

# Cold rolled non-oriented (CRNO) silicon steel production at Rourkela Steel Plant, SAIL

*Rourkela Steel Plant is the largest producer of cold rolled non-oriented (CRNO) steels in India. Control of steelmaking, casting and rolling are critical to achieve the necessary product magnetic properties, particularly core loss. This paper describes the basics of Si steel and its production route, then describes the efforts made during the primary and secondary steelmaking phases of production to improve and optimise practices. The addition pattern for the fluxes and blowing profile has been modified for improved BOF slag formation. Secondary refining practice was redesigned to improve de-oxidation, de-sulphurisation, and steel cleanliness was improved by optimising the characteristics of ladle top slag.*

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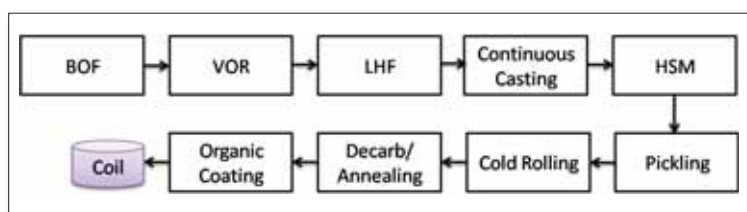


Fig 1 Schematic representation of processing of CRNO steel at RSP

## SILICON STEELS-BACKGROUND

Cold rolled silicon steels with silicon contents of 0.5-3.5% are used predominately in sheet form for the production of transformers and electric motors where they provide the best possible induction connection between rotor and stator. The main advantage of these sheets is low core loss. Increasing the silicon content generally ensures a decrease in core loss, however, it also decreases magnetic saturation and permeability.

The property requirements of such products have led to the development of low core loss, high permeability materials. The desired magnetic properties are achieved by appropriate control of composition, grain size and texture. To achieve a high magnetising ability at a constant level of core loss in the product, precise control of steelmaking operating parameters and rolling conditions are required. The magnetic properties of CRNO steels are dependent on their chemical composition and, ideally, C < 0.003%, S < 0.02% and P < 0.02% are desirable, as well as control of other factors. Carbon is an undesirable element and promotes formation of austenite when present in amounts

greater than 0.003%. The addition of Si is dictated by the grade requirements.

## CRNO PRODUCTION AT RSP

Rourkela Steel Plant (RSP) is the largest producer of CRNO steels in India. A schematic of the process route is shown in Figure 1.

**BOF** – The small 66t converters at Steel Melting Shop-I, RSP, are an appropriate heat size to meet the order size for these grades.

**VOR** (vacuum oxygen refining) comprises vacuum arc degassing (VAD)/vacuum oxygen degassing (VOD).

The chemical compositions for the different CRNO electrical steels grades produced are given in Table 1. It is evident that the grades with the lower core losses have the lowest C, S and P contents and the highest Si contents.

**BOF steel refining** At Rourkela, typical hot metal composition is: C 3.9-4.2 %, Mn 0.03-0.07%, Si 0.5-0.8%, S 0.05-0.08%, P 0.15-0.2%. Both S and P contents are high so this places a heavy burden on refining to maximise S and P removal by good blowing practice and slag development. The need to minimise both vessel lining wear and slag carryover at tap are also extremely important.

**De-oxidation** The standard tapping C is < 0.03% and the oxygen content of liquid steel in the ladle at the start of secondary steelmaking is kept high ~ 400-1,000ppm (0.04-0.1%) by optimum additions during BOF tapping so that vacuum decarburisation occurs during the degassing

Grade	Max core loss, W/ kg	C max	Mn max	P max	S max	Si	Al
RSP 1000	10.0	0.04	0.50	0.03	0.025	0.3-0.7	0.06-0.10
RSP 900	9.0	0.04	0.45	0.03	0.025	0.4-0.8	0.06-0.10
CRNO M-47 A	7.0	0.035	0.35	0.025	0.025	1.4-1.7	0.06-0.15
CRNO M-47 B	8.0	0.035	0.35	0.025	0.025	0.5-0.8	0.06-0.10
CRNO M-45	6.3	0.03	0.35	0.025	0.025	1.45-1.8	0.06-0.15
	6.0	0.03	0.30	0.025	0.020	1.5-1.8	0.08-0.15
	5.3	0.03	0.30	0.025	0.015	1.55-1.9	0.08-0.15
RWL	4.7	0.028	0.30	0.025	0.012	1.6-1.9	0.09-0.15
M43	4.0	0.027	0.30	0.025	0.01	1.8-2.6	0.10-0.20
M36	3.5	0.025	0.25	0.025	0.008	2.2-2.8	0.10-0.20
M27	3.3	0.02	0.25	0.025	0.008	2.6-3.0	0.12-0.20

Table 1 Specification of different grades of hot rolled CRNO steel, wt %

phase. The addition of slag conditioner, de-oxidiser and ferroalloys during vacuum degassing is a regular practice to improve the recovery of Al and ferroalloys.

