# Effect of Binder and Mold parameters on Collapsibility and Surface Finish of Gray Cast Iron No-bake Sand Molds

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**Abstract:** Chemically bonded no-bake molds and cores have good mechanical properties and produce dimensionally accurate castings compared to green sand molds. Poor collapsibility property of CO2 hardened sodium silicate bonded sand mold and phenolic urethane no-bake (PUN) binder system, made the reclamation of the sands more important. In the present work fine silica sand is mixed with phenolic urethane no-bake binder and the sand sets in a very short time within few minutes. In this paper it is focused on optimizing the process parameters of PUN binder based sand castings for better collapsibility and surface finish of gray cast iron using Taguchi design. The findings were successfully verified through experiments.
Keywords: Phenolic urethane binder, Collapsibility, Surface roughness.

## 1. Introduction

Metal casting is the most preferred process to make near-net shape metal parts due to its ability to produce intricate shaped parts at low cost compared to other manufacturing processes. But limitations like dimensional accuracy, surface finish and soundness of castings in case of green sand castings are overcome by using chemical binders instead of clay or bentonite. The quality of these molds depends on the type of sand used, grain size, proportion of resign and catalyst and curing time [1]. Several researchers have investigated the effect of molding parameters of carbon dioxide molding and other chemically bonded sand castings on the mechanical properties. Himanshu Khandelwal [1] reported compression strength, shear strength, core hardness and core shrinkage properties of urethane binder system.

In no-bake molding we mix urethane binder with the fine silica sand, and the sand sets in a very short time within few minutes. The pattern used may be wood, metal or plastic and fine silica sand and urethane binder as molding material. When we mix urethane binder with fine silica sand, it will be hardened within few minutes at room temperature and offers excellent dimensional tolerance and very good surface finish unlike the green sand molding, where dimensional tolerance and surface finish are poor. But the only limitation is the binder is it is very expensive. As urethane reacts with silica sand very quickly and within few minutes it will be hardened, the mold should be done quickly.

Phenolic urethane no-bake (PUN) binders are widely used for the production of both ferrous and nonferrous castings and can be successfully used for high-production operations or jobbing shops because of their chemical reaction time and ease of operation. PUN binder induces fast uniform hardening to the depth of the cast, it is ideal as a binder for main molds and cores for small and midsize casts. It is used in a broad array of applications including plain cast iron, ductile cast iron, cast steel and light alloys. PUN binder has the highest hardening velocity among ambient temperature self-hardening binders. In addition, it is characterized with a long usable time in

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comparison with the cast removing time. It offers the highest work time to strip time ratio of any no-bake chemical binder and excellent dimensional accuracy. As it produces good internal hardening results, it is a self-hardening binder with a top forming velocity. The recovered sand can be easily reclaimed with a normal mechanical reclamation machine. The amount of binder to be added to the reclaimed sand may be smaller than that added to new sand. Studies have shown that sulfur is a primary factor causing graphite degeneration at the metal-mold interface. M. Holtzer et al. [2] claimed that Phenol-urethane resin does not contain sulfur.

The polyurethane no-bake (PUN or PUNB) binder is a three-component system comprising of a liquid phenol-formaldehyde resin (part1), liquid polyisocyanate (part2) and a liquid catalyst (part3). A simplified version of the curing mechanism for phenolic urethane no-bake systems is:

Liquid phenolic resin (Part I) + Liquid polyisocyanate (Part II)+ Liquid amine catalyst (Part III) = Solid resin + heat

It is common to offset the ratio of Part I to Part II at 55:45 or 60:40. The third-part catalyst level is based on the weight of Part I. Total binder level for the PUN system is 0.7 to 2% based on the weight of sand as per AFS 2007 [3]. The PUNB system can be mixed in batch as well as continuous mixers but the latter is preferred due to the rapid speed of the reaction. Addition of the part 3 (catalyst) can be adjusted to get the desired stripping time. Varying the ratio of part1 and part2 does not change the speed of the reaction. Khandelwal [1] studied the effect of change of resin binder percentage between 1.6 and 2.4 and reported that compression strength, shear strength and core hardness are more at 2.4% of binder. Although many types of mixers can be used with PUN binders, zero-retention high-speed continuous mixers are the most widely used. There are various features of this system, which make it an excellent choice for steel, ferrous and non-ferrous castings like rapid strength development, excellent dimensional accuracy, very good breakdown properties, very high productivity, excellent hot strengths, very good sand flow ability, high sand reclamation and mixing takes place rapidly. Compaction of the mixed sand can be accomplished by vibration, ramming, and tucking. The good flow ability of PUN sand mixes allows good density with minimum effort. Because the PUN system cures very rapidly, the time required for the compacted pattern to reach rollover and strip must coincide with the setup or cure time of the sand mix.

