# CHAPTER 3

# MODEL FOUNDATION

A basic fundamental of secondary metallurgy and principle calculations with suitable assumptions are necessary for the development of a secondary steel treatment model. The main objective of the model is to point out the secondary metallurgy steel treatments for extra low carbon steel (ELC) and ultra low carbon steel (ULC).

The available variables for the model:

1) tapping temperature,
2) tapping steel composition,
3) aimed steel composition,
4) slag tapping condition from EAF (free slag tapping or slag carry over tapping),
5) steel weight

The model will present the following information:

1) necessary slag amount and composition,
2) deoxidation operation,

3) temperature profile during treatment,

4) heating time for LHF,

5) treatment time for VOD,

6) composition adjustment, alloying,

7) predicted final composition and temperature

The important operations will be generalized to the basic treatments for ELC and ULC production.

## 3.1 Description of steel flow in the NSM meltshop

About 180 tons of molten steel in EAF is tapped into ladle which is located on a EAF-ferry. From the tapping position, the ferry carries the ladle to the rest position where a crane-601 is waiting. This crane takes the ladle from the EAF-ferry and puts it on a LHF-ferry. Afterwards, the ladle is transported to a LHF heating position (the layout of the steel plant is shown in Figure 3.1). Heating to the desired temperature is performed at this position, furthermore desulfurization can be carried out during temperature heating and homogenizing. After the steel temperature has reached the target and is homogenized, the LHF-ferry moves the ladle out of the heating position to the rest position where the crane-601 or 601A is waiting to send the ladle further to a VOD-ferry which will transport the ladle to the VOD unit. At the VOD facility, decarburization, desulfurization and degassing, and the adjustment of the final steel composition and steel temperature are carried out before the ladle leaves to the casting unit.

The crude steel composition from the EAF which will be treated in the secondary step to produce ELC, ULC steel grades are shown in Table 3.1.

Table 3.1 Chemical compositions of crude steel, ELC and ULC

| | **C** (%) | **Mn** (%) | **Si** (%) | **P** (%) | **S** (%) | **N** (%) | **Al** (%) | **Ti** (%) |
|---|---|---|---|---|---|---|---|---|
| **crude steel** | 0.04 | 0.145 | 0.002 | 0.006 | 0.107 | 0.008 | - | - |
| **ELC,CQ*** | 0.05 | 0.300 | 0.150 | 0.008 | 0.010 | 0.004 | 0.040 | - |
| **ULC** | 0.005 | 0.150 | 0.030 | 0.009 | 0.005 | 0.0035 | 0.045 | - |

CQ* is the abbreviation of Comercial Quality

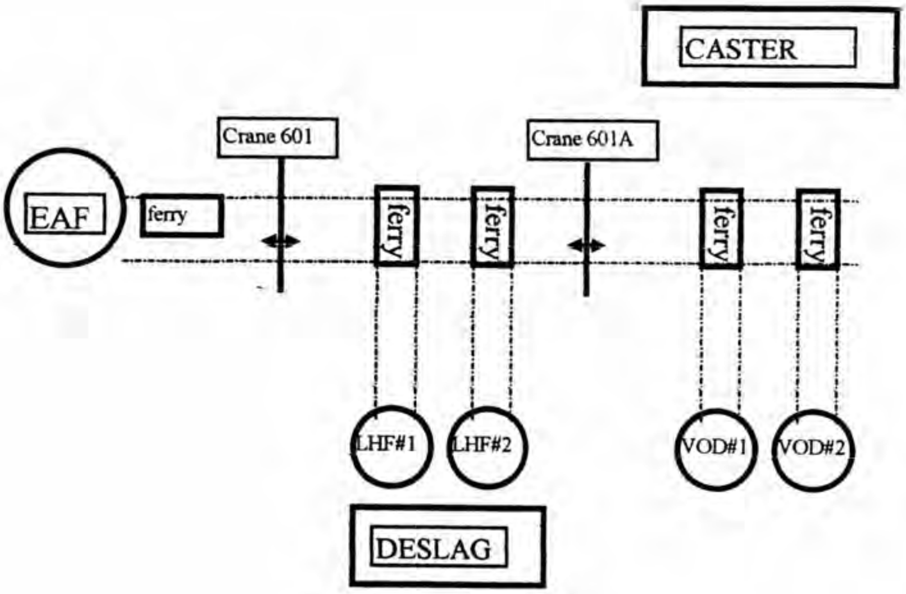


Figure 3.1 Layout of NSM melt shop

The main task for secondary metallurgy is desulfurization and denitrogenization and additional decarburization for ULC steel grades. The metallurgical fundamentals for these treatments will be shown in the following sections.

## 3.2 Metallurgical treatment of the model for ULC and ELC

### 3.2.1 Desulfurization practice

The degree of desulfurization during the secondary metallurgical treatment and the achievable final sulfur content is highly influenced by the initial sulfur content in the crude steel. As the desulfurization potential (see page 13) is mainly dependent on slag composition and the target final sulfur content is fixed by the steel grade, it is necessary to have the value of initial sulfur content before desulfurization treatment to achieve the desired final sulfur content. The sulfur content of the crude steel should be limited to a certain level, otherwise the final sulfur content can not be obtained to a level which is required by the customer. The crude steel from EAF should contain sulfur in the range of effective desulfurization. For example, if the initial sulfur content after tapping is 0.1% and the refining process reaches the desulfurization degree of 95% (which can be obtained by lime saturated slag and vacuum operation), the lowest final sulfur content will be 0.005% (see Figure 3.2). If the final sulfur content less than 0.005% is required, the initial sulfur content must be less than 0.1%.

For the desulfurization procedure, the specific slag amount can be determined by the degree of desulfurization. Consequently, fluxes can be added to form lime saturated slag. To promote the slag/steel desulfurization reaction, the treatment by vacuum operation is obviously effective.

Initial and final sulfur contents are related to the degree of desulfurization (see Eq.(3.1) and Figure 3.2). Starting at the initial sulfur content in the tapping steel from EAF and the target final sulfur content after desulfurization, the degree of desulfurization can be determined by using Figure 3.2. In addition if the degree of desulfurization of lime saturated slag is specified, the allowable initial sulfur content can be determined from the target final sulfur content. From the degree of desulfurization in Figure 3.2, the specific slag amount can be determined by Eq.(3.3) and is shown in Figure 3.3.

$$\eta_S = (\frac{S_i - S_f}{S_i}).100 \qquad (3.1)$$

where $\eta_S$ is degree of desulfurization (%)

$S_i$ is initial sulfur content (%)

$S_f$ is final sulfur content (%)

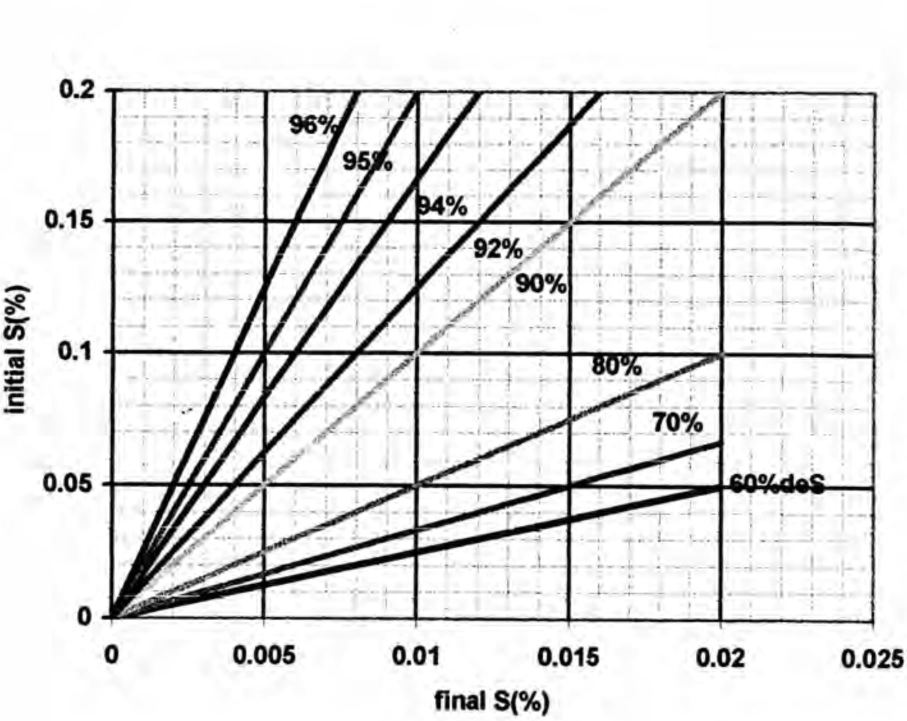


Figure 3.2 Degree of desulfurization with various initial sulfur and final sulfur contents

From sulfur balance in the slag and molten steel:

*Sulfur input (crude steel)* = *Sulfur output (slag + molten steel)*

For simplification of the model the amount of crude steel is assumed to equal to the amount of molten steel and there is no further sulfur input e.g. by slag forming agents such as lime etc., then the sulfur balance can be written by a basis of 1 ton of molten steel:

$$S_i = L_S \cdot S_f \cdot \frac{W_S}{1000} + S_f \tag{3.2}$$

$$\eta_S = 100 - \frac{100}{(\frac{L_s \cdot W_S}{1000} + 1)} \tag{3.3}$$

where $L_s$ is sulfur partition ratio ( sulfur in slag phase/sulfur in the metal phase)

$W_s$ is slag weight (kg/t.steel)

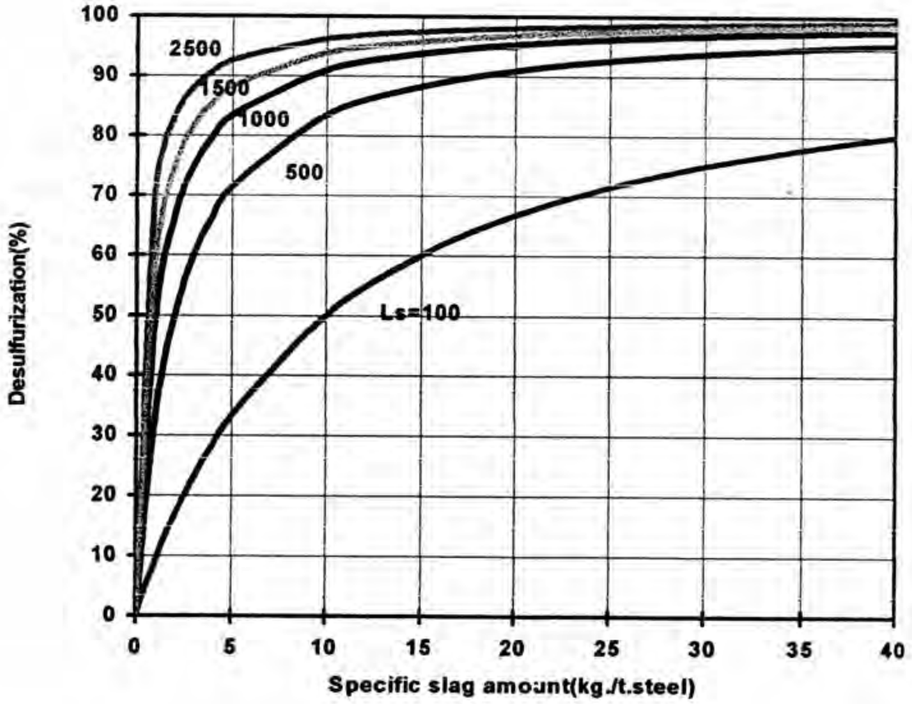


Figure 3.3 Specific slag amount for desulfurization with various sulfur partition ratios

Figure 3.3 shows the relationship between specific slag amount, degree of desulfurization and various sulfur partition ratios. The sulfur partition ratio for lime saturated slag is about 1000 up to 1500, consequently the necessary slag amount can be determined for the desired desulfurization degree.