**Casting** Continuous casting of high Si grades is difficult due to their high fluidity which causes delayed, slow and disturbed solidification in the mould, resulting in front end bleeding and dummy bar disengagement and start-up breakouts. Also, these grades, because of their low carbon ( $\leq 0.03\%C$ ) and high silicon ( $\geq 1.5\%Si$ ), result in fully ferritic solidification. As the creep strength of  $\delta$  ferrite is only 15-20% of  $\gamma$  at high temperature, mould sticking and high mould friction is associated with casting of these grades. Poor shell strength leads to bulging of the strand and formation of inter-columnar transverse cracks in solidifying shell.

High Si also reduces the thermal conductivity of the solidifying shell, leading to a slower growth rate, causing longer solidification time. A thin shell, hence with lower strength, is particularly susceptible to bulging and consequent generation of inter-columnar cracks. Additionally, the temperature gradient in the solidifying shell is steeper, resulting in increased tendency for columnar grains. This aids easier propagation of already nucleated internal cracks. High ductile to brittle temperature ( $>100^\circ C$ ) makes the cast slabs brittle and prone to breakage at ambient temperature.

Based on the above understanding, the following measures are used to overcome difficulties associated with continuous casting of CRNO grades:

- Slab size : 210 x 1,090mm
- Superheat :  $<25^\circ C$
- Casting speed : 0.7m/min
- Lower mould taper than conventional C steels
- Specially formulated mould powder with melting point  $\sim 1,000-1,020^\circ C$ , viscosity  $\sim 2.0-2.3$  poise, basicity  $\sim 0.7-0.75$

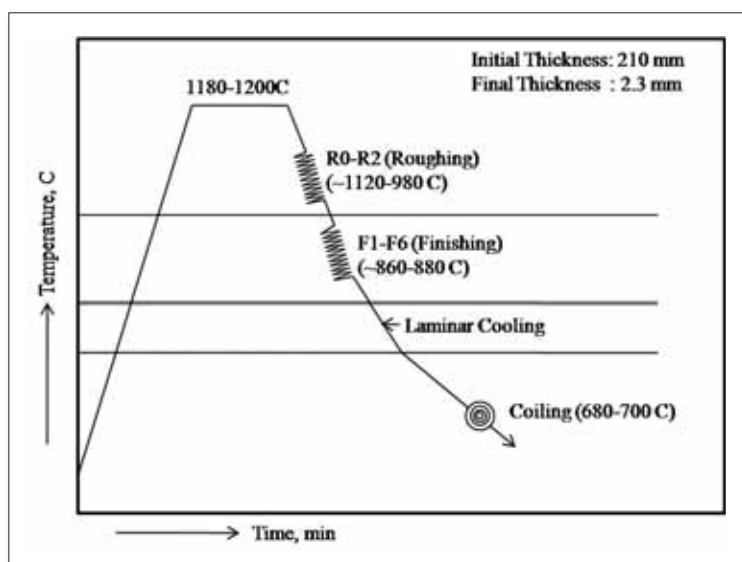


Fig 2 Schematic representation of rolling schedule for CRNO steel

- Hard secondary cooling
- Hot transfer of slabs with cover to reheating furnace for rolling
- Addition of basic flux for inclusion absorption in the tundish. The composition of tundish flux used is:  $SiO_2$  - 2-5%,  $Al_2O_3$  - 25-30%,  $CaO$  - 45-55%,  $MgO$  - 0-5%,  $Fe_2O_3$  - 1-5%,  $TiO_2$  - 1-5% and Free C -  $<0.5\%$ . Rice husk addition above the tundish flux is also practised.

**Rolling** The cast slabs are kept under hoods, transported to the hot strip mill (HSM) and hot charged into the reheating furnace within 24 hours of production, then heated to  $1,180-1,200^\circ C$  for 4 hours to ensure complete homogenisation. The optimum reheating temperature is selected by considering the required temperature for the higher silicon content and mill limitations. Slabs are