For certain ferrous applications (most commonly steels), the addition of 2 to 3% iron oxide to the sand mix can improve casting surface finish. The PUN resin system contains about 3.0 to 3.8% N (which is about 0.04% based on sand). To reduce the chance of nitrogen-related casting defects, it has also been shown that as little as 0.25% red iron oxide is effective in suppressing the ferrous casting subsurface porosity associated with nitrogen in the melt and/or evolved from the PUN binder. Reactivity, strengths, and work-time-to-strip-time ratio are relatively good for this binder and collapsibility of standard phenolic urethane is better than modified polyol urethane [4]. As a result of increased acceptance and consumption of phenolic urethane binders, occurrences of binder-related gas defects have at times, become very troublesome in foundries using these systems [4]. R.L. Naro [5] studied gas porosity defects in the casting because of urethane binder.

Knockout or collapsibility property of no-bake sand molds is poor compared to sand castings and sodium silicate casings. There appears to be very little work investigating the effect of mold parameters and binder parameters on the properties of no-bake chemically bonded sand molds, in particular properties like collapsibility of the mold material and surface finish of the castings obtained. This has been taken up in the present work. Design of experiments was carried out using Taguchi orthogonal array, followed by analysis of results and finding the influence of individual parameters on collapsibility and surface finish and finally validation of the optimized model. The overall methodology is described in the following sections.

## 2. Methodology

The experimental work was taken up to investigate the effect of mold parameters like Grain Fineness Number of silica sand and percentage of iron oxide along with binder parameters like percentage of catalyst added to the binder on the collapsibility and surface finish of the casting. To improve the knockout property of no-bake sand molds, in the present investigation an attempt is made to optimize the process parameters percentage of binder, percentage of iron oxide added to the molding sand and Grain Fineness Number (GFN) of the fine silica sand are varied in different proportions and collapsibility or retained compression strength and surface finish of the gray cast iron castings obtained are measured. Strength of the mold after heating and cooling cycle is called retained strength. Retained strength is a measure of collapsibility of the mold. As the retained compression strength is more collapsibility is less. Retained strength after standard specimens are heated to a temperature of 10000 C for a period of 10 minutes and cooled to room temperature is a measure of collapsibility [5]. Collapsibility can be assessed through determination of the time to failure under constant load and collapsibility determines the readiness with which the molding material will break down in knockout and cleaning operations [6]. Full reclamation is feasible, subject to the avoidance of excessive nitrogen build up [6]

Hence in the present work an attempt is made using Taguchi design to bring the process to an optimal condition by conducting minimum number of experiments. The selection of process parameters and their levels are selected from the available literature. The process parameters and their levels used in the experimental study are shown in table 1. From the literature review it is clear that total binder level for the PUN system is 1.6 to 2.4% based on the weight of sand [1]. It has also been shown that as little as 0.25% red iron oxide is effective in suppressing the ferrous casting subsurface porosity with PUN binder and maximum of 3% can be added to the sand mix which can improve casting surface finish. So % of iron oxide was varied in three levels:0.2,1.6 and 3 by weight percentage of sand. Fine silica sand is desired to make PUN binder no bake sand molds. Hence GFN of silica sand is varied between narrow range of 40 to 60 and hence GFN was varied in three levels 40,50 and 60.

