Quality Engineering, 13(3), 501–519 (2001)

REDUCTION OF CARBON PERCENTAGE OF HOT METAL PRODUCED BY A MINI BLAST FURNACE

Arup Ranjan Mukhopadhyay
SQC & OR Unit
Indian Statistical Institute
27-B Camac Street
Calcutta—700016, India

Key Words

Hot blast temperature (HBT); Hot blast volume (HBV); Slag basicity; Sulfur loading; Fe/C ratio; R^2; Adjusted R^2; Standard error; NLP; LP.

Introduction

The study pertains to a ductile iron (DI) plant in India. The plant manufactures DI pipes of various sizes ranging from 80 to 1000 mm. The hot metal is prepared in a Mini Blast Furnace (MBF) for this DI pipe manufacture. One of the vital chemical constituents for this hot-metal preparation is the carbon percentage in hot metal [C%]. The specification for [C%] is supposed to be within 3.6% to 4.0% for obtaining a smooth flow of production. The problem is of producing hot metal, containing [C%] higher than the upper specification limit. The adverse effect of high [C%] is twofold.

First, it results in brittleness in the ultimate product—the DI pipe. Second, it causes environmental pollution in the form of emission of shiny and tiny carbon particles to the atmosphere. It may be worthwhile to note here that these silverlike shiny carbon particles are formed due to a sudden temperature drop which takes place when the carbon particle along with the MBF fume, having a very high temperature of the order of 1300–1400°C, suddenly come into contact with the atmosphere, at ambient temperature.

The first adverse effect of a high [C%] (i.e., generation of brittleness in DI pipes) is accorded priority by the plant personnel because it is directly related to its core business area of manufacturing quality DI pipes. Keeping that in mind, the existing practice adopted by the plant is to add scrap to the induction furnace or Mini Hill Furnace (MHF), the next stage of hot-metal preparation after MBF. Needless to say, the very purpose of this scrap addition is to reduce [C%] so that brittleness is avoided.

As a matter of fact, even though the scrap addition is done with the intention of avoiding brittleness, it is undesirable because it achieves *quality* by compromising *cost of production and productivity*. The cost of production and productivity are compromised as follows. The addition of metal scrap reduces the hot-metal temperature at the induction furnace or MHF. To compensate for such a loss in temperature, extra heating is required for additional time. Because of this extra heating, the cost of production increases, and because of the extra time required, the productivity gets hampered.

Because the MBF plant was newly commissioned at the time of carrying out this study, adequate control did not exist in the process due to the ad hoc operational approach. This study is an exploratory one to arrive at the process control features.

The study is undertaken with a view to finding feasible and beneficial ways and means of reducing [C%] in the hot metal produced by MBF.