For example, when the initial sulfur content is 0.05%, and the final sulfur content of 0.005% is required, a desulfurization of 90% is necessary (see Figure 3.2). Figure 3.3 shows that the slag amount should be 10 kg/t.steel for the sulfur partition ratio of 1000.

### 3.2.2 Aluminium addition practice

Desulfurization is favored by low oxygen potential. Therefore the dissolved oxygen in the molten steel is deoxidized.

In this work, aluminium deoxidation is divided into 2 categories:

1) for ELC, with using aluminium deoxidation for 600 ppm oxygen during tapping
2) for ULC, with using aluminium deoxidation for 400 ppm oxygen after vacuum decarburization

The amount of aluminium addition includes that for reducing the oxygen content in the molten steel, for aluminium alloying in the steel and for aluminium losses. The amount of aluminium additions are summarized as follows:

**Aluminium additions:**

1) Aluminium addition for deoxidation (600 ppm oxygen for ELC and 400 ppm oxygen for ULC):

$$2Al + 3\underline{O} = Al_2O_3 \qquad (I)$$

2) Aluminium addition for alloying:

$$Al = [Al]_{\text{in steel}} \qquad (II)$$

3) Excess aluminium addition for aluminium losses, the term aluminium losses denotes aluminium-oxidation reaction with other sources of oxygen (except dissolved oxygen in the steel) such as FeO in the slag or aluminium loss by atmospheric oxidation:

$$2Al + 3MO = Al_2O_3 + 3M \qquad (III)$$

where MO is species of oxygen sources or oxygen from the atmosphere

The assumption of an amount of aluminium losses is around 40% of those consumed by aluminium deoxidation and alloying (practical knowledge from the steel plant of Dillinger Huette GTS, Germany).

Figure 3.4 and Figure 3.5 show the amount of aluminium additions as a function of aluminium content in the steel for ULC and ELC, respectively. From these Figures, the required aluminium addition for deoxidation, alloying and losses can be determined easily, and furthermore the total aluminium additions can be determined for 180 tons of steel.

For ULC:

(I) $2Al + 3\underline{O} = Al_2O_3$

Al-addition $= 27/16 \times 2/3 \times 400\text{ppm} \times 180\text{t.(steel)}$

$= 81$ kg.

(II) $Al = [Al]_{\text{in steel}}$

Al-addition (kg) $= [Al] \times 1800$

(III) Al-losses (kg) $= (I + II) \times 40/100$

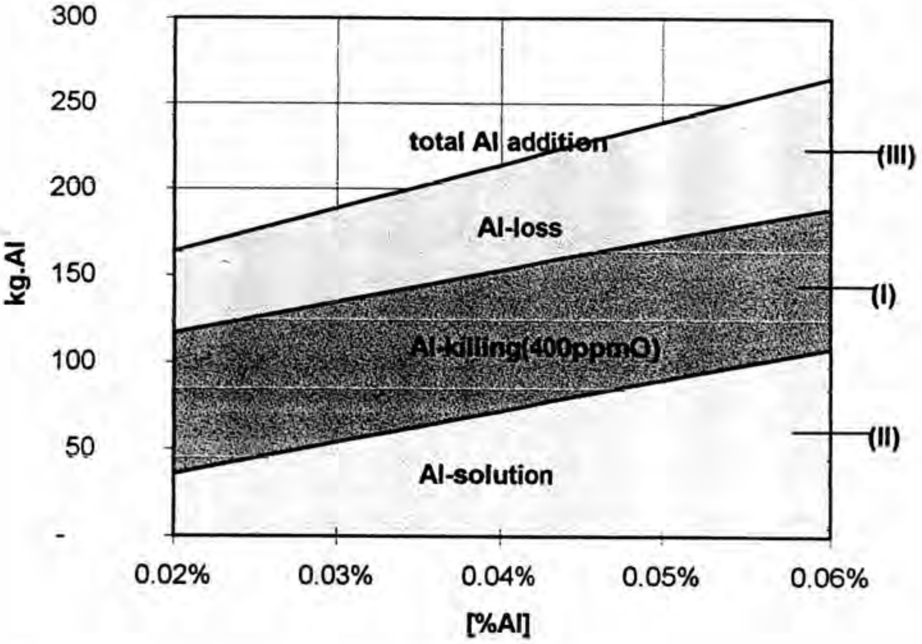


Figure 3.4 Aluminium addition for ULC

For ELC:

(I) $2Al + 3\underline{O} = Al_2O_3$

Al-addition = 27/16 x 2/3 x 600ppm x 180t.(steel)

= 121.5 kg.

(II) Al = $[Al]_{\text{in steel}}$

Al-addition (kg) = [Al] x 1800

(III) Al-losses (kg) = (I + II) x 40/100

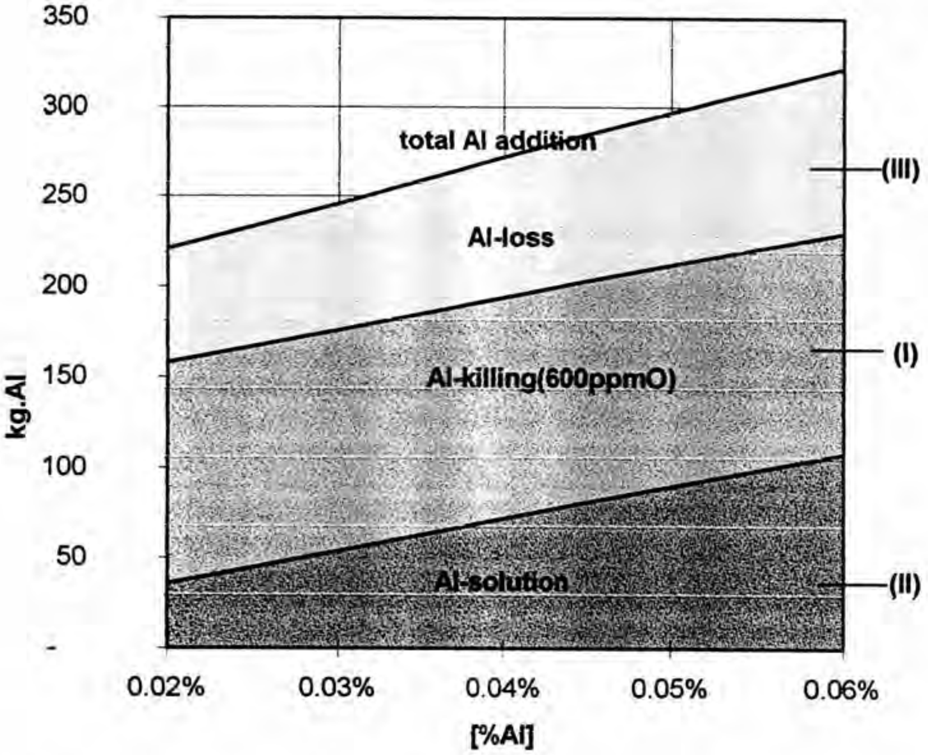


Figure 3.5 Aluminium addition for ELC

The aluminium addition practices for ELC and ULC are different and should be performed as follows:

1) <u>Aluminium addition practice for ELC</u>

1.1) Aluminium droplet is added at the tapping position of the EAF to decrease the oxygen potential of the treated steel and slag before desulfurization, 1.2) After vacuum desulfurization and degassing, aluminium wire is fed to deoxidize oxygen and correct the aluminium content in steel at the VOD unit.

2) Aluminium addition practice for ULC

2.1) No aluminium adding at the tapping position because the dissolved oxygen in the steel is kept for decarburization,

2.2) After vacuum decarburization, aluminium droplet is added to decrease oxygen potential before desulfurization and alloying of steel,

2.3) After vacuum desulfurization and degassing, aluminium wire is fed to deoxidize oxygen and to adjust the aluminium content in the steel

### 3.2.3 Slag forming practice

The main constituents of ladle slag are CaO, $Al_2O_3$ and $SiO_2$. The amount and composition of the slag are purposed to reach a high degree of refining, especially for desulfurization. The highest desulfurization potential is achieved by lime saturated slag. To adjust the lime saturated slag, a ternary $CaO$-$Al_2O_3$-$SiO_2$-saturation index is used to find the desired slag composition.

With slag free tapping and less amount of Si in crude steel from the EAF consequently $SiO_2$ is less. The selected slag composition should be 60%CaO, 37%$Al_2O_3$ and 3%$SiO_2$. This slag composition represents the lime saturated line which can be seen in Figure 3.6.

The main source of CaO comes from lime addition and the main sources of $Al_2O_3$ comes from Al-oxidation reaction and $Al_2O_3$addition. The alternative source of CaO and $Al_2O_3$ addition is 12CaO.7$Al_2O_3$. With the ratio by weight about 50%CaO-50%$Al_2O_3$, this compound can be a partial source of CaO and $Al_2O_3$ addition [54].

Sources of $SiO_2$ in the slag are:

1) slag carry over from EAF which contains about 7-10% $SiO_2$,
2) residual $SiO_2$ in the slag forming agents (e.g., lime will contain about 1% $SiO_2$),
3) remained slag in the ladle from the previous heat,
4) Si deoxidation, but the silicon content in the crude steel from the EAF is trace (e.g. 0.002%) and if the steel is killed with Al, the Si deoxidation is negligible, therefore the amount of $SiO_2$ from the Si deoxidation reaction can be negligible.

When the slag carry over from the EAF and the remained slag in the ladle from the previous heat are minimized, the total $SiO_2'$ in the actual slag will be 2-4% for a slag amount of 10-20 kg/t.steel. It should be mentioned that the amount of 3% $SiO_2'$ in the ladle top slag will be a cause of the silicon pick up during vacuum treatment. Si content will increase due to $SiO_2$reduction [55]:

$$3(SiO_2) + 4[Al] \quad = \quad 2(Al_2O_3) + 3[Si] \tag{3.4}$$

The equilibrium at 1600 °C; $$\frac{(\%SiO_2)}{[\%Si]} = \frac{0.1}{[\%Al]^{4/3}} \tag{3.5}$$

By the Si balance, one obtains:

$$\{W_s(\%SiO_2)M_{Si}/M_{SiO2} + W_{st}[\%Si]\}_{\text{before vacuum}} = \{W_s(\%SiO_2)M_{Si}/M_{SiO2}+W_{st}[\%Si]\}_{\text{after vacuum}} \tag{3.6}$$

where $W_s$ is slag weight,

$W_{st}$ is steel weight, 180 tons

$M_{Si}$ and $M_{SiO2}$ are the molecular weight of Si and $SiO_2$, 28 and 60, respectively

[ ] denotes the element content in the steel

( ) denotes the element content in the slag

The increase of Si after vacuum treatment is mainly influenced by initial (%$SiO_2$) in the slag, slag weight, initial [%Si] before vacuum treatment and [%Al] after vacuum treatment.

From Eq.(3.5) and the silicon balance assuming as 20 kg/t.steel of slag is used, the initial Si content before vacuum =0.002% and [%Al] after vacuum treatment is 0.04%, then Si content at the equilibrium after vacuum treatment will be approximately 0.028% . This amount of Si content can be accepted for ULC steel grades which normally accepts the maximum Si content of 0.03%. Therefore, the amount of 3% $SiO_2$ in the ladle top slag does not deteriorate the steel composition control after vacuum treatment when the used slag amount is limited to 22 kg/t.steel (Si-pick up = 0.03%).