Table 1. Process parameters and their respective levels

| Process parameters | Notation | Level-1 | Level-2 | Level-3 |
|---|---|---|---|---|
| % Binder | A | 1.6 | 2 | 2.4 |
| % Iron oxide | B | 0.2 | 1.6 | 3 |
| GFN | C | 40 | 50 | 60 |

## 3. Experimental Procedure

Sand molds are prepared as per the Taguchi's experimental plan shown in table-1. Cylindrical test samples of 5 cm diameter and 5cm height were prepared by urethane binder system as per AFS (American Foundry Society) standard guidelines. All the samples were cured for 4 hours as reported by Khandelwal [1] to achieve better mold properties. Then standard specimens were heated to a temperature of $1000^0$ C for a period of 10 minutes and cooled to room temperature and retained compressive strength of the sand mixture were measured. To find the surface roughness, molten grey cast iron was poured into the simple rectangular shape molds and castings were made. Surface roughness values (Ra) of the cast rectangular blocks were measured at three different locations.

Taguchi design of experiments methodology was adopted to find the optimum number of experiments and to study the influence of three parameters selected on collapsibility of the mold material for sand reclamation and surface roughness of gray cast iron castings made. As there are three factors and each one is having three levels, degree of freedom of each factor is two (number of levels-1). So total degree of freedom of the problem without interactions is 1+6=7. Hence L9(34) orthogonal array was selected, which consists of nine experimental runs. Degree of freedom of L9 orthogonal array is 9-1=8. Orthogonal array selected should have DOF greater than or equal to the DOF of the problem that is 7. As noise factors are not considered, each run of the experiment is replicated three times and average of the three values is taken as response. Signal to noise (S/N) ratio is a quality indicator term used in Taguchi design helps the experimenters to evaluate the effect of change in design parameter on the outcome of the product or process [7]. Quality characteristic (S/N) for retained strength (collapsibility) and surface roughness is "Smaller the better".

$$(S/N) = -10 * \log10(\Sigma(yi2)/n))$$

After identifying the optimum settings of the parameters for minimum collapsibility and surface roughness, predicted performance characteristics like Mean and S/N ratios were found and at these optimum settings, confirmation experiment was carried out and the values of collapsibility and surface roughness were compared with the predicted values.

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## 4. Results & Discussion

The quality attributes of sand molds measured in this work are collapsibility and surface roughness. Collapsibility of molding sands is very important for sand reclamation process and surface finish of gray cast iron castings is also important factor to be studies especially when iron oxide power is mixed in the molding sand along with no-bake binders. These properties were measured for all nine experimental conditions shown in Table 1 and are reported in Table 2. Analysis of variance (ANOVA) were performed to investigate the significance of the parameters. ANOVA results for both collapsibility and surface roughness were tabulated in Table 3 and 4 respectively. From table:3, it is clear that P-value of % Binder is less than 0.05 and hence its % contribution of is very high, which is around 93% when compared with other factors % Iron oxide and GFN. From table-4, it is clear that there is no effect of binder percentage of surface roughness and % iron oxide and GFN play almost equal role in achieving good surface finish.

Table 2. Experimental observation and S/N ration for surface roughness and collapsibility

| Exp No | A | B | C | Avg. Collapsibility, Y (Kg/cm2) | Avg. Surface roughness, Ra (μm) | S/N ratio for Y | S/N ratio for Ra |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 2.85 | 0.82 | -9.0969 | 1.72372 |
| 2 | 1 | 2 | 2 | 3.42 | 1.23 | -10.6805 | -1.79810 |
| 3 | 1 | 3 | 3 | 2.94 | 0.98 | -9.3669 | 0.17548 |
| 4 | 2 | 1 | 2 | 5.3 | 1.20 | -14.4855 | -1.58362 |
| 5 | 2 | 2 | 3 | 6.53 | 1.40 | -16.2983 | -2.92256 |
| 6 | 2 | 3 | 1 | 4.31 | 0.68 | -12.6895 | 3.34982 |
| 7 | 3 | 1 | 3 | 7.85 | 1.45 | -17.8974 | -3.22736 |
| 8 | 3 | 2 | 1 | 8.52 | 0.85 | -18.6088 | 1.41162 |
| 9 | 3 | 3 | 2 | 8.74 | 0.53 | -18.8302 | 5.51448 |

Table: 3 ANOVA table for Collapsibility

| Source | DF | Adj SS | Adj MS | F-Value | P-Value | %Contribution |
|---|---|---|---|---|---|---|
| % Binder | 2 | 42.3662 | 21.1831 | 39.33 | 0.025 | 93.2 |
| % Iron Oxide | 2 | 1.3613 | 0.6806 | 1.26 | 0.442 | 3 |
| GFN | 2 | 0.6531 | 0.3265 | 0.61 | 0.623 | 1.4 |
| Error | 2 | 1.0771 | 0.5385 | | | 2.4 |
| Total | 8 | 45.4576 | | | | 100 |

