FERRO SILICON OPERATION AT IMFA – A CRITICAL ANALYSIS

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ABSTRACT

Carbothermic process of Ferro Silicon production is primarily a slag-less process. However, slag formation is observed in the regular operation as experienced by almost all the Ferro Silicon Producers in different proportions.

The problem of slagging in the furnaces may be due to:

a) Variation in the input burden charge material quality
b) Fluctuations in the Carbon balance

and/or
c) Fluctuations in the Electrode penetrations

The problem will be more severe in nature with the increase of the size of the furnace. The operation performance of the furnace gets badly affected if the slag formed in the furnace is not removed from the bath in time and to the maximum extent possible.

It is, therefore, very essential to know the characteristics of the slag formed in the Ferro Silicon Furnaces, besides eliminating the very cause of formation itself; and to find the routes of draining of the same from the furnace bath effectively.

This paper envisages the effects of using the LIME STONE in the Ferro Silicon Burden in stabilizing the 48 MVA Furnace for improved performance and better consistency.

Quality fluctuations in the available Raw Materials are compared with that of the requirements for the Ferro Silicon production. The furnace operational data is compared for 12 months period each for the period corresponding to the before and after usage of lime stone in the burden and found encouraging results in the performance.

Implications of use of Lime Stone in the burden on the quality of the output alloy are also studied.

1. INTRODUCTION

Ferro Silicon is produced in Sub-merged Electric Arc Furnaces by the Carbothermic smelting of the Quartz. Even though the process is a slag less there is some inevitable generation of slag in the process. The extent of slag formation depends on the control exercised on the furnace parameters and the raw material quality.

IMFA is operating Ferro alloy furnaces since 1967 producing Ferro Silicon, Silicon Metal and Charge Chrome. It has one 10 MVA, one 24 MVA and one 48 MVA furnace. This paper mainly deals with the operational experience in 48 MVA Furnace producing Ferro Silicon.

The Furnace was operated up to a maximum capacity and faced all typical problems of Ferro Silicon operation. Consistency could be established during the period 2000 to 2004 with optimized performance due to continual operation. Thereafter constantly good quality Quartz could not be procured due to opening up of new mines, leading to use of inferior quality of Quartz. In spite of best control in the furnace operation slag used to be generated in the furnace bath leading to severe disturbances in the operation. IMFA made attempts to overcome these problems aiming to avoid the tapping problems and clear the bath for better smelting efficiency.

Introduction of Lime Stone as a deck correction and in the burden lead to reduction of furnace tapping problems and improvement of overall efficiency, improved production and productivity. Slag formed got effectively drained out thereby improving the furnace top condition and overall efficiency.

However, due to addition of Lime Stone slight variation in the alloy chemistry occurred. All the consequent problems were anticipated and addressed in the post tapping operation.

1.1 Quality Norms Of Raw Materials At IMFA

A)

Quartz - A type		Quartz – B type	
SiO2	99.5% min.	SiO2	98.5% min.
Thermal Stability	10% max (-25 mm generations)	Thermal Stability	10% max (-25 mm generations)
Pure white			
Size	10 to 100 mm	Size	10 to 100 mm

B) Charcoal

Fixed Carbon	65% min.
Ash	7 to 9%
V.M	15 to 23 %
Size	6 to 50 mm

C) Mill Scale / Gas Cuttings

Fe	70% min
Al	0.5% max

1.2 Quality Deviations Experienced By IMFA

QUARTZ: Main problem in the Quartz was the purity of the material due to earth contamination and the presence of over burden material layers in the rock. Due to reduced availability of A grade Quartz, increased amount of B grade Quartz with more over burden was used. Due to lack of washing facility at site, it was not possible to separate the contamination. From Table-1 it is evident that presence of overburden material increased gradually over the period.