The amounts of required CaO and $Al_2O_3$ to form of lime saturated slags are shown in Figure 3.7.

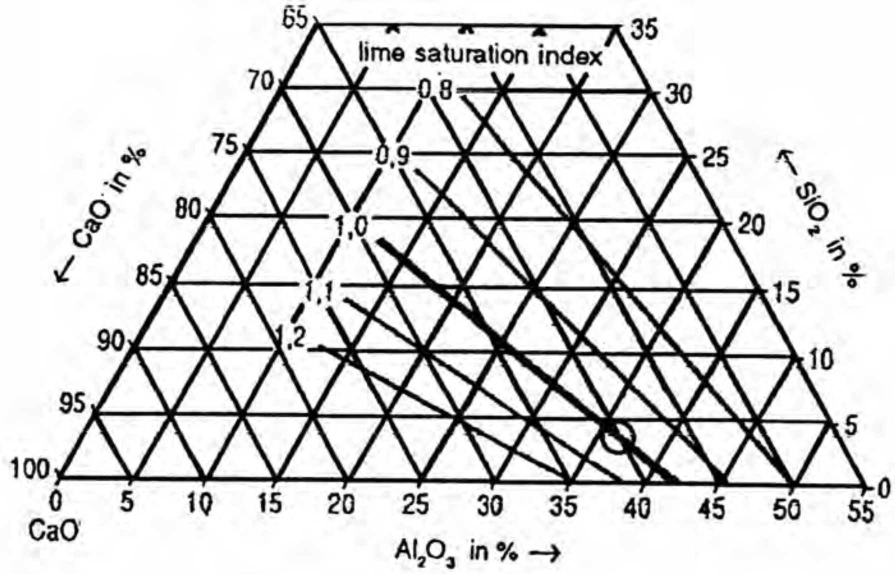


Figure 3.6 Selected slag composition in ternary $CaO-Al_2O_3-SiO_2$ system

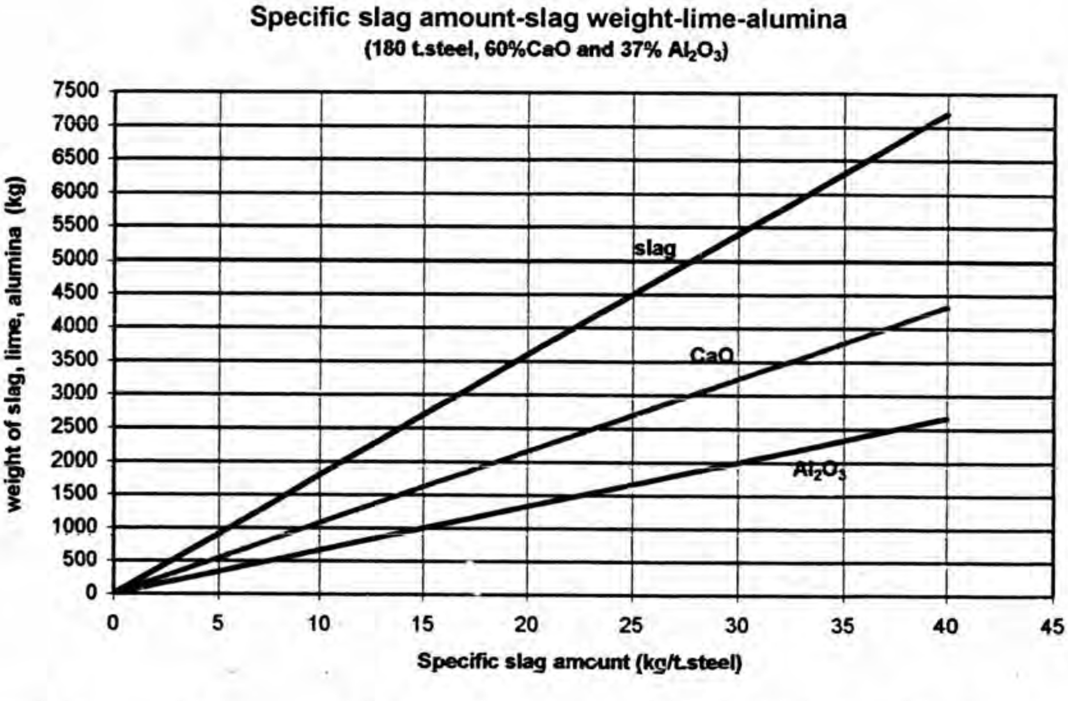


Figure 3.7 Amounts of CaO and $Al_2O_3$ to form a lime saturated ladle slag

With $Al_2O_3$ from *Al-oxidation* reaction (*Al-deoxidation* + *Al-losses*) in Figure 3.8, the amount of $Al_2O_3$-addition can be determined by:

$$Al_2O_{3\,addition} = \text{required } Al_2O_3 \text{ in } \textbf{Figure 3.7} - \text{total } Al_2O_3 \text{ from reaction in } \textbf{Figure 3.8} \qquad (3.7)$$

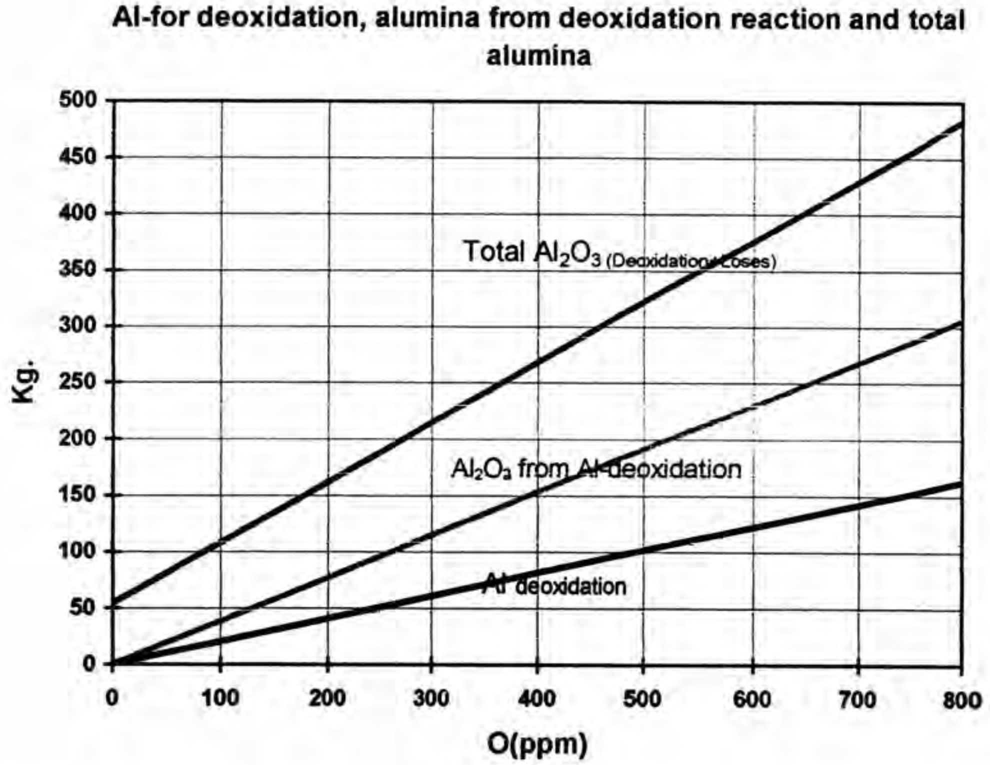


Figure 3.8 Total amount of $Al_2O_3$ from oxidation reaction

For ELC steel treatment, slag forming is carried out at the tapping position or at the heating position.

For ULC steel treatment, slag is formed during tapping and again after decarburization at the VOD position. In these work the amount of slag former during tapping is about 30% and after finish of vacuum decarburization 70%. Since this amount of slag during tapping is wanted as an the insulator for prevention of heat loss through the bath surface of the molten steel. Nevertheless, before vacuum decarburiaztion the slag amount should be less because the formed CO can escape easily through the layer of the slag with a lower thickness. Depending on the required total slag, the amount before vacuum decarburization should be 20-40% of the total slag.

### 3.2.4 Denitrogenization practice

Denitrogenization is performed in the VOD unit. The treatment time of denitrogenization by the vacuum operation and argon gas purging time can be determined by Figure 3.9 and Figure 3.10 which are obtained from the practice in the steel plant of Dillinger Huette GTS, Germany.

Vacuum denitrogenization time mainly depends on the initial nitrogen content, argon flow rate, oxygen and sulfur content before vacuum and the final nitrogen content after vacuum treatment. Denitrogenization is favored by low oxygen and sulfur contents in the vacuum treatment. The oxygen content is decreased by deoxidization with aluminium and sulfur content is decreased by desulfurization before the performance of denitrogenization.

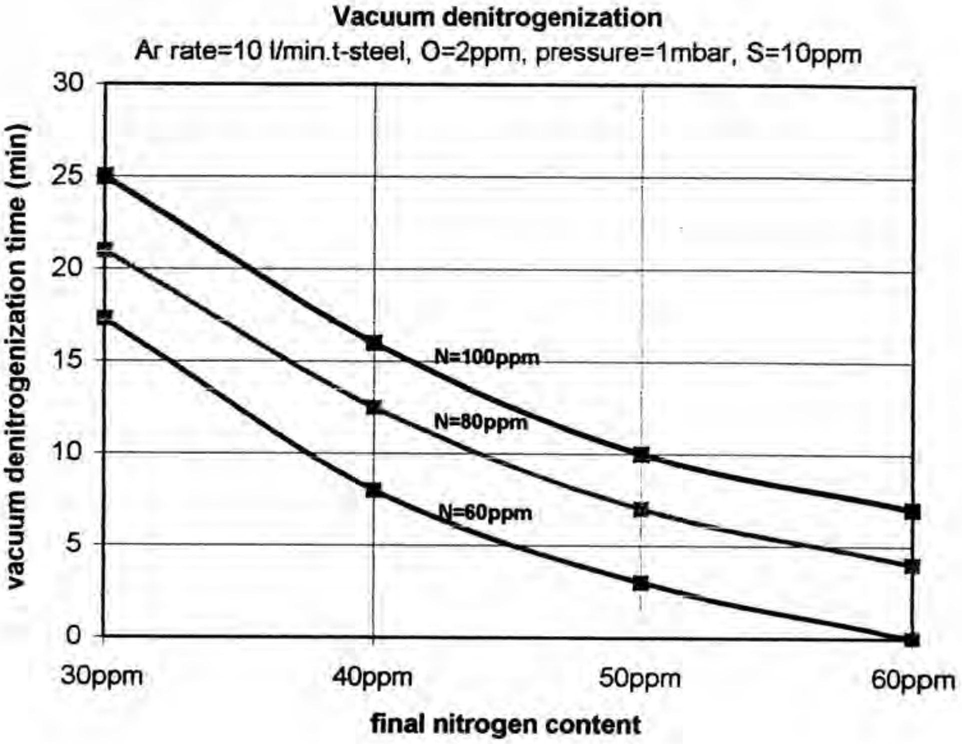


Figure 3.9 Vacuum denitrogenization time versus final nitrogen content for various initial nitrogen contents

