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Research Article

Energy Conservation in Foundry Industry by Modeling and Experimental Investigation of Induction Furnace Process Parameters

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Abstract

The study analyses the effect of four process parameters for energy conservation in Spheroidal graphite iron (S.G. Iron) manufacturing in induction furnace. Bundled steel, loose steel, cleaned and uncleaned scrap are the process parameters. Mixture design of experiments is used to study the effect of process parameters on power consumption. Analysis of variance (ANOVA) is performed to test the statistical efficacy of the model. The use of bundled steel and cleaned scrap is found to significantly reduce the power consumption in induction furnace. The experimental values were in good agreement with the predicted values and the key finding is that 44 kWh/ton is conserved with optimal values of process parameters.

Key Words: *Castings; Induction furnace; Mixture design of experiments; Analysis of Variance*

1. Introduction

Foundry manufactures S.G. Iron and grey iron castings used in automobile, textile and other ancillary industries. Electrical energy is consumed at all stages in the preparation of castings like melting of scrap, pouring, mould and core making, cooling, separation, fettling and painting. The furnaces commonly employed in foundries are cupola furnace, rotary furnace and induction furnace. Among these, induction furnace consumes huge power for melting scrap, steel and holding the metal and it is done at high temperature ranging from 1500°C to 1560°C depending upon the casting produced. The amount of energy consumed for melting one ton of metal is in the range of 600 kWh/ton to 680 kWh/ton with high energy intensity per unit of output. Therefore by redesigning the process parameters, wastage of energy can be avoided with optimum energy consumption. Hence an investigation of induction furnace in a foundry was done to optimize the process parameters.

2. Review of literature

Datta *et al*, 2007 examined energy consumption pattern in foundry industry and suggested energy saving measures like pre-heating of scrap and optimizing the furnace lining thickness for 10-12 % savings in total energy consumption in a foundry. Whiting *et al*,1987 identified the length of the melting period, holding power of the furnace, coil efficiency, open losses in lid, charge size, composition of liquid metal and temperature as factors affecting the shape, location and orientation of the furnace system. Experiments conducted with sized scrap by Ashok *et al*, 2001, resulted in an energy consumption of 690 kWh/ton and reduction in melting time by 25 minutes with a minimum scrap cost of Rs 7,063. Ming *et al*, 1998 suggested high capacity furnace for minimum power consumption and improved energy efficiency by 73-82 %. Landfeld, 1978, conducted experiments on silica and alumina furnace linings and found that alumina linings are more stable than silica linings due to greater resistance to chemical attack. Zavertkin, 2008, examined the effect of mixture composition on lining stability of a crucible induction furnace. It was found that the slag components most actively influencing the resistance of the lining are magnesium and calcium oxides, which are produced on modifying cast iron, ferrous oxide and manganese on account of reduction in the viscosity of the slag, increase in its wetting power, and penetration into the pores and unevenness in the walls of the crucible.

There is no detailed study regarding raw materials used in induction furnace towards energy optimization. Therefore the study focuses on varying the process parameters to reduce electrical energy use and thermal energy wastage in foundry industry.

3. Methodology

3.1 Design of experiments

The design of experiment is based on the simultaneous evaluation of two or more factors for their impact on the average of particular process characteristics. The design of experiment process has three major phases as planning

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phase, conducting phase and analysis phase. The planning phase provides the expected information about the process. Sensible and measurable parameters affecting the quality of the product are identified in this phase. The second phase is the conducting phase where all experiments are planned, conducted and test results are collected. This phase gives positive and or negative information about the process and parameter level. The third phase is the analysis phase which uses statistical tools for comparing the experimental results with predicted results.

The mixture design used in conducting experiments is a combination of statistical and mathematical methods for modeling and analyzing engineering problems. The design procedure of mixture design is as follows: The process parameters – bundled steel, loose steel, cleaned and uncleaned scrap are the critical variables designated as X_1, X_2, X_3 and X_4 respectively. The ranges and values of process parameters are given in Table 1.

Table 1 Process parameters – Ranges and values

S.No.	Mixture	Process parameters	Charge material weight in %
1	Mixture-1	X_1+X_2	50
2	Mixture -2	X_3+X_4	50

The table shows two combinations, bundled steel and loose steel charge mix; cleaned and uncleaned scrap charge mix. The maximum limit for each component of the mixture is 50 % and the quantity of the components can be varied to maintain the required chemical composition as per the charge mix calculation.

3.2 Materials

Bundled steel, loose steel, cleaned and uncleaned scrap were used for melting in induction furnace.