Table 1: % of Overburdened material in the Quartz lots consumed in the period of study

Year	*Month*											
	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
2004	0.8	3.05	1.73	1.5	1.9	3.19	4.25	3.17	6.31	4.3	6.36	4.58
2005	8.77	5.71	6.77	7.37	5.35	8.76	8.7	9.16	7.03	9.45	8.47	7.8

The thermal stability tests as per the IMFA Lab procedure indicated the inferior quality, which had resulted in the formation of slag in the furnace.

CHARCOAL : Charcoal suffers the variation in fixed carbon at the cost of ash content with regard to the efficiency of wood burning during charcoal formation and also due to the variations in screening efficiency because of moisture variations.

MILLSCALE / GAS CUTTING : Mill Scale / Gas cutting is used as a source of iron in the burden in place of Iron ore to minimize the slag formation and to have the Fixed Carbon requirement reduction. However, the material is contaminated with oil, solid metallics and dust which is very difficult to separate. It is experienced that there is about 5 to 7% of such contamination in the material.

2.0 FERRO SILICON PROCESS DESCRIPTION

In the Ferro Silicon process the important reactions are:

1. $SiO_2 + C = SiO + CO$
2. $SiO + 2C = SiC + CO$
3. $2SiO_2 + SiC = 3SiO + CO$
4. $SiO + SiC = 2Si + CO$

The impurities and alloying elements entering the process for carbothermic reduction of silica in the form of oxides or interoxidic compound are exposed to the reducing power of free carbon in equilibrium with CO at atmospheric pressure up to a temperature of 1512 deg C. The reduction potential thereafter is defined by the reaction between Silica and SiC in the presence of CO appearing with a pressure which is decreasing with increasing temperature up to a point where liquid metal starts to form (around 1811 deg C). [1]

The Ellingham diagram (Fig-1) describes the standard energies of formation of oxides and the stability of different metals relative to those of Silicon and Carbon. The impurities, oxides of Ca, Ti, Al requires a lower oxygen potential than SiO_2 to react and form metal in its standard state.