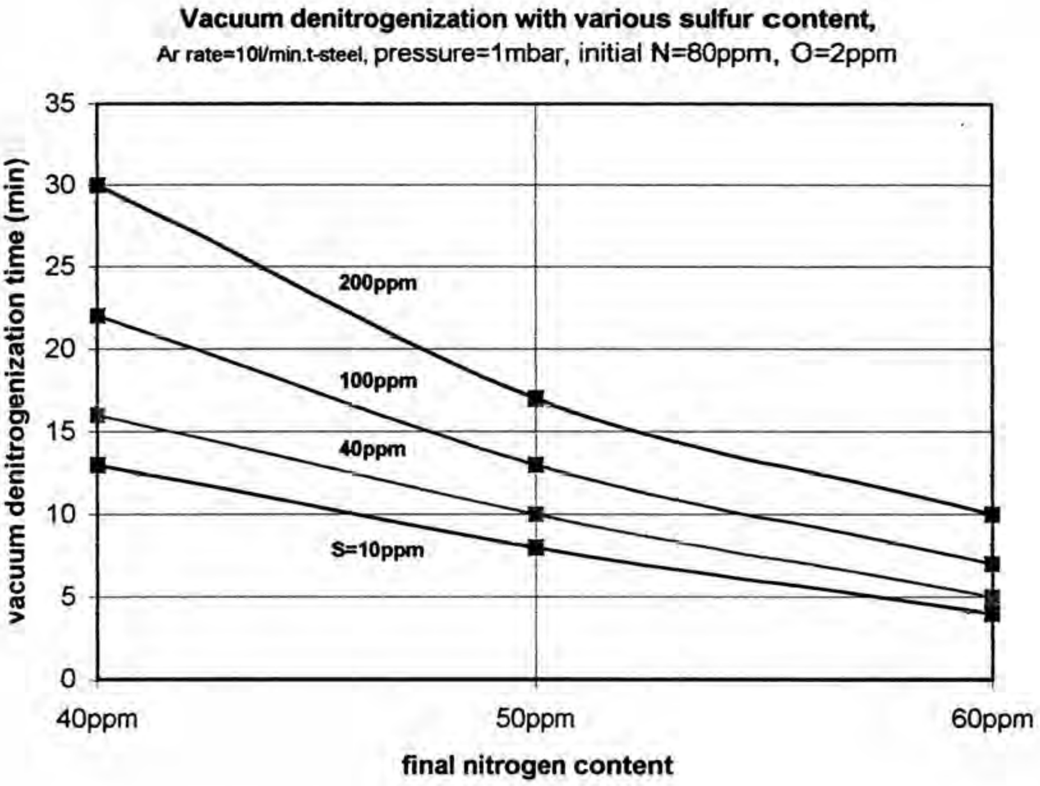


Figure 3.10 Vacuum denitrogenization time versus final sulfur content for various sulfur contents

ELC and ULC are performed both desulfurization and denitrogenization and these tasks are mainly carried out in the VOD unit. Due to denitrogenization taking much longer than desulfurization for vacuum operation, the vacuum time can be approximated from the following:

1) evacuation time about 4 minutes (limitation of the vacuum system),

2) desulfurization to reach lower sulfur value which has no effect on depressing denitrogenization reaction, about 5 minutes (practical knowledge),

3) denitrogenization time which depends on initial nitrogen, sulfur and oxygen contents before vacuum and the target final nitrogen content after vacuum.

### 3.2.5 Decarburization practice

In the present work, decarburization is only performed for ULC steel grades by vacuum oxygen blowing in the VOD unit.

The treatment condition in the VOD unit promotes every factor which enhances decarburization:

- oxygen potential adjustment by oxygen blowing,
- CO evolution by lower pressure,
- increase reaction sites and diffusion rates by Ar stirring.

The combination of decarburization, desulfurization and degassing (N, H) is applied for ULC. Double steps of the VOD-treatment might be a suitable treatment for VOD-decarburization, desulfurization and degassing. After the ladle from the heating position reaches the vacuum bay. Argon connection, EMF and sampling are taken, then oxygen blowing and vacuum operation are carried out for a sufficient time. Afterwards, only vacuum operation is performed until the desired carbon content is reached. Then EMF and sample are taken again to ensure the desired carbon content and to check the oxygen content for the following deoxidation with aluminium. Aluminium for deoxidation is added to decrease oxygen content, by the time, lime or flux is fed into the ladle to adjust slag composition again. Desulfurization and denitrogenization are then performed. Final correction and other necessary operations are finished at the end of VOD-operation.

In the present work, decarburization of ULC is carried out with 2 steps:

1) Vacuum oxygen blowing, in this step the oxygen is blown at the beginning of vacuum operation. The aim of the blowing is to raise the oxygen potential and to decarburize the molten steel. The decarburization reactions which are predominant in this step are as follows:

$$2[C] + \{O_2\} = 2\{CO\} \tag{2.18}$$

$$\{CO\} + 1/2\{O_2\} = \{CO_2\} \tag{2.19}$$

$$[C] + \{O_2\} = \{CO_2\} \tag{2.20}$$

According to the work of Janke [56] the oxygen consumption for carbon removal equals 0.65 kg.C removed per $Nm^3$ oxygen (60% oxygen blowing efficiency), the amount of oxygen can be determined from this figure. The oxygen blowing period with various oxygen blowing rates and initial carbon contents is shown in the Figure 3.11. At the end of this step, carbon content is reduced to approximately 0.02%.

2) Vacuum deep decarburization, in this step only vacuum operation without oxygen blowing is performed. The predominant decarburization reactions are equation (2.17), (2.21). Refering to the work of Bannenberg [50], vacuum deep decarburiaztion time in this period is in the range of 20-25 minutes after vacuum oxygen blowing operation. The carbon content in this step is supposed to be reduced from 0.02% to the target final value 0.004%.

From equation (2.24); $\ln\frac{C}{C_o} = -kt$

Substituting the apparent kinetic rate constant, *k* for deep decarburization period, initial carbon content, C with 0.02% and vacuum deep decarburization time, t with 25 minutes, into Eq.(2.24), the final carbon content in this case is about 0.004%.

Figure 3.12 illustrates the decarburization route of the treatment of ULC steel. The initial carbon content of crude steel is located at the region (1) and during vacuum oxygen blowing period, carbon content is reduced to intermediate region (2). At the end of oxygen blowing, the C-O composition at the region (2) is proper to reach the target carbon content at the region (3) by vacuum deep decarburization.

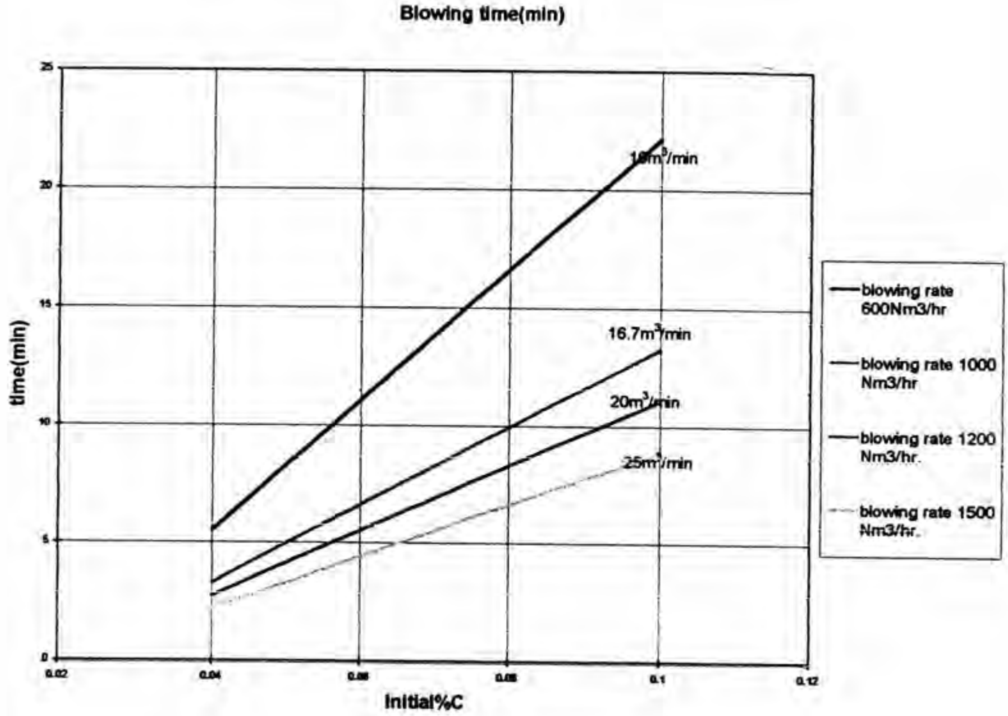


Figure 3.11 Oxygen blowing time versus initial carbon content at various oxygen blowing rate (final carbon content is 0.02%)

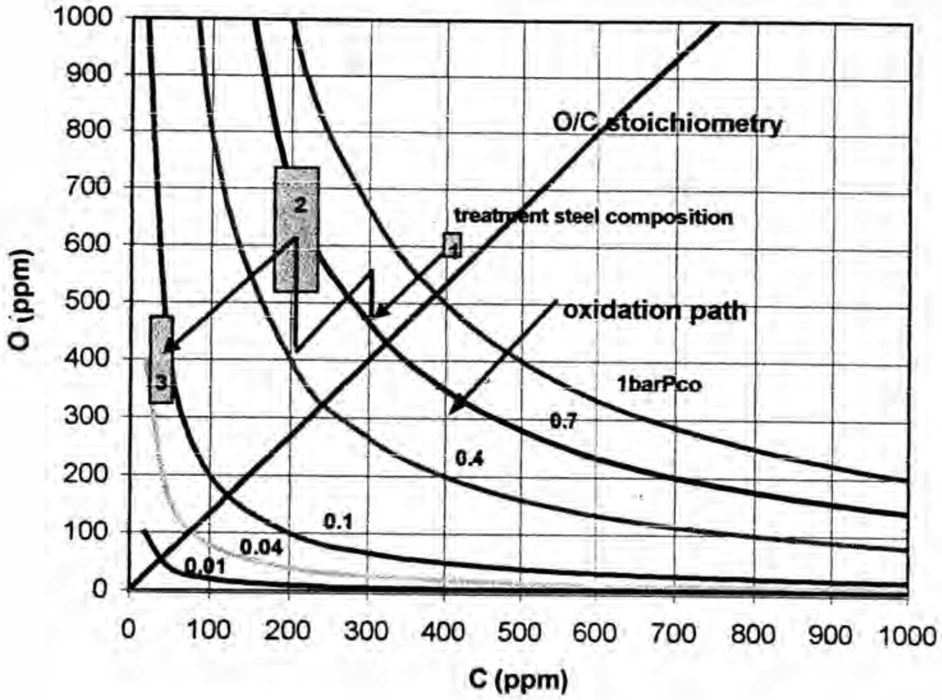


Figure 3.12 The path of vacuum oxygen decarburization by oxygen blowing and vacuum operation for ULC

### 3.2.6 Temperature control during treatment

The tapping temperature from the EAF is not sufficiently high for the temperature drop throughout the treatment especially for slag free tapping and the ladle top slag only comes from flux additions. LHF (ladle heating furnace) is one of the facility which can supply the compensated heat. The steel temperature can be adjusted by heating via LHF to the desired value which is high enough to compensate the temperature drop over the process (from tapping to the start of casting). For rough consideration, the calculation should be started from the casting temperature backwards to the tapping temperature and control temperature during the treatment via LHF.

Temperature drop during secondary treatment mainly varies with treatment time, flux and alloy additions. The amount of flux depends on desulfurization treatment. The more sulfur removal is required, the more slag amount is necessary leading to higher temperature drop. In addition, treatment time is mainly dependent on vacuum denitrogenization treatment, which depends on initial nitrogen, sulfur, oxygen and final nitrogen contents. For example, when a higher degree of desulfurization and a longer vacuum denitrogenization treatment is performed, a higher temperature drop is occurring, consequently the heating via LHF needs a longer time to reach the temperature which is high enough to compensate for the overall temperature drop by the process.