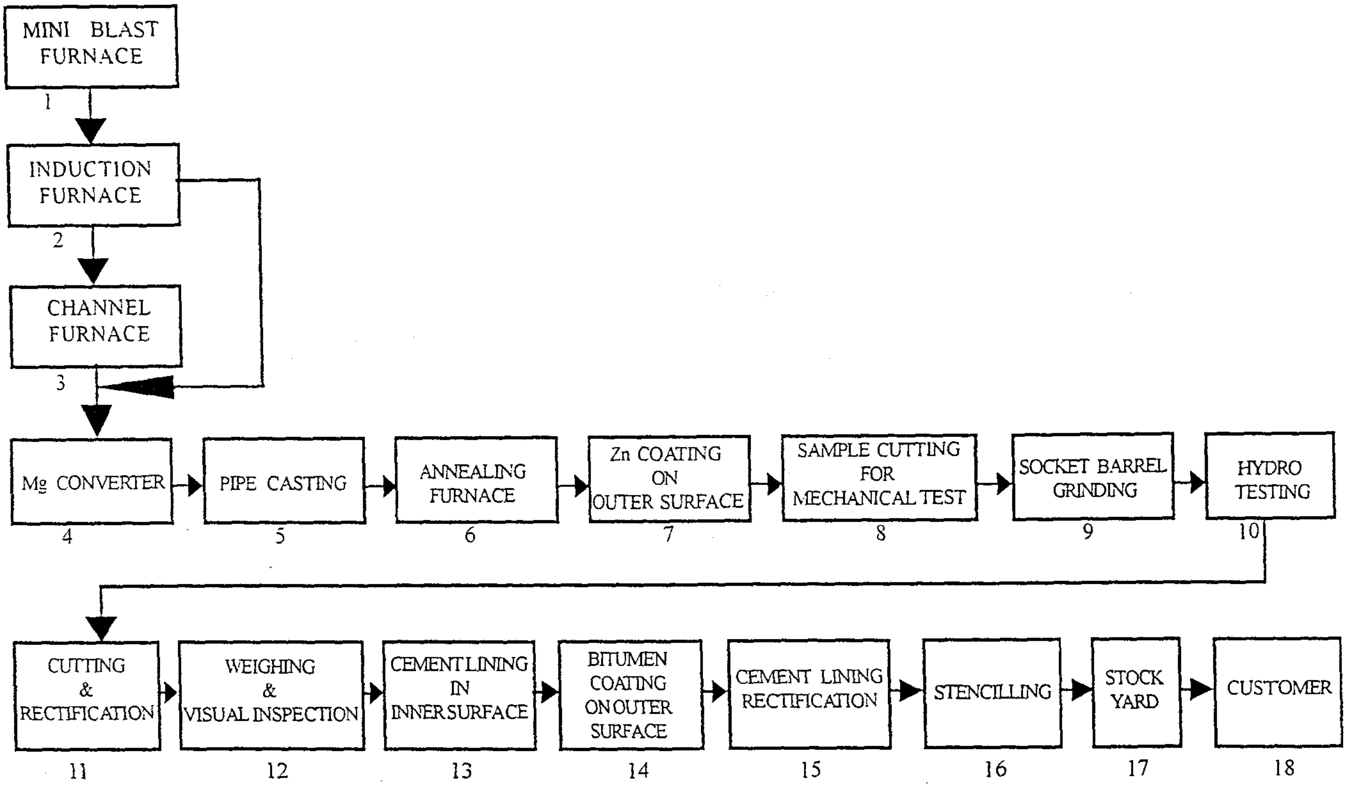

Figure 1. Process flowchart for ductile iron pipe manufacture.

Background Information

The magnitude of the problem of high [C%] in the hot metal produced by MBF can be conceived of from the existing distribution of [C%] (see Table 1). It may be worthwhile to recall here that the specification of [C%] is 3.6% to 4.0%. It can be observed from Table 1 that about 89% of the tapping subsequent to MBF operation contains carbon above 4%.

Data

At the outset, data are collected on the chemical composition after MBF operation. These observations (see Appendix 1) are the outcome of spectrographic analysis of the MBF samples. Chemical compositions of C%, Si%, Mn%, S%, and P% of MBF metal are thus found.

Subsequently, data are collected by two groups of people on the MBF shop floor. Group 1 collected data on Si% of a charge mix and the corresponding process parameters [i.e., HBT, HBV, Fe/C (see Appendix 2)]. Group 2 collected data on S% of a charge mix and the relevant process parameters [i.e., sulfur loading (amount of S in the charge mix from coke), slag basicity (CaO/SiO_2 ratio in slag), slag volume, slag temperature, MgO% in slag (see Appendix 3)]. The process parameters are noted down corresponding to a charge mix from the control panel and then the MBF metal sample is sent to the laboratory for spectrographic analysis of Si% or S%.

Analysis and Information

Because the objective of the study is to obtain feasible and beneficial ways and means of reducing [C%], the relationship between [C%] and other chemical constituents (viz. [Si%], [S%], [Mn%], [P%]) was examined at the existing techno-economic setup.

The technique adopted for the purpose was stepwise regression. The SPSS package in a VAX environment was used for this purpose. The best relation arrived at was between [C%] versus [Si%] and [S%]. The number of obser-

Table 1. Frequency Distribution of [C%] at MBF

CLASS INTERVAL	FREQUENCY	CUMULATIVE FREQUENCY (GREATER THAN TYPE)	% CUMULATIVE RELATIVE FREQUENCY (GREATER THAN TYPE)
3.555–3.645	2	270	100.00
3.645–3.735	0	268	99.26
3.735–3.825	6	268	99.26
3.825–3.915	10	262	97.04
3.915–4.005	11	252	93.34
4.005–4.095	35	241	89.26
4.095–4.185	66	206	76.30
4.185–4.275	103	140	51.85
4.275–4.365	37	37	13.70
Total	270		

vations considered for the purpose was 270. The relationship used was

$$[C\%] = 4.453 - 0.054[Si\%]^2 - 32.656[S\%]^2 \qquad (1)$$

with adjusted $R^2 = 0.65$ and standard error (S.E.) = 0.076.