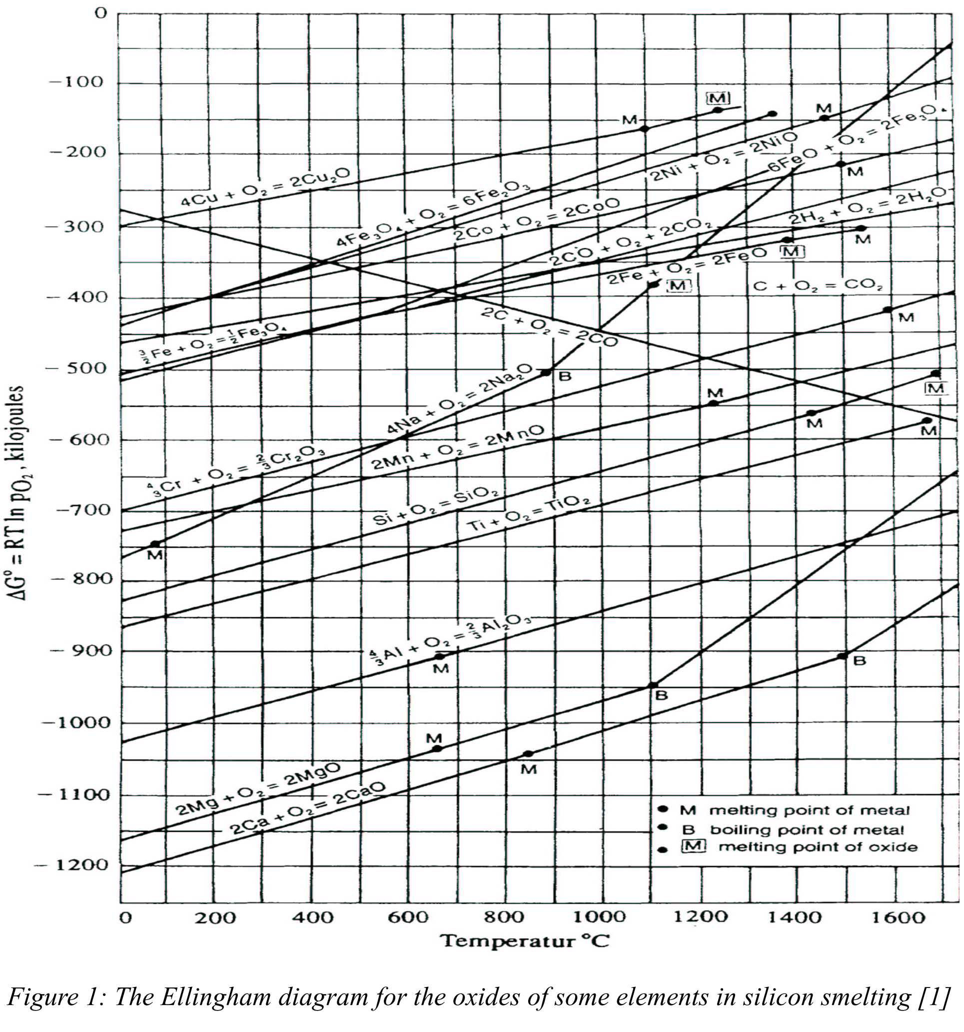

Figure 1: The Ellingham diagram for the oxides of some elements in silicon smelting [1]

The high stability of these oxides and the fact that they enter as impurities tied up in the silicate minerals with oxide activity less than unity make them remain as oxides up to the melting point of silica at around 1700 deg C where they become dissolved in a glassy slag.[1]

Oxides of Ti, Al lowers the melting point of silica and forms eutectics at a temp of 1550 and 1595 deg C respectively. The slag is formed like $3Al_2O_3 + 2SiO_2 = 3Al2O_3.2SiO_2$. [1]

Table 2: Impurity oxide activities at equilibrium with liquid silicon with 0.1% Me at 1600 deg C. [1]

Impurity Me_xO_y/Me	$k_{e\,f} = 3.56M_{Me} \cdot (K_{[3.4]})^{\frac{y}{2x}}$	γ^0_{Me} (Bakke 1997)	$a_{Me_xO_y}$ in additional phase [1]	$a_{Me_xO_y}$ at [%Me]=0.1	[%Me] at formation add. phase
$FeO/\underline{Fe}$	$9.98 \cdot 10^5$	$4.80 \cdot 10^{-2}$	0.37	$4.8 \cdot 10^{-9}$	xx)
$MnO/\underline{Me}$	$3.49 \cdot 10^3$	$3.59 \cdot 10^{-2}$	0.12	$1.0 \cdot 10^{-6}$	xx)
$Cr_2O_3/\underline{Cr}$	$2.07 \cdot 10^5$	$1.01 \cdot 10^{-2}$	0.12	$2.4 \cdot 10^{-17}$	xx)
$TiO_2/\underline{Ti}$	$6.62 \cdot 10^1$	$4.5 \cdot 10^{-5}$	0.6	$6.8 \cdot 10^{-8}$	xx)
$TiO/\underline{Ti}$	$9.57 \cdot 10^{-1}$			$4.7 \cdot 10^{-6}$	xx)
$Al_2O_3/\underline{Al}$	$1.09 \cdot 10^{-1}$	$2.4 \cdot 10^{-1}$	0.6	0.05	0.35
$CaO/\underline{Ca}$	$1.17 \cdot 10^{-2}$	$1.08 \cdot 10^{-3}$	0.0022	0.0092	0.024
$MgO/\underline{Mg}$	$1.10 \cdot 10^{-2}$	$1.5 \cdot 10^{-2}$	0.23	1.4	0.17

The two sets of oxide activities values are more comparable for Aluminium and Calcium. A Ca level of 0.1% and Al of 0.1% each cannot be reached in the system of unit activity of SiO_2 at 1600 deg C because the maximum equilibrium constant (Table-2) is 0.024% for Ca and 0.35% for Al, below which Al and Ca when present as impurities are distributed quantitatively in the metal phase. However, when present together, as is the case in the real process, their oxides will mix and form a multi-component slag with oxide activity that are less than the experimented values, consequently limiting the metal concentration of these elements. When sum of concentrations of these elements exceeds about 0.5% of the total SiO_2 in the charge, they will lead to the formation of slag resulting in contamination of metal tapped.[1]

2.1 Formation of Slags in Ferro Silicon

The impurities in the input carbon will also form the slag. The impurities present in the raw materials entering the furnace will lead to slag formation as well as elemental impurities dissolved in Ferro Silicon. The extent of the elemental impurities and the slag as oxide will depend on the temperature in the furnace as well as the composition of the slag.