In addition to treatment time and the amount of addition, other significant factors which involve in temperature changes are as follows:

*Temperature decrease:*

1. Temperature drop with lime addition,
2. Temperature drop with alumina addition,
3. Temperature drop with alloying addition,

4. Temperature drop with radiation during tapping and refractory heat balance of ladle, 20-25 °C (practical knowledge),
5. Temperature drop during the time period from tapping to the start of heating (1 °C/min), 10°C (practical knowledge),
6. Temperature drop during the treatment period from the end of heating to the start of casting (the temperature drop during this period is influenced by the empty ladle time)

*Temperature increase :*

1. Temperature increase with Al- oxidation reaction,
2. Temperature increase with heating via LHF,
3. Temperature increase with oxygen blowing for the case of oxygen blowing decarburization

Figure 3.13 can be used for determining temperature drop due to the CaO, 12CaO.7Al$_2$O$_3$ (C$_{12}$A$_7$) and Al$_2$O$_3$ addition. It varies with amount of lime and alumina addition (respect to a cooling coefficient of addition from [53] and thermochemical properties of inorganic substances [57]).

$$\text{Temperature drop with } Al_2O_3 \text{ addition } (^\circ C) = \text{kg.Addition} \times \frac{2.5}{100} \qquad (3.8)$$

$$\text{Temperature drop with CaO addition } (^\circ C) = \text{kg.Addition} \times \frac{1.45}{100} \qquad (3.9)$$

$$\text{Temperature drop with } C_{12}A_7 \text{ addition } (^oC) = \text{kg.Addition} \times \frac{1.9}{100} \quad (3.10)$$

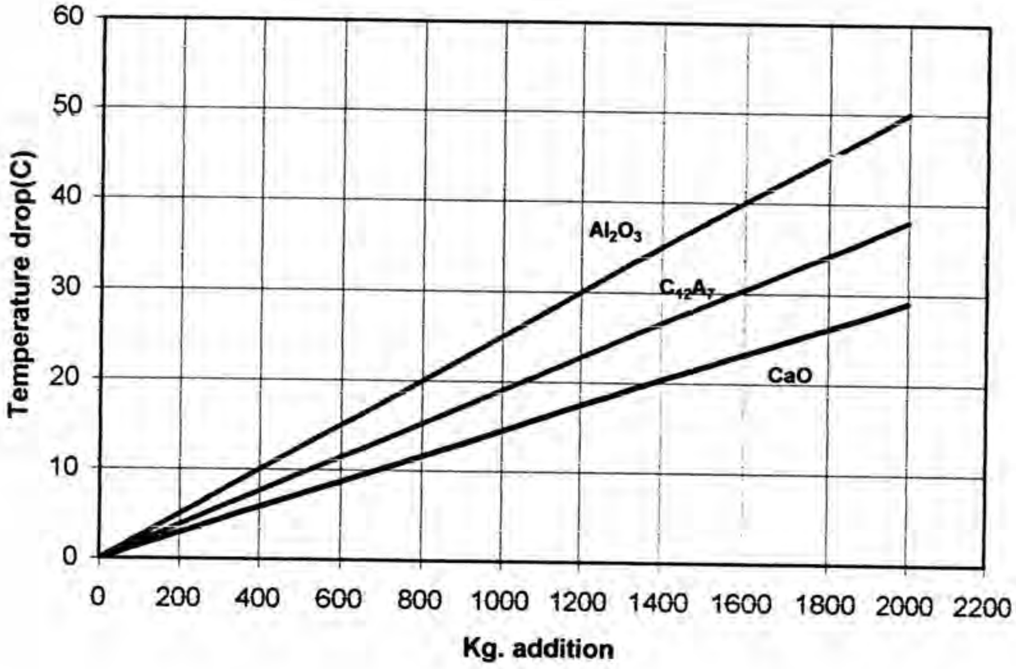


Figure 3.13 Temperature drop versus addition amounts of CaO, $C_{12}A_7$ and $Al_2O_3$ for 180 ton steel

For temperature change due to alloy addition, Figure 3.14 can be applied.

$$\text{Temperature drop with C addition } (^oC) = \text{kg.Addition} \times \frac{3.1}{100} \quad (3.11)$$

$$\text{Temperature drop with Cu addition } (^oC) = \text{kg.Addition} \times \frac{1.2}{100} \quad (3.12)$$

$$\text{Temperature drop with FeMn addition } (^oC) = \text{kg.Addition} \times \frac{1.2}{100} \quad (3.13)$$

Temperature drop with V addition (°C) $= \text{kg.Addition} \times \frac{1.0}{100}$ (3.14)

Temperature drop with FeTi addition (°C) $= \text{kg.Addition} \times \frac{0.7}{100}$ (3.15)

Temperature drop with FeNb addition (°C) $= \text{kg.Addition} \times \frac{0.6}{100}$ (3.16)

Temperature increase with FeSi addition (°C)$= \text{kg.Addition} \times \frac{0.25}{100}$ (3.17)

Temperature increase $= \left\{\text{Kg. Al.addition} - \frac{[\%\text{Al}]}{100}\text{xSteel wt.(kg)}\right\} \text{x}\frac{8.5}{100}$ (3.18)

Note that [%Al] remaining in steel is 0.04%

The temperature increase with aluminium addition is only applicable when the amount of addition is greater than 72 kg for 180 tons of steel or 74 kg for 185 tons of steel.

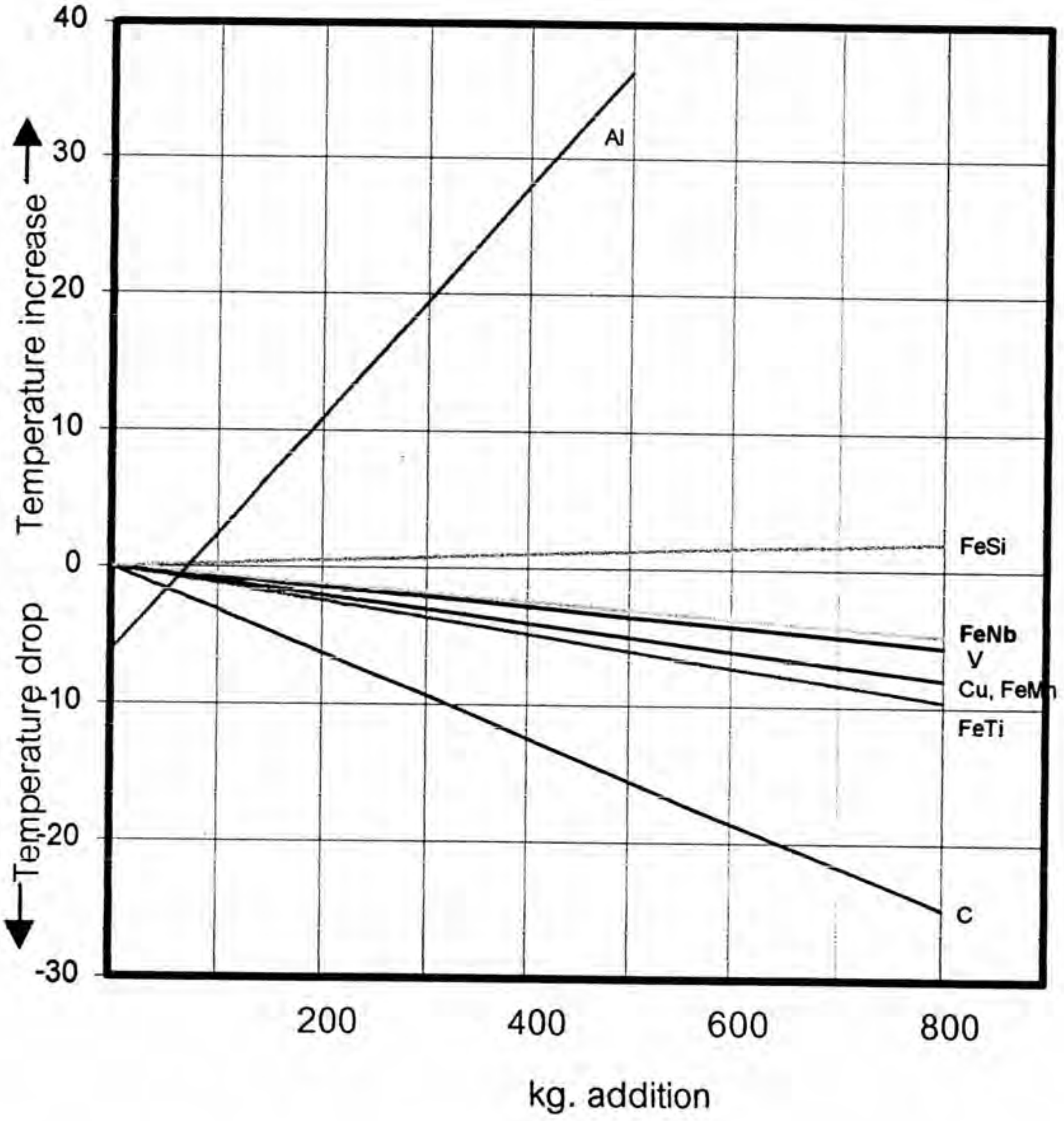


Figure 3.14 Temperature drop and temperature increase versus alloy addition amounts for 180 ton steel

For ELC production the refining slag is formed before heating. The rough estimation of the temperature drop will consider only:

1) temperature drop caused by radiation during tapping and heat balance to the ladle's refractory, including the time period from tapping to beginning of heating (10 minutes), the temperature drop in this item is about 30 °C (practical knowledge)
2) temperature drop with lime and alumina addition to form slag for desulfurization, it varies with desulfurization (varying amount of flux addition)
3) temperature increase with aluminium addition. With 271 kg of Al addition it is about 17 °C (from Figure 3.5 at [Al] = 0.04%)
4) the temperature drop during treatment period from the end of heating to the start of casting (70minutes) is about 50 °C (from Figure 2.15, with the ladle empty time of 60 minutes and treatment time of 70 minutes)

And the result is shown in Figure 3.15.