Relation (1) holds under the following conditions:

- Normal operation of the MBF
- Variation of [P%] between 0.17% and 0.83%
- Variation of [Mn%] between 0.02% and 0.08%
- Variation of [Si%] between 0.99% and 4.40%
- Variation of [S%] between 0.01% and 0.13%

It is obvious from Eq. (1) that the relation between [C%] versus [Si%] and [C%] versus [S%] is inverse in nature. This implies that if [Si%] and [S%] increase within the ranges of 0.99–4.40% and 0.01–0.13%, respectively, [C%] decreases and vice versa.

Because the objective is to control [C%] on the lower side (in particular within the range 3.6–4.0%), it is clear from relation (1) that this is achievable by adjusting both [Si%] and [S%] on the higher side. This task of finding the optimum composition of [Si%] and [S%] corresponding to a target C% of 3.8% is performed by the nonlinear programming method with the help of an IMSL package in the VAX environment. The formulation of the problem is

$$\text{Minimize } (4.453 - 0.054[Si\%]^2 - 32.656[S\%]^2 - 3.8)^2$$
$$\text{Subject to } 4.453 - 0.054[Si\%]^2 - 32.656[S\%]^2 = 3.8$$

The optimum composition of [Si%] and [S%] is [Si%] = 2.951% and [S%] = 0.076%.

It is to be noted that these optimum compositions remain within the existing operating zones of [Si%] and [S%]. It may be recalled that the existing operating zone of [Si%] is 0.99–4.40% and that of [S%] is 0.01–0.13%.

Having found the optimum composition of [Si%] and [S%] for reducing [C%], the next logical step is to establish a relation among [Si%], [S%], and the corresponding process parameters. This task is also accomplished by resorting to stepwise regression with the help of an SPSS package in a VAX environment. The relationship is

$$[Si\%] = 26.540 - 20.147(Fe/C) + 8.153(Fe/C)^2 - 0.011(Fe/C)HBT \qquad (2)$$

with adjusted $R^2 = 0.67$, standard error = 0.189, and number of observations = 38. The above relationship holds good for the following conditions:

- Normal operation of the MBF
- Variation of HBT within 740–760°C
- Variation of Fe/C within 1.37–1.76
- Variation of HBV within 19,430–30,070

$$[S\%] = 0.062 + 0.040(\text{sulfur loading}) - 0.189(\text{slag basicity}) \qquad (3)$$

with adjusted $R^2 = 0.72$, standard error = 0.011, and number of observations = 30. Relation (3) holds for the following conditions:

- Normal operation of the MBF
- Variation of sulfur loading within 3.67 kg/THM (tons of hot metal) to 4.42 kg/THM

- Variation of slag basicity within 0.76 to 1.07
- Variation of slag volume within 225.3 kg/THM to 274.1 kg/THM
- Variation of theoretical slag temperature within 1518°C to 1571°C

The optimum levels of the process parameters Fe/C and HBT corresponding to Eq. (2) for meeting the target [Si%] of 2.951 are determined by solving the following nonlinear programming (NLP) with the help of an IMSL package in the VAX environment:

$$\text{Minimize } [26.540 - 20.147(\text{Fe/C}) + 8.153(\text{Fe/C})^2 - 0.011(\text{Fe/C})\text{HBT} - 2.951]^2$$

$$\text{Subject to } 26.540 - 20.147(\text{Fe/C}) + 8.153(\text{Fe/C})^2 - 0.011(\text{Fe/C})\text{HBT} = 2.951.$$

The optimum level of Fe/C and HBT is Fe/C = 1.40 and HBT = 747.5. It is to be noted that these optimum levels remain within the existing operating zones of Fe/C and HBT. It may be recalled that the existing operating zone of Fe/C is 1.37–1.76 and that of HBT is 740–760°C.

The optimum levels of the process parameters sulfur loading and slag basicity corresponding to Eq. (3) for meeting the target [S%] of 0.076 are determined by solving the following linear programming problem (LPP):

$$\text{Minimize } [0.062 + 0.040(\text{sulfur loading}) - 0.189(\text{slag basicity}) - 0.076]$$

$$\begin{aligned}\text{Subject to } 3.67 &\le \text{sulfur loading} \le 4.42\\ 0.76 &\le \text{slag basicity} \le 1.07\\ 0.062 &+ 0.040(\text{sulfur loading}) - 0.189(\text{slag basicity}) = 0.076.\end{aligned}$$

The optimum level of sulfur loading and slag basicity is sulfur loading = 3.92 and slag basicity = 0.76.

Recommendations

- Because the desirable range of [C%] is 3.6–4.0%, the target for [C%] is 3.8%. To meet the target [C%] of 3.8%, [Si%] should be maintained at 2.951% and [S%] should be maintained at 0.076%.
- To obtain [Si%] at 2.951%, the Fe/C ratio should be maintained at 1.40 and HBT should be maintained at 747.5°C.
- To obtain [S%] at 0.076%, sulfur loading should be maintained at 3.92 and slag basicity should be maintained at 0.76.