Main raw materials for Ferro Silicon production are quartz, charcoal and mill scale.

Quartz contains chemical gangue besides the conglomerates of surface sticking mud coat and earth materials which contributes for slag forming tendencies. Other important parameter is its ability to withstand the high temperature crumbling called the thermal stability. When the thermal stability is poor the quartz disintegrates before it is reduced. Quartz typically contains 1-2% impurities such as Al_20_3, FeO, CaO, etc. Mud and earth materials also contribute towards slag formation. Thermal stability of quartz is very important and quartz with poor thermal stability disintegrates in the furnace burden forming slag.

The impurities embedded in the quartzites are not accessible for reduction before the quartzite lumps decripate or melt. In the latter case, they become dissolved in a glassy phase where they become more and more enriched as the silica is consumed in the formation of SiO(g) and Si(l). The metal oxide activities increases and the silica activity decrease during this stage, and the temperature needed for further consumption of silica increases. Eventually the consumption of silica slows down and stops, leaving some silica behind tied up in a very viscous melt that is highly enriched in alumina. This melt tends to accumulate in the furnace unless it gets the opportunity to react with calcium in the metal as expressed by the reaction

$$3\ Ca + (Al_2O_3)_{slag} = 2\ Al + 3\ (CaO)_{slag}$$

This exchange reaction with calcium makes the slag sufficiently fluid to be tapped together with the metal.[1]

2.2 Types of Slags[1]

The term SLAG for the molten oxide is analogy from the production of other metals, where the ore normally contains more of impurity elements that are less nobler than the metal that is to be produced. The main metal is extracted as metal phase and the less noble impurities are left as slag which is normally the mix of impurity oxides and being in molten form can easily be separated from the metal phase.

In the Ferro Silicon operation, formation of deposits in the furnace are observed which are of 3 types:

1. Incompletely converted charge
2. SiC with Si at the bottom
3. Crusts of sintered charge materials in the upper parts of the furnace

2.3 Characteristics of Different Kinds of Slags

2.3.1 Incompletely converted charge (Slagging)

The main reactants in the inner zones of the Ferro Silicon furnaces are SiO_2 and SiC as mentioned earlier. When this mixture is heated at equilibrium the temperature rises to 1811 deg C where the Si is formed until either SiO_2 or SiC is consumed. If SiO_2 is left it will react with Si and form SiO which vaporizes at temp below 1900 deg C. In real operation the rate of some reactions will be low and the temp will rise more than 2000 deg C before the vaporization is rapid. All the SiO_2 will vaporize and only Si and SiC will be left over.

In that condition if oxides of metal nobler than silicon are present, the metal will enter the silicon phase (like Fe) and the oxygen is given off as SiO or CO/CO_2. For oxides of metals less noble than silicon like Al_2O_3 and CaO a compound silicate phase will be formed which requires further higher temperatures to vaporize than SiO_2. The final vaporized product will be a silicon alloy and SiC at 2200 deg C. Therefore, if the furnace produces slag it is because of the heating being insufficient. The temperature may be high enough but the flow of the reactants into the inner zones can be too high for complete consumption.

The slag of ferrosilicon consists of mainly SiO_2 with some SiC which are very valuable materials in the process. That is, the slag formed in the ferrosilicon furnace is not of impurity but from the incompletely converted charge along with the impurity oxides of Al and Ca. Deposits of these can build up to larger amounts if the content of Al_2O_3 is high.