Figure 3.16 shows a rough estimation of the temperature drop by the process of ULC treatment. The refining slag is added two times, one before heating (about 30% of the total slag amount) and the ther after decarburization in the VOD unit (about 70%). The rough estimation of the temperature drop in this case is considered only:

1) temperature drop due to the radiation during tapping and heat balance to ladle's refractory including the time period from tapping to begin of heating (10 minutes), the temperature drop in this item is about 30 °C (practical knowledge)
2) temperature drop by lime and other flux addition to form slag for desulfurization, it will varies with the degree of desulfurization
3) temperature increase with aluminium addition, addition of with 214 kg of aluminium gives about 12.4 °C (see Figure 3.4 at [Al] = 0.04%)
4) the temperature drop during treatment period from the end of heating to the start of casting (100 minutes) is about 70 °C (from Figure 2.15, with the ladle empty time of 60 minutes and treatment time of 100 minutes)

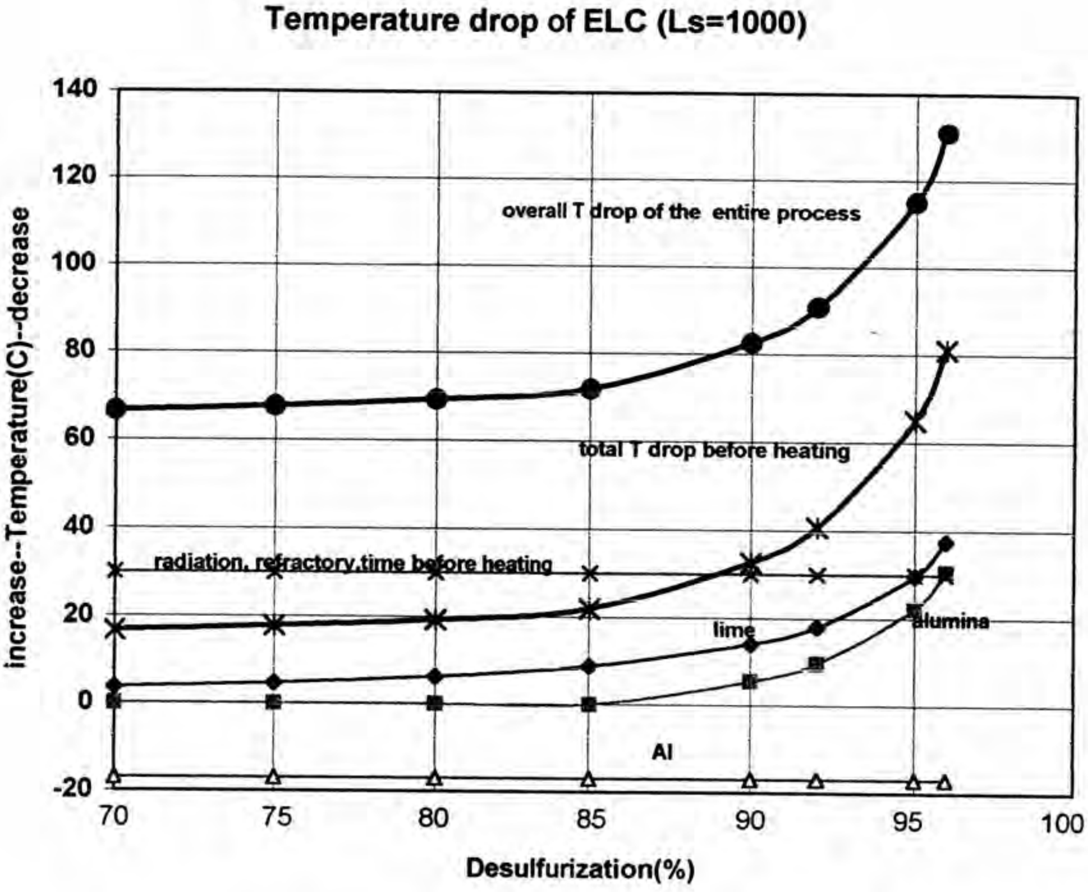


Figure 3.15 Rough temperature change versus %desulfurization for ELC

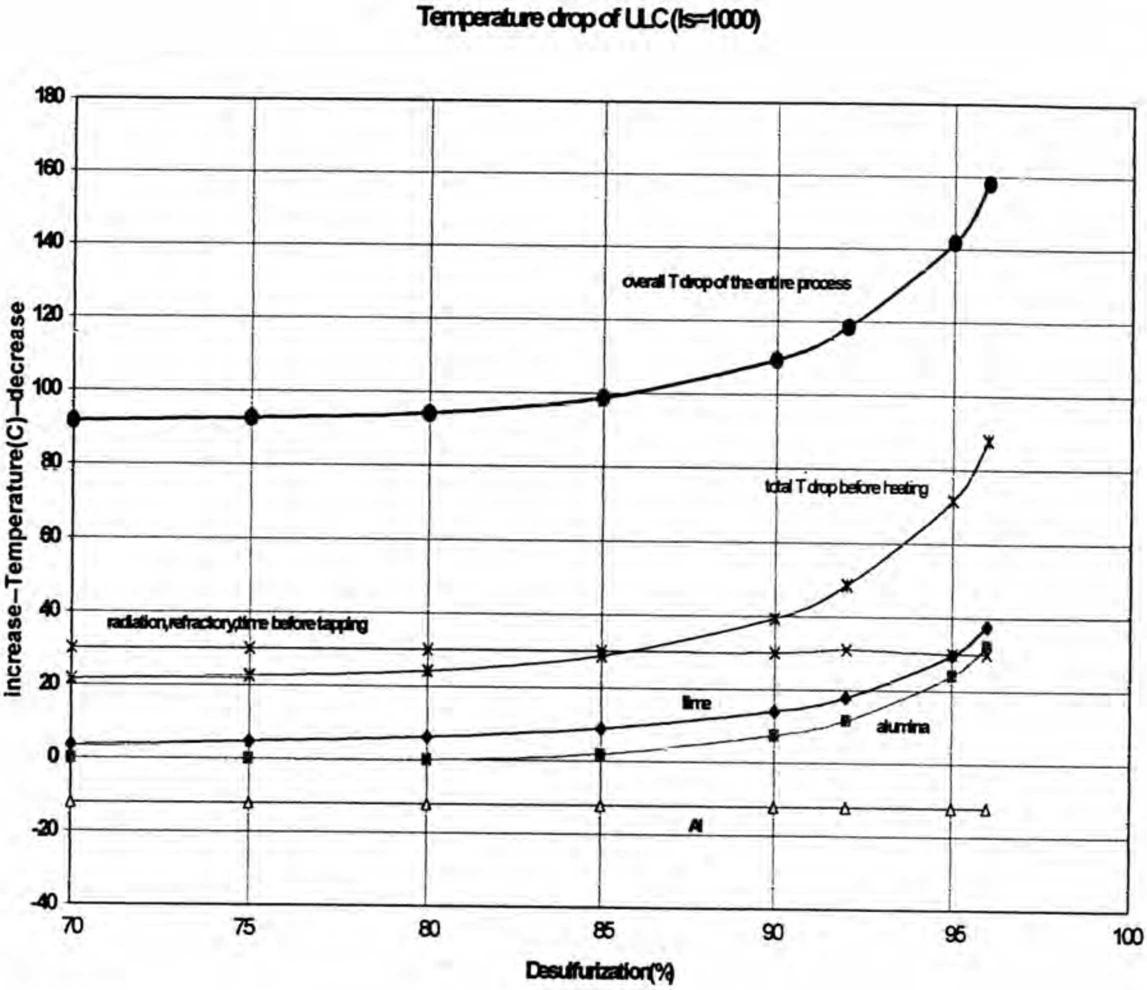


Figure 3.16 Rough temperature change versus %desulfurization for ULC

The rough temperature profiles of ELC and ULC for various degree of desulfurization are shown in Figure 3.17 and Figure 3.18.

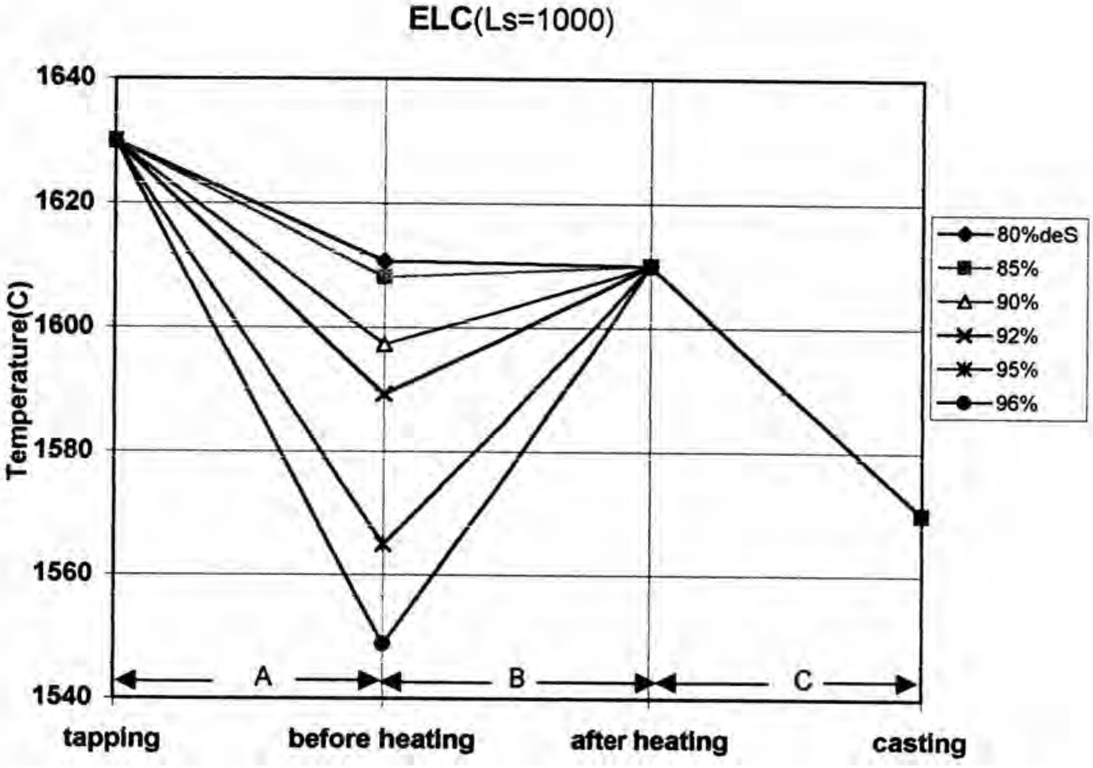


Figure 3.17 Rough temperature profile of ELC with various degree of desulfurization at Ls =1000 (A = slag former added, B = heating and C = vacuum desulfurization and denitrogenization)

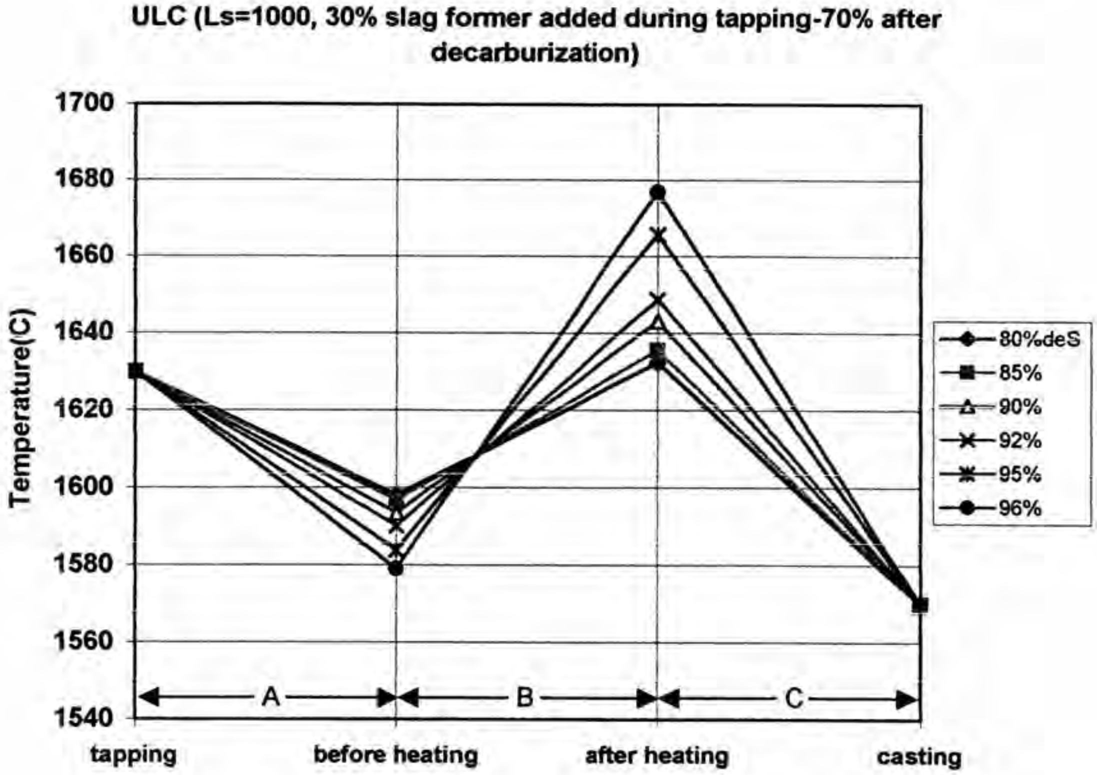
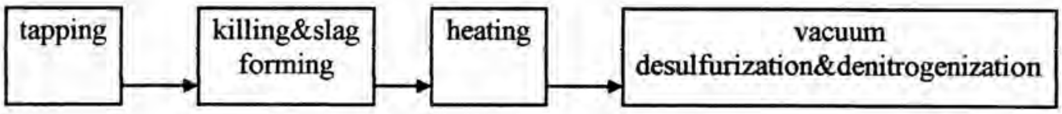


Figure 3.18 Rough temperature profile of ULC with various degree of desulfurization at Ls =1000 (A = 30% slag former added, B = heating and C = vacuum decarburization, 70% slag former added, vacuum desulfurization and denitrogenization)

Figures 3.13 - 3.18 are useful for the temperature consideration of ELC and ULC. The temperature drop throughout the process can be estimated and consequently, heating via LHF can be done.