3.3 Machineries

For melting scrap and steel, 500 kg capacity, 550 kW, 1000 Hz medium frequency induction furnace manufactured by Inductotherm (India) Ltd, Ahemadabad, India is used; To check the chemical composition of steel, scrap and liquid metal Spectrometer manufactured by ARL, Switzerland is used; To measure the temperature of liquid metal in the induction furnace Portable Pyrometer manufactured by Suyash Solutions (Pvt) Ltd, Pune, India is used.

3.4 Experiments

In the study, 29 experiments were conducted in the induction furnace by varying the process parameters as per the design matrix given in Table 2. Before charging, the bundled steel, loose steel, cleaned and uncleaned scrap was carefully weighed as per the design matrix and chemical composition was checked using spectrometer. Before the melt start up, carbon and silicon were added to the path metal based on the charge mix calculation. The weighed steel and scrap are frequently charged and melted. In between the metal charging, generated slag is removed to get slag free metal. From the slag free liquid metal, samples were taken and tested in the Spectrometer. After adjustment of the required chemical composition, liquid metal temperature is raised to 1560°C. The melt was transferred into a tundish cover reactor and treated with Ferrosilicon magnesium. Prior to the casting operation the melt was poured into the ladle and during the transfer operation inoculation was performed.

Table 2 Experimental design matrix

Expt. No.	Bundled steel	Loose steel	Cleaned scrap	Uncleaned scrap
	(% by weight)			
1	12.5	37.5	37.5	12.5
2	25	25	25	25
3	37.5	12.5	12.5	37.5
4	50	0	50	0
5	50	0	37.5	12.5
6	37.5	12.5	50	0
7	25	25	25	25
8	25	25	25	25
9	50	0	25	25
10	12.5	37.5	12.5	37.5
11	37.5	12.5	0	50
12	25	25	12.5	37.5
13	37.5	12.5	25	25
14	25	25	25	25
15	25	25	0	50
16	12.5	37.5	0	50
17	12.5	37.5	25	25
18	25	25	37.5	12.5
19	0	50	50	0
20	50	0	12.5	37.5
21	0	50	25	25
22	0	50	0	50
23	37.5	12.5	37.5	12.5
24	0	50	12.5	37.5
25	25	25	25	25
26	0	50	37.5	12.5
27	50	0	0	50
28	25	25	50	0
29	12.5	37.5	50	0

4. Results and Discussion

The design of experiments uses mixture design with design expert software. Independent variables are used to obtain the combination of values that optimizes the response within the region of the three dimensional observation space, facilitating minimal number of experimental runs. Using the regression equation, the level of power consumption as a function of bundled steel, loose steel, cleaned and uncleaned scrap is estimated. All terms regardless of their significance are listed in the following equation.

$$Y = 0.23\, X_1X_3 + 0.25\, X_1X_4 + 0.25\, X_2X_3 + 0.26\, X_2X_4 + 6.79\times10^{-5}\, X_1X_2X_3 + 3.34\times10^{-4}\, X_1X_2X_4 - 7.59\times10^{-6}\, X_1X_2X_3\,(X_1 - X_2) + 1.59\times10^{-5}\, X_1X_2X_4\,(X_1 - X_2)$$

where, 'Y' is the predicted power consumption. The power consumption of experimental points is listed in Table 3 along with the predicted values. The stability of the statistical model for power consumption analysis is verified from the analysis of variance (ANOVA) as given in Table 4. The software output shows that the model is significant with probability (P) 0.0001 and lack of fit with P = 0.2082 which is larger than the reference limit 'P' of 0.05. The normal probability of the response residuals is shown in Figure 1. The convergence of data indicates minimum deviation from the fit. The goodness of fit (R^2 = 0.9632) confirms that the levels are within acceptable limit.