Implementation

Subsequent to implementing the above recommendations, the distribution of [C%] of MBF hot metal is found. Comparison with the distribution of [C%] after scrap addition at the MHF, the practice adhered to earlier to reduce [C%] in the hot metal produced by the MBF reveals clearly that with respect to both the mean and standard deviation,

Table 2. Comparison of Distribution of [C%] at the MBF After Implementation with That of [C%] at the MHF Before Implementation Following the Practice of Scrap Addition

	[C%] AT MHF BEFORE IMPLEMENTATION AFTER SCRAP ADDITION			[C%] AT MBF AFTER IMPLEMENTATION		
CLASS INTERVAL	FREQUENCY	CUMULATIVE FREQ. (LESS THAN TYPE)	% CUMULATIVE RELATIVE FREQ. (LESS THAN TYPE)	FREQUENCY	CUMULATIVE FREQ. (LESS THAN TYPE)	% CUMULATIVE RELATIVE FREQ. (LESS THAN TYPE)
3.585–3.645	5	5	3.25	2	2	1.18
3.645–3.705	5	10	6.49	16	18	10.59
3.705–3.765	15	25	16.23	56	74	43.53
3.765–3.825	41	66	42.86	73	147	86.47
3.825–3.885	66	132	85.71	22	169	99.41
3.885–3.945	20	152	98.70	1	170	100.00
3.945–4.005	1	153	99.35			
4.005–4.065	1	154	100.00			
		Minimum	= 3.59	3.64		
		Maximum	= 4.06	3.91		
		$\overline{X}$	= 3.8234	3.7703		
		σ_{n-1}	= 0.0714	0.0537		

the recommendations resulted in statistically significant lower values (see Table 2).

Consequently, the earlier practice of scrap addition at the MHF was discarded. The departmental procedure and work instruction with regard to hot-metal procurement from the MBF to the MHF were modified accordingly.

However, it is to be noted that both distributions of C% [before implementation (Table 1) and after implementation (Table 2)] are left-skewed. It requires further exploration after this exploratory study to ascertain the reasons for such a skewness.

Cost–Benefit Analysis

It is to be noted that before implementation, 89% of the tapping subsequent to the MBF operation contained [C%] above 4%. Iron scrap used to be added to the MHF with a view to reducing [C%] by 10% of a day's production of about 290 metric tons (MT). The cost of scrap is about Rs 6000/MT (Rs = rupees). Hence, 10% scrap addition per day implies an extra Rs 174,000 (Rs 6000 × 29) per day.

Again, for 10% addition of scrap, loss in temperature used to take place at 65°C per MT at the MHF. It is to be noted that 100°C per MT loss in temperature implies an additional consumption of 45 units of electricity. Because the cost of 1 unit of electricity was about Rs 4 during the period of conducting this study, the cost of additional electricity consumption for this scrap addition is (Rs 4 × 65 × 45/100) per MT = Rs 117/MT (i.e., Rs 117 × 290 per day = Rs 33,930 per day).

Hence, total cost incurred for reduction of [C%] is Rs 207,930 per day (approximately) (Rs 174,000 + Rs 33,930 per day). The implementation of the above-mentioned recommendations resulted in a cost savings of Rs 207,930 per day (approximately).

It may be worthwhile to mention here that the concerned technicians were thinking of installing steam injection methodology as an alternative to the practice of scrap addition at the MHF for reducing [C%]. However, to facilitate steam injection, the HBT has to be raised from 750 ± 10°C to 950 ± 10°C. In order to do this, one would have to change the heating system from the metallic blast preheater (MBP) to stoves. This change itself would cost around Rs 4 million. The total additional cost for steam injection will be around Rs 120 million, including the cost of conversion from the MBP to stoves.

Bibliography

Draper, N. R., and Smith, H. *Applied Regression Analysis.*

IMSL Mathematical Manual.

Metallurgist's Handbook, Foreign Language Publishing House, Moscow.

About the Author: Arup Ranjan Mukhopadhyay is working as a faculty in the SQC & OR Division of the Indian Statistical Institute, Calcutta since January 1990, which involves consultancy, teaching, and applied research in the field of quality management and operations research. He is a Certified Lead Assessor for ISO 9000 Quality Assurance System implementation. He has a B.Tech. from Calcutta University and a post-graduate diploma in SQC & OR and Specialist Development Fellowship Programme from ISI.