2.3.2 SiC with Si at the Bottom

When sufficient heat is available, all the oxygen in the bottom deposit will evaporate, while pure Si – SiC will be left to form deposits at the furnace bottom at normal operating conditions. An optimum carbon content in the burden gives a maximum silicon recovery at operational conditions. If the carbon content is lower than the optimum, all the SiC intermediate is consumed, but the loss as SiO is higher than at the optimum. Some SiO is lost even at the optimum carbon content. If the carbon content is increased beyond the optimum, the loss as SiO will decrease, but the silicon loss as SiC more than balances the gain. This SiC is deposited at the furnace bottom and when deposit becomes too large, it will obstruct the operation severely. The optimum carbon content depends on the state of the furnace. Operation needs to be observed continuously to determine the carbon input close to optimum.

2.3.3 Crusts of sintered charge materials in the upper parts of the furnace

The active part of the furnace is about 30-40 cm around the electrodes, where stoking operation can be done. In this area stoking and charging is easy and gas distribution is uniform. In the passive volume, that is the other parts of the furnace between the active volumes, charge is referred to as dead burden. SiO flows and diffuses into the passive volume and gradually fill then ends up with SiC and condensate (SiO_2 + Si). The mass in the passive volumes will be partly molten SiO_2, condensate and carbon materials partly converted to SiC. The mass will stay hot since the heat losses from it are low. When it cools, it forms a sinter mass that is difficult to break. The downward movement of the cold charge in the active volume increases the wall thickness of the passive volume and thereby crust advances towards the electrode. The gas from the inner zone breaks out where the charge layer is thinnest. This results in poor countercurrent, much blowing and low Si recovery. These crusts can be heated up by keeping the electrodes in higher position and then it may be possible to stoke them. Once broken and pushed to the crater these react readily.

The most important among the above three cases is the first type, i.e., the incompletely converted charge (slagging), the concern of this paper.

3. DESCRIPTION OF THE FURNACE

Make	ELKEM
Electrode Diameter	1,550 mm
Transformer capacity	48 MVA
Voltage range	205-252V in Delta
Secondary current	95-135KA
No of tap holes	6
Bath rotation	Exists

Furnace operation is controlled with resistance base Minstral Controller and having very good automatic B/W and furnace feeding system.

3.1 Operating Conditions of the Furnace

Efficiency of furnace operation can be known from silicon recovery and specific power consumption. Since higher the silicon recovery lower is the specific power consumption. Also all other parameters improve with higher silicon recovery.

The furnace was operating with reasonable consistency as can be seen from the data presented in the Table 3

Table 3: Operation parameters of IMFA for the period 2001 to 2005

YEAR	*SP.POWER (KWH)*	*SILICON RECOVERY (%)*
2001-2002	8209	88.45
2002-2003	8207	88.12
2003-2004	8115	90.38
2004-2005	8134	88.84
AVERAGE	8166	88.95

However, the following problems were encountered during the above period :

a) Tap hole choking due to slag obstruction

b) Tapping problems
c) Electrode breakages
d) Frequent lining failures near tap holes area etc.

3.2 Problems in the Furnace

The performance of the furnace during the 12 months period of study before the introduction of limestone in the burden i.e., during the year 2004 is also comparable with that of these 4 year performance but significant changes in the deteriorating conditions were marked in all the operating parameters from the month of July, 2004 as can be seen from table-4.

Further, the projections in the quality of the Quartz available for future consumption indicates that the overburdened material in it would be still more than that was in the year 2004, hence alternative routes for avoiding the furnace problems arising out of the slagging in the furnace were thought of and the objective was to drain out the slag formed due to poor quality of the quartz completely out of the furnace by making it fluid enough so as to be drained out during the tapping.