## 3.3 Information and basic treatment of ELC

| | C | Mn | Si | P | S | N | Al | Ti |
|---|---|---|---|---|---|---|---|---|
| **crude steel** | 0.04% | 0.145% | 0.002% | 0.006% | 0.107% | 0.008% | - | - |
| **ELC,CQ** | 0.05% | 0.300% | 0.150% | 0.008% | 0.010% | 0.004% | 0.04% | - |



1) Steel weight = 180 tons

2) Tapping temperature from EAF = 1630 °C

3) Casting temperature = 1570 °C

4) Desulfurization; using Equation 28, $\eta_S = (\frac{S_i - S_f}{S_i}).100$ to determine the desulfurization degree at the initial sulfur content of 0.107% and the final sulfur content of 0.010%, the desulfurization degree= 90.7%

5) Slag composition $3\%SiO_2$, $37\%Al_2O_3$, $60\%CaO$

6) Sulfur partition ratio = 1000

7) Slag weight; using Figure 3.3 to determine the slag weight for 90.7% of degree of desulfurization at sulfur partition ratio = 1000, the necessary slag amount should be = 1980 kg (11 kg/t.steel)

8) CaO addition; using Figure 3.7 to determine the amount of CaO to form 11 kg/t.steel of slag, the amount of CaO addition

= 1188 kg (6.6 kg/t.steel)

9) Al addition; using Figure 3.5 to determine the amount of aluminium addition for ELC, the total amount of aluminium addition

= 271 kg (1.505 kg/t.steel)

10) $Al_2O_3$ addition; using Equation 33 to determine the amount of alumina to form the desired slag amount and slag composition, the amount of alumina addition = 357 kg (1.98 kg/t.steel)

11) FeMn addition (70%Mn)= $1800/0.7 \times \{[\%Mn]_{ELC} - [\%Mn]_{crude\ steel}\}$

$= 1800/0.7 \times (0.300 - 0.145)$

= 399 kg (2.22 kg/t.steel)

12) Time from the beginning of tapping to the starting of casting (see Table 3.2) = 100 minutes

13) Temperature changes:

13.1) temperature decrease with 399 kg of FeMn-addition, using Figure 3.14 to determine the temperature drop = -4.8 °C

13.2) temperature decrease with 1188 kg of CaO-addition, using Figure 3.13 to determine the temperature drop = -17.2°C

13.3) temperature decrease with 357 kg of $Al_2O_3$ addition, using Figure 3.13 to determine the temperature drop = -8.9 °C

13.4) temperature decrease with radiation and refractory heating (from practical knowledge) = -20 °C

13.5) temperature increase with 271 kg of Al addition, using Figure 3.14 to determine the temperature increase

=+16.9°C

13.6) temperature decrease with time 10 minutes from the end of tapping to the beginning of heating (from practical knowledge) = -10 °C

13.7) heating and homogenizing in LHF (see Table 3.2) = +34 °C

13.8) temperature decrease with treatment time from the end of heating to the beginning of casting (70 minutes); using Figure 2.15 to determine the temperature drop for the treatment time of 70 minutes with the ladle empty time of 60 minutes = -50 °C

The temperature evolution throughout the process is summarized in number Figure 3.17

Table 3.2 Function and time of ELC

| FUNCTION | TIME (min) |
|---|---|
| 1) Tapping & addition; about 180 tons of crude steel is tapped into a ladle, by the time fluxes and alloying elements as well as aluminium are added into the ladle | 5 |
| 2) Transportation, electrode setting; the ladle is sent to LHF position, electrodes are set up for heating | 10 |
| 3) Heating & homogenizing in LHF(average heating rate=3 °C/min); the treated steel is heated to the desired temperature and is kept on at this temperature to homogenize the steel temperature (12 minutes for heating and 5 minutes for homogenizing) | 17 |
| 4) Handling time before vacuum treatment: | 8 |
| 4.1) resetting, moving to treatment position and setting; move the electrodes out off the ladle and move the ladle to the VOD unit | 4 |
| 4.2) connecting Ar lines and starting rinsing; argon lines are connected to the argon-system of the ladle and then argon is blown into the treated steel through porous plugs | 1 |
| 4.3) temp. measurement & sampling; the steel temperature is measured meanwhile the steel and slag samples are taken and sent to the laboratory to check the steel and slag compositions | 2 |
| 4.4) covering; the cover of vacuum vessel moves down and the system is ready to start vacuum treatment | 1 |

Table 3.2 (continued) Function and time of ELC

| FUNCTION | TIME (min) |
|---|---|
| 5) Vacuum treatment: | 40 |
| 5.1) evacuation; the vacuum pump evacuates the atmospheric pressure in the vacuum vessel to the level of millibar | 5 |
| 5.2)desulfurization and denitrogenization; the desulfurization reactions and denitrogenization mechanisms are carried out | 30 |
| 5.3) homogenization and flooding; the steel composition and temperature are homogenized by soft stirring of argon, inclusion is floated to the slag layer | 3 |
| 5.4) flushing to 1 bar and lifting the cover; the pressure in the vacuum vessel is released to the normal atmosphere and the cover is lift from the vessel | 2 |
| 6) Handling time after vacuum treatment: | 20 |
| 6.1) temp. and sampling; the steel temperature is measured meanwhile the steel sample is taken and sent to the laboratory to check the steel composition | 2 |
| 6.2) time for analysis; the duration time of steel composition analysis is normally about 3 minutes | 3 |
| 6.3) wire feeding; wires such as CaSi are fed into the treated steel to fix the retained sulfur which floats into the slag and to modify inclusion | 3 |
| 6.4) final correction; the final alloying correction is carried out based on the laboratory analysis of steel composition and in case the steel temperature is too high, the scrap is added to correct the steel temperature | 3 |

Table 3.2 (continued) Function and time of ELC

| FUNCTION | TIME (min) |
|---|---|
| 6.5) disconnecting Ar lines; argon lines are disconnected from the ladle which is ready to leave the VOD unit for the caster | 1 |
| 6.6) setting, transportation and preparing before casting; the crane moves the ladle to the rest position of the caster thereafter the nozzle is installed into the tap hole | 8 |
| Total time from tapping to the starting of casting for ELC | 100 |

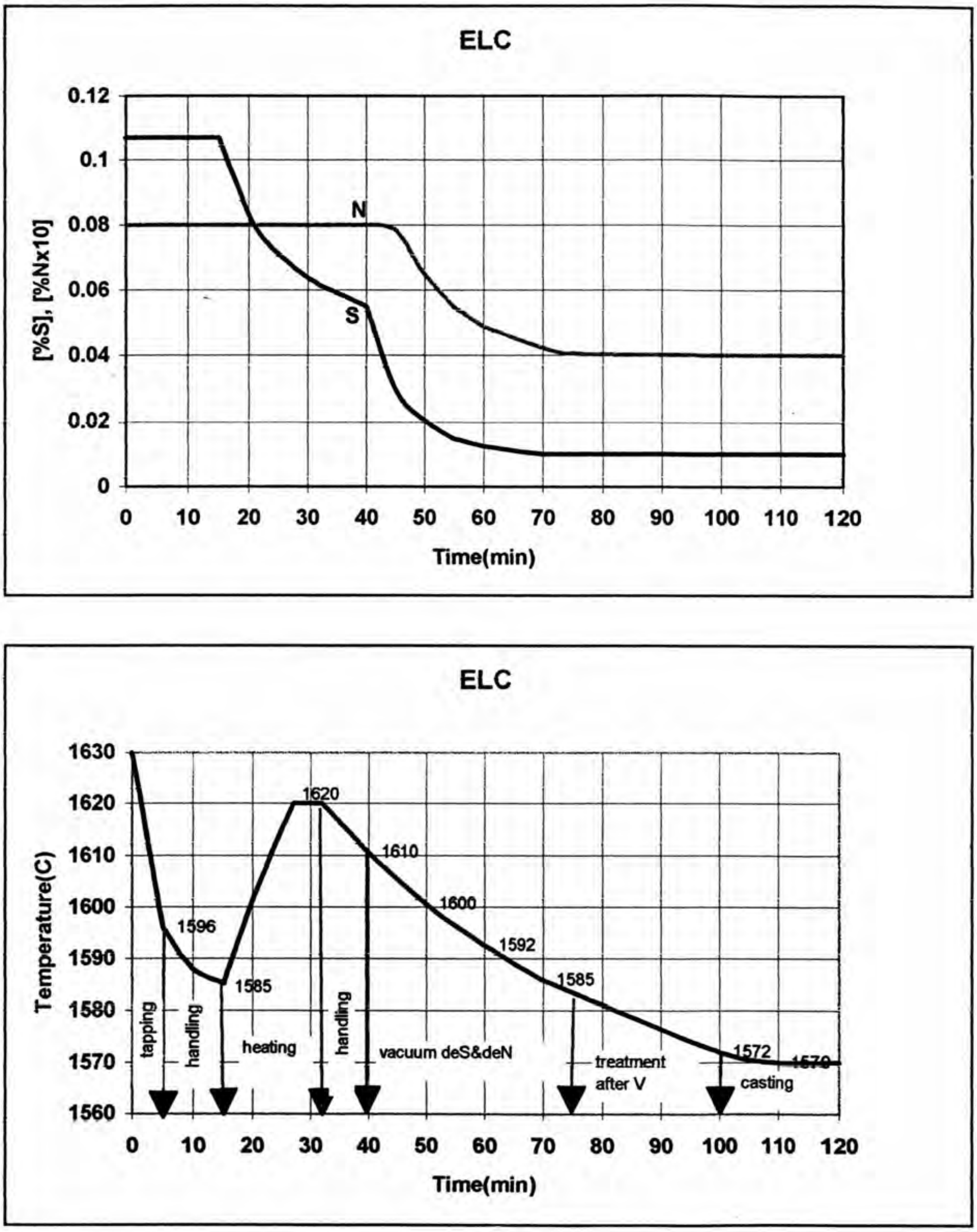
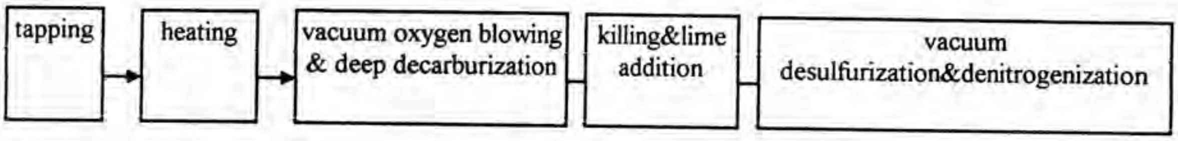