Table: 4 ANOVA table for Surface roughness

| Source | DF | Adj SS | Adj MS | F-Value | P-Value | % Contribution |
|---|---|---|---|---|---|---|
| %Binder | 2 | 0.03389 | 0.01694 | 0.55 | 0.647 | 4 |
| %Iron Oxide | 2 | 0.36696 | 0.18348 | 5.9 | 0.145 | 44.11 |
| GFN | 2 | 0.36882 | 0.18441 | 5.93 | 0.144 | 44.33 |
| Error | 2 | 0.06216 | 0.03108 | | | 7.5 |
| Total | 8 | 0.83182 | | | | 100 |

From Taguchi design analysis using Minitab® 17 statistical tool, main effect plots for Means were drawn for collapsibility and surface roughness as shown in Figure 1 and 2 respectively. More the slope of the plot, more significant effect of the individual parameter [9]. S/N ratios (Smaller-the-better) for both the process parameters are shown in Table 2.

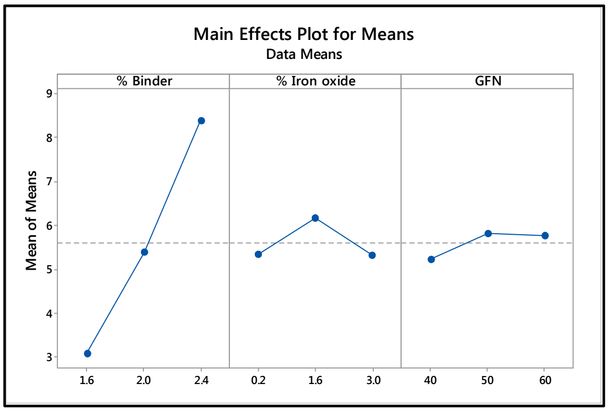


Fig.1 Main effects plot for collapsibility

From the Main effects plot shown in Figure 1, % binder was found to be the most dominant parameter for collapsibility property and optimum values were found at 2.4% of binder, 1.6 % of iron oxide and 50 GFN. Predicted mean and S/N ratio at these settings were found using Minitab and shown in Table 5. The phenomenon can be explained in terms of curing and mechanisms of chemically bonded mold. When binder is mixed with silica sand, the mixing process allows a thin coating of binders on individual sand particles. When the surfaces of two binder coated sand particles come in close proximity, then they crosslink with each other, and form a resign bridge. During curing these resin bridges shorten due to the evaporation of the solvent present in the binder and the result in hardening of the bridges [1]. As the hardening increases, its collapsibility also increases. An increase in grain finesses number of sand leads more sand particles being coated with the same amount of binder. This provides less strength to the crosslink bond between two sand particles, resulting in lower compressive strength as well as retained compressive strength (collapsibility). This observation is in agreement with previous research [1, 8]. As the resin binder percentage increases, the same number of sand particles are coated with more amount of binder, which results in an increase in collapsibility properties. From main effects plot for surface roughness shown in Figure 2, optimum values are obtained at 2% binder, 1.6% of iron oxide and 60 GFN.

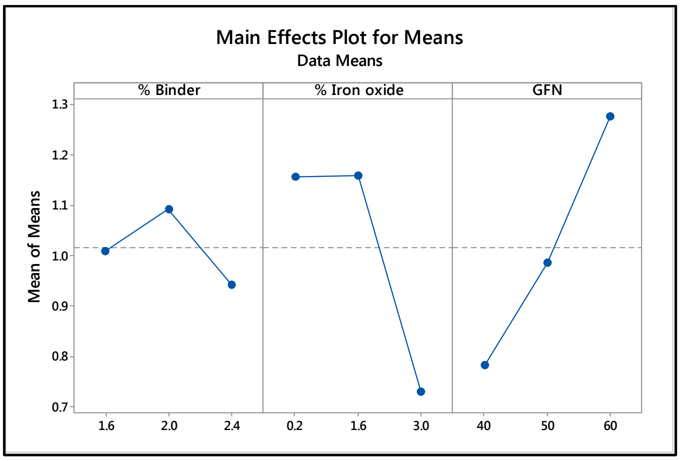


Fig.2 Main effects plot for surface roughness

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Regression Analysis: The experimental results were used to obtain empirical relationship between the variables and the collapsibility property using Minitab® V17 statistical software. The regression model can determine how a response property changes when a predictor variable changes. The equations were developed by least square fitting, which is suitable for fitting data to linear model. Minitab® uses the data obtained from the experiments to develop these regression equations, which will take the following form [1].