Table 4: Performance of the furnace during the year 2004 when Lime Stone was NOT in the burden

MONTH	*SP.POWER (KWH)*	*SILICON RECOVERY (%)*
Jan	8141	94.87
Feb	7615	94.06
Mar	7772	94.62
Apr	7753	91.59
May	7986	87.71
Jun	7833	91.82
Average	7848	92.44
Jul	8214	88.73
Aug	8044	87.56
Sep	8544	86.60
Oct	8236	83.72
Nov	8592	87.97
Dec	8646	84.48
Average	8362	86.51
Total Average	8115	89.48

As seen from the data and the quality survey of the Quartz during the year 2004 it can be observed that due to the decrease in the Quartz quality the furnace performance was affected because of more slag formation and severe tapping disturbances were also experienced. In addition to the above cited operational problems it was observed that the furnace smoke stack chimneys were getting jammed due to periodic charge shrinkages because of high top temperature at the top of the burden, high electrode holder positions and slag boiling at the top.

3.3 Observations on the Deteriorating Conditions

1. During the year 2004, there was occurrence of electrode breakages in almost all the months as mentioned in table 5.

Table 5: No of electrode breakages in the year 2004

Month	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
No. of Breakages	3	3	2	2	2	0	1	2	5	0	2	1

As the electrode breakages were experienced frequently in the previous years also the source of paste was changed twice in the year 2004, once in the month of February and again in the month of May 2004. However the electrode breakages could not be avoided. Further to this it was found that the consumption pattern was also erratic and slipping rates had to be adjusted to obtain the desired penetration from time to time.

2. Lining failures near the tap hole regions were encountered 9 times during the year 2004. This was thought because of the accumulations due to staggered tapings and improper slag drain out from the furnace.
3. During tapings frequent choking of tap holes were noticed because of the solid slag mass obstructing the flow and poor ejection of gases through the tap hole.
4. Due to high hot top conditions in the furnace, equipments were subjected to severe temperature and the down time used to be more due to failure of cooling equipment.
5. During the year 2004 due to slag formation and subsequent poor smelting conditions in the furnace, periodic charge eruptions / shrinkages occurred and slag boiling behaviour were marked. This had resulted in choking of the smoke stack chimneys and it was required to shutdown the furnace as many as 9 occasions for explicitly cleaning the chimneys.
6. Due to frequent shutdowns, electrode breakages and tapping disturbances, operation had become inconsistent which reflected in the poor alloy yield in the tapings from the month of July, 2004 and continued till December, 2004.
7. All the furnace operating norms were severely affected.

The ideal slag composition of a Ferro Silicon furnace is expected to be in the following range:

SiO_2	30 to 32%
Al_2O_3	35 to 40%
CaO	25 to 28%

The slags from the IMFA furnace had the following analysis:

SiO_2	23 to 80%
SiC	4 to 35%
Al_2O_3	2.5 to 9.5%
CaO	4 to 26%

This suggests that the SiO_2 loss increased with increase of the impurities and increase in the volume of slag produced. The difficulty in draining out the slag was because of viscous nature and attempt was made to make the slag fluid with addition of limestone.

4. INTRODUCTION OF LIME STONE IN THE BURDEN

Lime Stone was first introduced into the furnace as a correction in the month of November, 2004, at 200 to 300 Kg in 12 hours duration of a day, in the span of 3 to 4 days interval and the subsequent tapings were found to have easened with simultaneous draining of slag. Then from December, 2004 onwards it was introduced as a regular burden constituent at 20 Kg per 600 Kg Quartz batch.

4.1 Variation in the Slag Properties

With the introduction of Lime Stone in the burden the slag became fluid and tapings were free without much strain on the tap hole condition. The analysis of the slag is found to be as follows:

SiO_2	28 to 45%
SiC	12 to 23%
CaO	11 to 30%
Al_2O_3	3 to 5%

4.2 Operating Data

The furnace could be operated consistently with improved performance as most of the tapping problems eliminated and the furnace top also behaved normal with improved electrode penetration and uniform charge consumption pattern. The operating data for the year 2005 is shown in the Table 6, which can be compared with the year 2004 and can be found that the furnace performance has improved substantially.