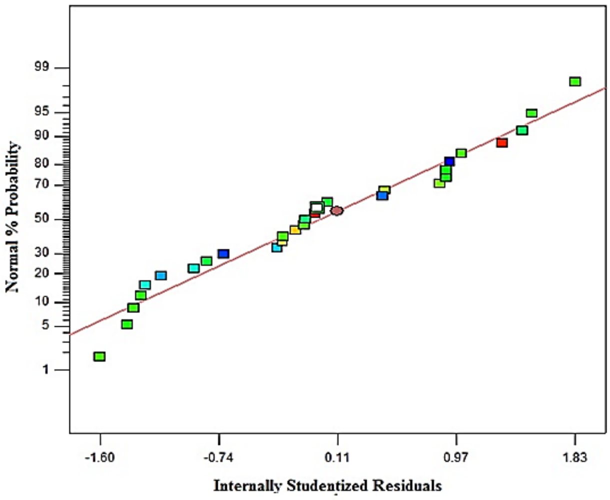

Fig. 1 Normal plot of residuals

The contour plot representing the interaction effect of bundled steel and loose steel, cleaned scrap and uncleaned scrap on power consumption is shown in Figure 2. The figure shows that minimum power consumption of 596 kWh per ton is obtained using 50 % bundled steel and 50 % of cleaned scrap. When the percentage of cleaned scrap is reduced from 50 % it can be adjusted with increase in the percentage of uncleaned scrap. The uncleaned scrap has rust and moulding sand impurities. During the melting process, sand and rust components react with furnace lining material, consuming extra power to generate the slag and removal of slag. When the bundled steel is reduced from 50 % level it can be adjusted with increase in the percentage of loose steel for maintaining the required chemical composition. Bridge formation takes place at the top of the furnace due to low bulk density of loose steel. Loose steel does not come in contact with the liquid metal in the furnace resulting in a gap between loose steel- bridge and liquid metal. These changes increase the temperature of liquid metal, consuming more power and reducing the furnace lining life.

Table 3 Experimental and predicted values of power consumption

Expt No.	Power consumption (kWh/ton)	
	Experimental value	Predicted value
1	632	632.83
2	628	625.1
3	625	627.46
4	596	594.02
5	600	601.99
6	603	601.91
7	630	625.1
8	631	625.1
9	609	609.96
10	630	633.86
11	632	635.97
12	632	628.83
13	615	618.94
14	625	625.1
15	635	632.56
16	631	634.37
17	629	633.34
18	621	621.37
19	638	637.02
20	622	617.96
21	648	648.56
22	660	660.11
23	607	610.43
24	658	654.34
25	628	625.1
26	642	642.79
27	626	625.91
28	615	617.65
29	632	632.31

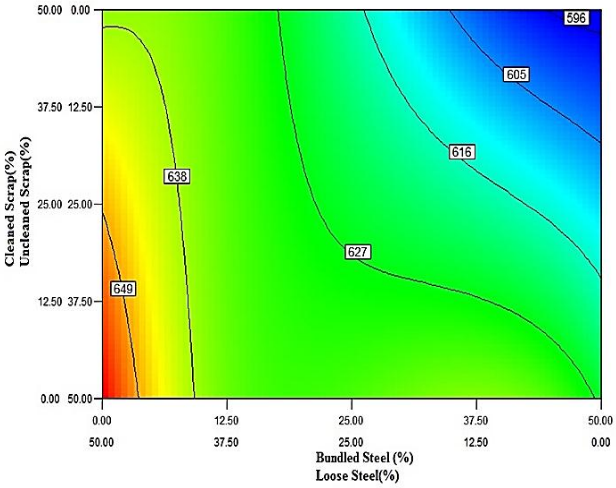

Fig. 2 Contour plot for power consumption vs process parameters

Table 4 ANOVA for power consumption

Source	Sum of squares	df	Mean square	F value	p-value Prob>F
Model	6169.12	7	881.3	78.56	< 0.0001
Linear x Linear	5753.54	3	1917.85	170.97	< 0.0001
ABC	6.69	1	6.96	0.62	0.4396
ABD	168.4	1	168.4	15.01	0.0009
ABC (A-B)	52.81	1	52.81	4.71	0.0417
ABD (A-B)	233.13	1	233.13	20.78	0.0002
Residual	235.57	21	11.22	-	-
Lack of fit	214.37	17	12.61	2.38	0.2082
Pure error	21.2	4	5.3	-	-
Cor total	6404.69	28	-	-	-

Conclusions of the study

Mixture design of experiments is used to analyze the impact of process parameters on power consumption which works on the regression analysis of the experimental data collected. The predicted model was tested using ANOVA. Twenty nine experiments were conducted and the optimal combination of process parameters identified. Following are the inferences of the analysis of the study.

- Bundled steel and cleaned scrap are major determinants of minimizing power consumption in the induction furnace.
- Statistically, 45 % bundled steel, 5 % loose steel, 49.83 % cleaned scrap and 0.17 % uncleaned scrap results in saving of 596 kWh/ton with 500 kg, 550 kWh and 1000 Hz medium frequency induction furnace in the S.G.Iron production in a foundry.
- The use of uncleaned scrap with its rust and sand impurities consumes more time for melting and removal of slag. Further it reduces the lining life of the furnace.
- The study clearly indicates the possibility of conserving energy with the optimal process parameters.

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