Response= constant + coefficient1 x predictor1 + ……. coefficient n x predictor n

Regression Analysis of Collapsibility(Y) versus % Binder, % Iron oxide, GFN are shown in table 5 and regression equation was as shown in equation 1.

Table 5 Regression analysis of collapsibility

| Term | Coef | SE Coef | T-Value | P-Value | VIF |
|---|---|---|---|---|---|
| Constant | -9.01 | 2.23 | -4.04 | 0.01 | |
| % Binder | 6.625 | 0.774 | 8.56 | 0 | 1 |
| % Iron Oxide | -0.001 | 0.221 | -0.01 | 0.996 | 1 |
| GFN | 0.0273 | 0.031 | 0.88 | 0.418 | 1 |

## Regression Equation

Collapsibility(Y) = -9.01 + 6.625 % Binder - 0.001 % Iron oxide + 0.0273 GFN (1)

Regression Analysis of Surface roughness (Ra) versus % Binder, % Iron oxide, GFN was shown in table 6 and regressionequation was as shown in equation 2.

Table 6. Regression analysis of surface roughness

| Term | Coef | SE Coef | T-Value | P-Value | VIF |
|---|---|---|---|---|---|
| Constant | 0.193 | 0.569 | 0.34 | 0.749 | |
| % Binder | -0.083 | 0.197 | -0.42 | 0.69 | 1 |
| % Iron Oxide | -0.1524 | 0.0564 | -2.7 | 0.043 | 1 |
| GFN | 0.02467 | 0.0079 | 3.12 | 0.026 | 1 |

## Regression Equation

Surface roughness (Ra) = 0.193 - 0.083 % Binder - 0.1524 % Iron oxide + 0.02467 GFN (2)

Empirical relations (1) and (2) can be used to estimate the properties of collapsibility and surface roughness of casting in case of phenolic urethane no-bake (PUN) binder system. Predicted values of collapsibility at optimum process parameters 2.4% binder, 1.6% iron oxide and 50 GFN are shown in table.7. Similarly, predicted values of surface roughness at optimum process parameters 2% binder, 1.6% iron oxide and 60 GFN are shown in table 8.

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Table.7 Taguchi predicted values of collapsibility

| S/N Ratio | Mean |
|---|---|
| -8.57222 | 2.41667 |

Table.8 Taguchi predicted values of surface roughness

| S/N Ratio | Mean |
|---|---|
| -4.06739 | 1.49889 |

**Confirmation experiments:**The confirmation experiments conducted at the suggested optimum parameter settings for both collapsibility and surface roughness and presented in table 9. Experimental values at optimum levels are matching with Taguchi predicted values shown in table 7 and table 8.

Table.9 Confirmation experiment results at optimum levels

| Methodology | Responses | Optimum levels | Average experimental values |
|---|---|---|---|
| Taguchi Analysis | Collapsibility | $A_3B_2C_2$ | 2.46 Kg/cm2 |
| | Surface roughness | $A_2B_2C_3$ | 1.52 µm |

## 5. Conclusions

Taguchiparametric design is adopted for the polyurethane no-bake (PUN or PUNB) binder sand molds to find collapsibility property for sand reclamation and to find surface roughness of gray cast iron castings by conducting minimum number of experiments. L9 orthogonal array was adopted to conduct the experiments. Quality indicator term S/N ratio (Smaller-the-better), ANOVA was performed to find out the significant contribution of each factor towards the response. Regression analysis was done to establish the relationship between the factors and responses. Optimum levels were found from main effects plot and confirmation experiments conducted at these optimum levels suggested by Taguchi and achieved 2.46 Kg/cm2 collapsibility and 1.52 µm surface roughness.

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