Table 6: Performance of the furnace during the year 2005 after introduction of Lime Stone in the burden and its continuous use

MONTH	*SP.POWER (KWH)*	*SILICON RECOVERY (%)*
Jan	8187	92.27
Feb	7990	87.36
Mar	7859	94.09
Apr *	7758	94.45
May	7625	94.41
Jun	7415	109.38
Jul	8138	90.28
Aug	8032	95.83
Sep	7825	94.93
Oct	8004	89.84
Nov	8061	92.88
Dec		
Average	7899	94.16

4.3 Improvements in the Furnace Performance

It can be seen from the above data that all the operational norms improved than compared to the previous years. Further to this the problems of electrode breakages, tap hole side shell punctures and smoke stack chimney jamming problems were eliminated. The furnace top became very active with uniform smelting efficiency at different zones. The most important aspect to be noticed is that during the year 2005 the Quartz quality was inferior to the previous year with increased proportion of overburdened material. The furnace was operated with improved efficiency by overcoming all the previously cited operational problems. Blowouts and shrinkages of charge in the furnace top were in very much control thereby reducing the stress on the equipments and reducing the down time.

5.0 COMPARISON OF OUTPUT ALLOY ANALYSIS

As expected with increase of CaO in the furnace input material the % Ca in the alloy has also increased to a noticeable extent. The average analysis during the year 2004 and 2005 is presented in the table 7.

Table 7: Alloy analysis during the year 2004 and 2005

S. No.	*Element*	*2004* *(Before usage of Lime Stone)*	*2005* *(After usage of Lime Stone)*
1	Silicon	71 TO 73%	72 TO 74%
2	Iron	25 TO 27%	24 TO 26%
3	Aluminium	0.85 TO 0.92%	0.85 TO 1.25%
4	Calcium	0.9 TO 1.05%	1.1 TO 1.95%
5	Carbon	0.09 TO 0.12%	0.1 TO 0.15%

5.1 Detrimental Effects Of CaO In The Burden Charge

The CaO in the burden increased the quantity of gangue content in the furnace and increase of slag volume. This slag is drained out simultaneously with the alloy and contaminates it, if not separated properly, affecting the quality of the alloy physically. The increase in the Ca% in the output alloy increases the tendency of alloy disintegration. The mechanism of the decomposition is due to the fact that phosphides (arsenides) of aluminium, calcium and other elements disposed along the grain boundaries react with the moisture of the air, as a result of which gaseous phosphine PH_3 and arsine AsH_3 are formed and the surface of the grains is oxidized.[2]

5.2 Overcoming The Problem Of Alloy Disintegration

The disintegration problem of Fe -Si is a well-known phenomenon. The problem will be more severe in the humid conditions. The problem can be minimized by eliminating the iron segregation in the layers by inducing the proper cooling rates and monitoring the proper casting thickness in addition to maintaining silicon greater than 72%. During the peak periods of disintegration problem use of low ash imported coal was increased in the burden and casting operations were strictly monitored. Further IMFA is also having the refining facilities used for producing low Al / low C Fe-Si which also results in low calcium content in the product. IMFA has optimized the use of Limestone quantity in the burden to the extent of the need only and able to monitor on continual basis by eliminating the use of lime stone during smooth operating times and reintroducing in the time of need.

6. REMARKS AND CONCLUSION

Even though formation of slags in the Fe-Si furnaces is not desirable it would be utmost important to avoid the accumulations of the slags in the furnace bath with addition of suitable fluxes in right proportions and in right time so that the furnace performance is not paralysed. The need for forcible usage of inferior quality Quartz need not be at the cost of economic furnace operation. However, the continual usage or in large proportions will not be desirable due to its negative effects in the output alloy specification.

REFERENCES

[1] Ander Schei, Johan Kr Tuset, Halvard Tveit, “Production of High Silicon Alloys”, TAPIR forlag, Trondheim 1998, pp 73,77,78,85,86,88,183 to 190.

[2] V.P.Elyutin, Yu.A.Pavlov, B.E.Levin and E.M.Alekseev, “Production of Ferroalloys Electrometallurgy” The State Scientific and Technical Publishing House for Literature on Ferrous and Nonferrous Metallurgy,Moscow,1957, pp. 74.