Figure 3.19 S, N evolution and temperature profile of ELC

## 3.4 Information and basic treatment of ULC for NSM

| | C | Mn | Si | P | S | N | Al | Ti |
|---|---|---|---|---|---|---|---|---|
| **crude steel** | 0.04% | 0.145% | 0.002% | 0.006% | 0.107% | 0.008% | - | - |
| **ULC** | 0.005% | 0.150% | 0.030% | 0.009% | 0.005% | 0.0035% | 0.045% | - |



1) Steel weight = 180 tons

2) Tapping temperature from EAF = 1630 °C

3) Casting temperature = 1570 °C

4) Desulfurization; using Equation 28, $\eta_S = (\frac{S_i - S_f}{S_i}).100$ to determine the desulfurization degree at the initial sulfur content of 0.107% and the final sulfur content of 0.005%, the desulfurization degree= 95.5%

5) Slag composition $3\%SiO_2$, $37\%Al_2O_3$, $60\%CaO$

6) Sulfur partition ratio = 1000

7) Slag weight; using Figure 3.3 to determine the slag weight for 95.5% of degree of desulfurization at sulfur partition ratio = 1000, the necessary slag amount should be = 3960 kg (22 kg/t.steel)

8) Flux addition: 30% during tapping and 70% after decarburization

9) Al addition; using Figure 3.4 to determine the amount of aluminium addition for ULC, the total amount of aluminium addition

=214 kg (1.19 kg/t.steel)

10) CaO addition; using Figure 3.7 to determine the amount of CaO to form 22 kg/t.steel of slag, the amount of CaO addition (Add 299 kg. of CaO before heating and add 957 kg. after decarburization)

= 1256 kg (6.98 kg/t.steel)

11) $12CaO.7Al_2O_3$ addition; using Figure 3.7 to determine the amount of $12CaO.7Al_2O_3$ to form 22 kg/t.steel of slag, the amount of $12CaO.7Al_2O_3$ addition (Add 854 kg of $12CaO7Al_2O_3$ before heating and add 1456 kg. after decaburization)

= 2310 kg(12.83kg/t.steel)

12) Oxygen blowing; using the oxygen yield of 0.65 kg.C removal/Nm$^3$oxygen to determine the amount of oxygen used to reduce carbon content from 0.04% to 0.02% (blowing rate = 10 m$^3$/min) = 60 m$^3$

13) Time from the beginning of tapping to the starting of casting (see Table 3.3) = 145 minutes

14) Temperature changes:

*before heating:*

14.1) temperature decrease with 854 kg of $12CaO7Al_2O_3$ addition; using Figure 3.13 to determine the temperature drop =-16.2 °C

14.2) temperature decrease with 299 kg of CaO addition; using Figure 3.13 to determine the temperature drop = -4.3 °C

14.3) temperature decrease with radiation and refractory heating (from practical knowledge) = -20 °C

14.4) temperature decrease with time 10 minutes from the end of tapping to the beginning of heating(from practical knowledge) = -10 °C

14.5) heating and homogenizing in LHF (see Table 3.3) = +80 °C

*After finish of heating:*

14.6) temperature increase with oxygen blowing (from practical knowledge) = +5 °C

14.7) temperature increase with 214 kg of Al addition after decarburization; using Figure 3.14 to determine the temperature increase = +12 °C

14.8) temperature decrease with 1456 kg of $12CaO7Al_2O_3$ addition; using Figure 3.13 to determine the temperature drop =-27.7 °C

14.9) temperature decrease with 957 kg of CaO addition; using Figure 3.13 to determine the temperature drop =-13.9 °C

14.10) temperature decrease with treatment time from end of heating to the beginning of casting (97 minutes); using Figure 2.15 to determine the temperature drop for the treatment time of 100 minutes with the ladle empty time of 60 minutes = -70 °C

The temperature evolution throughout the process is summarized in Figure 3.18.

Table 3.3 Function and time of ULC

| FUNCTION | TIME (min) |
|---|---|
| 1) Tapping & addition; about 180 tons of crude steel is tapped into a ladle, by the time fluxes and alloying elements as well as aluminium are added into the ladle | 5 |
| 2) Transportation, electrodes setting; the ladle is sent to LHF position, electrodes is set up for heating | 10 |
| 3) Heating & homogenizing in LHF(average heating rate=3 °C/min) ); the treated steel is heated to the desired temperature and is kept on at this temperature to homogenize the steel temperature (27 minutes for heating and 5 minutes for homogenizing) | 32 |
| 4) Handling time before vacuum treatment: | 8 |
| 4.1) resetting, moving to treatment position and setting; move the electrodes out off the ladle and move the ladle to the VOD unit | 4 |
| 4.2) connecting Ar lines and starting rinsing; argon lines are connected to the argon system of the ladle and then argon is blown into the treated steel through porous plugs | 1 |
| 4.3) EMF & sampling; the steel temperature and the dissolved oxygen content are measured meanwhile the steel and slag sample are taken and sent to the laboratory to check the steel and slag compositions | 2 |
| 4.4) covering; the cover of vacuum vessel moves down to cover the vessel and the system is ready to start vacuum treatment | 1 |

Table 3.3 (continued) Function and time of ULC

| FUNCTION | TIME (min) |
|---|---|
| 5) Vacuum treatment: | 70 |
| 5.1) evacuation, oxygen blowing and deep decarburization; the vacuum pump evacuates the atmospheric pressure in the vacuum vessel to the level of millibar meanwhile a certain amount of oxygen is blown to the bath surface via the alumina consumable lance, by the time the deep decarburization predominates by the mechanism of argon bubbling and vacuum pressure | 30 |
| 5.2) EMF & sampling and killing & lime addition; the steel temperature and the dissolved oxygen content are measured meanwhile the steel and slag samples are taken and sent to the laboratory to check the steel and slag compositions, then aluminium is added to deoxidize while lime is added to adjust the slag composition to give high desulfurization potential | 5 |
| 5.3) desulfurization & denitrogenization; the desulfurization reactions and denitrogenization mechanisms are carried out | 30 |
| 5.4) homogenization & flooding; the steel composition and temperature are homogenized by soft stirring of argon, inclusion is floated to the slag layer | 3 |
| 5.5) flushing to 1 bar and lifting the cover; the pressure in the vacuum vessel is released to the normal atmosphere and the cover is lift from the vessel | 2 |

Table 3.3 (continued) Function and time of ULC

| FUNCTION | TIME (min) |
|---|---|
| 6) Handling time after vacuum treatment: | 20 |
| 6.1) temp. & sampling; the steel temperature is measured meanwhile the steel sample is taken and sent to the laboratory to check the steel composition | 2 |
| 6.2) time for analysis; the duration time of steel composition analysis is normally about 3 minutes | 3 |
| 6.3) wire feeding; wires such as CaSi are fed into the treated steel to fix the retained sulfur and to modify inclusion | 3 |
| 6.4) final correction; the final alloying correction is carried out based on the laboratory analysis of steel composition and in case the steel temperature is too high, the scrap is added to correct the steel temperature | 3 |
| 6.5) disconnecting Ar lines; argon lines are disconnected from the ladle which is ready to leave the VOD unit for the caster | 1 |
| 6.6) setting, transportation and preparing before casting; the crane moves the ladle to the rest position of the caster thereafter the nozzle is installed into the tap hole | 8 |
| Total time from tapping to the starting of casting for ULC | 145 |

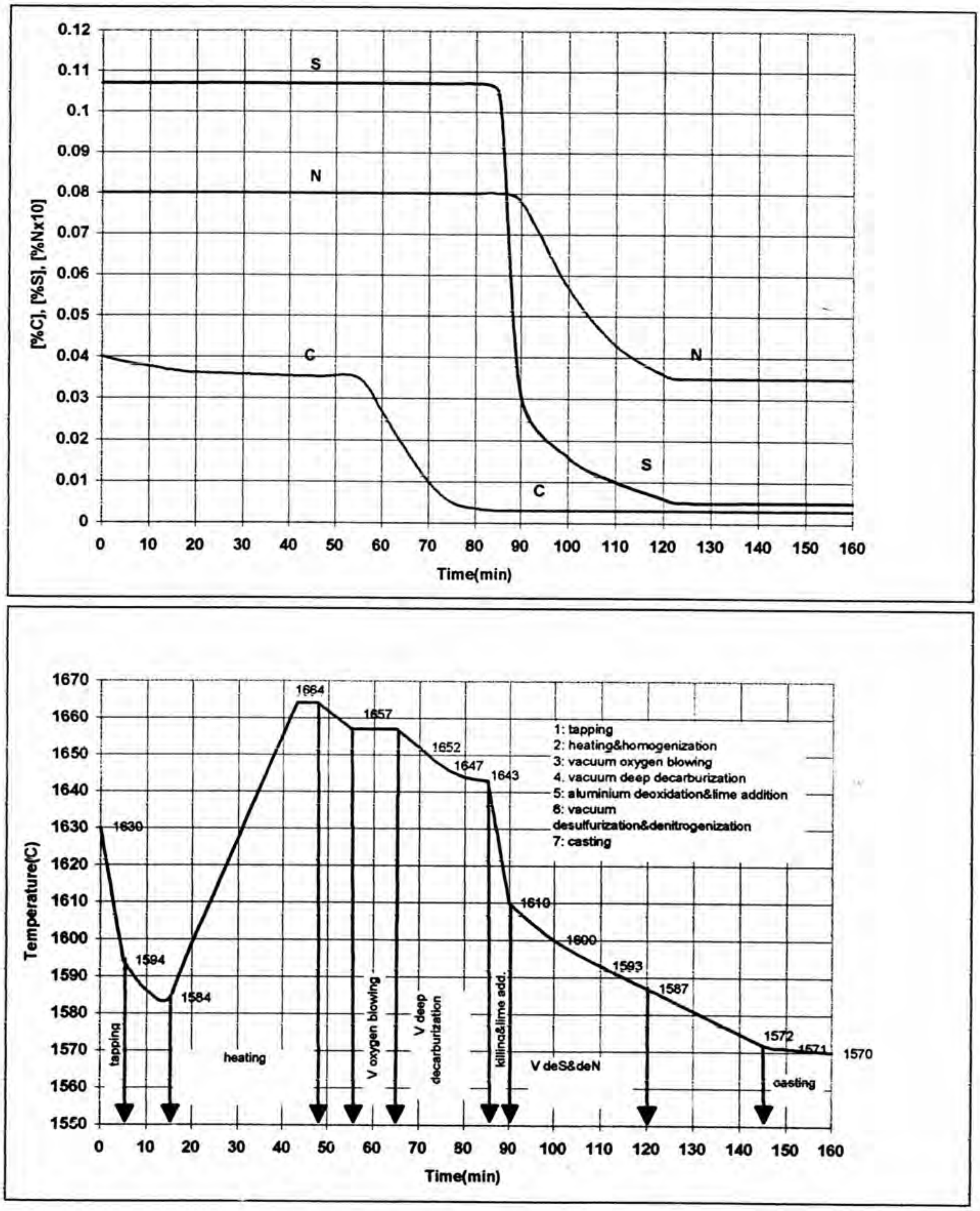


Figure 3.20 C, S, N evolution and temperature profile of ULC