor high resin level and moderate temperature. Figure 12, 13 show the plots of resin vs. temperature at 4.4 g catalyst and at 4.8 g catalyst. The scratch hardness plot is similar which indicate that level of a catalyst has little effect on the scratch hardness.
Fig. 13 Response surface contour in sand temperature direction and resin at 4.8 g catalyst (●, Design points)

By removing insignificant terms from above i.e. resin and catalyst; the compressive strength can be represented in quadratic terms as

\[
CS = -52.3054 + 5.2745A - 0.08870A^2 \quad (3)
\]

| Source                  | Sum of Squares | df | Mean Square | F Value | p-value | Prob > F | % Contribution |
|-------------------------|----------------|----|-------------|---------|---------|-----------|----------------|
| Model                   | 233.17         | 2  | 116.59      | 36.35   | < 0.0001 | 26.17     | significant    |
| A-A- Sand Temperature   | 206.48         | 1  | 206.48      | 64.37   | < 0.0001 | -3.33     |                |
| A^2                     | 26.69          | 1  | 26.69       | 8.32    | 0.0120   | -0.82     |                |
| Residual                | 44.90          | 14 | 3.21        |         |          |           |                |
| Cor Total               | 278.08         | 16 |             |         |          |           |                |
| Std. Dev.               | 1.79           |    | R-Squared   | 0.838518|         |           |                |
| Mean                    | 22.61          |    | Adj R-Squared| 0.81545|         |           |                |
| C.V. %                  | 7.92           |    | Pred R-Squared| 0.75522|         |           |                |
| PRESS                   | 68.07          |    | Adeq Precision| 12.24311|         |           |                |

By removing insignificant terms i.e. resin and catalyst; the scratch hardness can be represented in quadratic terms as

\[
SH = -45.2003 + 5.4303A - 0.06258A^2 \quad (4)
\]

Table 7 Analysis of Variance, or ANOVA partial sum of square for Scratch Hardness

| Source                  | Sum of Squares | df | Mean Square | F Value | p-value | Prob > F | % Contribution |
|-------------------------|----------------|----|-------------|---------|---------|-----------|----------------|
| Model                   | 510.31         | 2  | 255.15      | 9.28    | 0.0027  | 72.00     | significant    |
| A-A- Sand Temperature   | 497.03         | 1  | 497.03      | 18.09   | 0.0008  | 10.61     |                |
| A^2                     | 13.28          | 1  | 13.28       | 0.48    | 0.4983  | 4.70      |                |
| Residual                | 384.75         | 14 | 27.48       |         |         |           |                |
| Cor Total               | 895.06         | 16 |             |         |         |           |                |
| Std. Dev.               | 5.24           |    | R-Squared   | 0.57    |         |           |                |
| Mean                    | 65.76          |    | Adj R-Squared| 0.51   |         |           |                |
The percentage of co-efficient of variation (error in prediction) indicate lower value compared to prevailing analysis i.e. compressive strength 7.92% and scratch hardness 7.97 % which favor that analysis with a removal of insignificant terms is more error-free. The error in prediction in fig. 14 and fig.15 means by the percentage variation between prediction line and the design point. The corresponding one-factor design point diagrams of compressive strength and scratch hardness at 8.0 g resin and 4.60 g catalyst are shown in figures 14, 15 respectively.

![One Factor](image)

**Fig.14 One factor Compressive Strength diagram at 8.0 g resin and 4.6 g catalyst (●, Design points)**

This analysis shows that along with temperature there is a role of other parameters i.e. an amount of resin and hardener which is also affecting compressive strength and scratch hardness.

4. Conclusion

To obtain a better quality and lower rejection rate the sand temperature has to be between 28 to 34 °C. For temperature greater than 35 °C, whatever might be the combination of resin and catalyst required strength of mould can’t be achieved. For very low temperature i.e. below 20 °C, sand/resin mixture may become very viscous and unable to properly coat the sand grains.

An analysis suggests the feasible combination of parameters as temperature range 28 to 34 °C, resin range 8.4 to 8.5 g and catalyst or hardener range of 4.4 to 4.6 g per kg of sand.

This analysis is helpful to know the compressive strength (CS) and scratch hardness (SH) values before actual performance of experiments; this gives economical use of resin and catalyst.
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