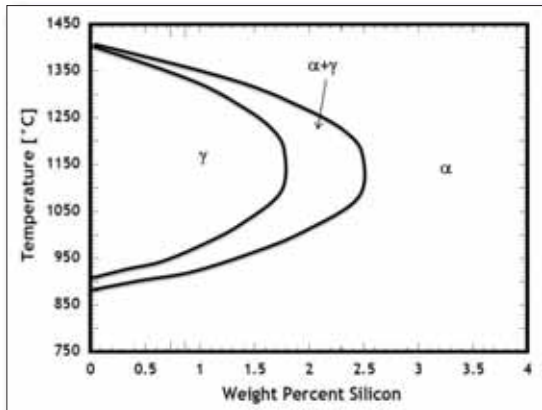


Fig 3 Fe-Si phase diagram of 0.01-0.02wt % carbon steel

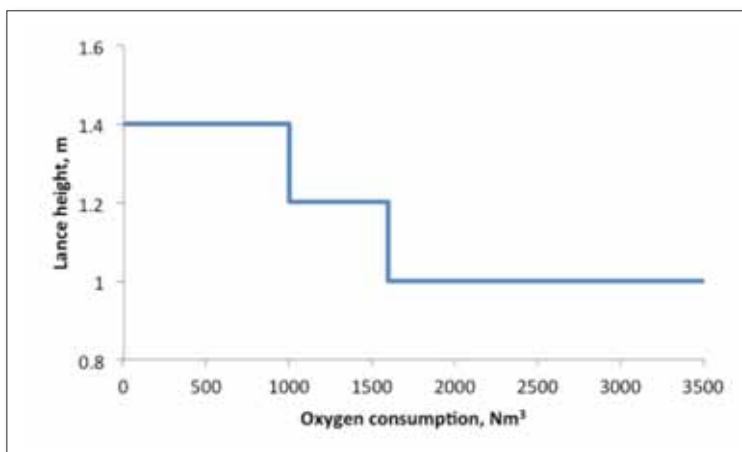


Fig 4 Typical lance height profile

hot rolled in the HSM to coils of  $\sim 2.3$ mm thickness. The thermal and deformation schedule followed is as per the recommendations by Hou et. al [1] to achieve the desired microstructure in the hot band. A schematic representation of the hot rolling process is shown in Figure 2.

The slab drop out temperature and exit temperature at R2 is maintained at  $\sim 1,120^\circ\text{C}$  and  $930-950^\circ\text{C}$ , respectively. The slabs are subjected to 8 passes in the roughing stand from 210mm to 21mm, then descaled, head end cropped and fed to the finishing mill. The slabs are then rolled from 21mm to the final gauge. The finish rolling and coiling temperatures are maintained at  $680-700^\circ\text{C}$ , respectively.

The hot bands are next processed in the CNRO mill where they are side trimmed, pickled, cold rolled to 0.5mm thickness and decarb-annealed to generate the desired C level ( $<0.003\%$ ) before coating. This is essential to prevent 'magnetic ageing' caused by carbide precipitation during the anneal cycle.

Rolling temperature during hot rolling plays an important role to achieve the desired gauge as high Si content leads

to rolling in a dual phase area resulting in high mill load as shown in Figure 3 [2]. It may be seen that Si contents in excess of 2.5% lead to a completely ferritic structure throughout the rolling range. Silicon less than 2.5% leads to co-existence of  $\gamma+\alpha$  phases within a narrow zone of rolling and complicates the flow stress behaviour of the steel.

Sulphur and nitrogen are undesirable elements and should be controlled to as low level as possible; in some grades to 50ppm maximum, respectively.

### STEEL PLANT TRIALS TO REDUCE S AND P

**BOF plant** It is well known that slags with high % FeO favours dephosphorisation, but they are not good for BOF lining life, and it is more difficult to control slag carryover to the steel ladle. To meet the desired end-blow condition while operating small sized converter is always a challenge – one of the most serious problems in operation is lance skulling and the metal build-up in the mouth and cone of the furnace due to spitting and slopping. The resulting frequent hood jamming and lance jamming need repeated shut downs for their clearing and, therefore, seriously affected shop productivity. To aim for better consistency in steel quality as well as shop productivity, extensive trials were carried out with the modifications described below.

A key aim was to improve slag formation and fluidity. Due to normal high operating basicity ( $>4$ ) used at the plant, the delayed dissolution of fluxes leads to viscous/dry slag. The material charge balance was modified to optimise the basicity to 3.0-3.2. High hot metal temperature, small size/light scrap, retained slag practice, softer oxygen blowing to provide favourable conditions for fluid as well as early slag formation.

The added fluxes, ie, calcined lime and calcined dolomite, dissolve in the presence of FeO to form the slag. The generation of FeO is controlled mainly by lance height for a given nozzle design. A typical lance height profile of BOF blowing is shown in Figure 4. The converters are designed to blow oxygen at a rate of  $10,000\text{Nm}^3/\text{hr}$  (ie,  $166\text{Nm}^3/\text{min}$ ). The total duration for the blowing is about 21 minutes. During the middle part of oxygen blowing (ie, peak decarburisation from 7 to 16 minutes), the slag FeO content reduces and the slag becomes viscous and dry causing phosphorus reversion and spitting. An immediate increase in lance is then sought to generate extra FeO to increase the fluidity of slag which in turn may result in extra slag generation to initiate slopping.

Alternatively, the use of iron ore or sinter is practised according to blowing conditions. It is added in 2-4 small batches of 50-100kg at an interval of 2 minutes as an immediate source of FeO during dry slag formation. Iron ore has higher cooling efficiency as it requires over three times higher energy than required to melt the same quantity of scrap. The BOF steel bath recovers about 75% of the iron

in the ore, the remainder contributes to the iron oxide in the slag [3]. This helps in increasing the FeO percentage in the slag and makes it foamy and increases its fluidity. The other choice is iron sinter which has similar chemical characteristics to the lump ore. The typical composition of sinter is: Fe(total) 55%, CaO 10%, SiO<sub>2</sub> 25%, Al<sub>2</sub>O<sub>3</sub> 2.5%, MgO 6%. However, sinter being in a reduced and pre-fluxed condition has a slightly different effect compared with ore. The iron oxide and flux in the sinter helps in the quick formation of more effective slag and chilling of the bath is relatively less than ore. It was noticed that the sinter has more foaming tendency than the lump ore, which results in increased slopping if added in large amounts. Smaller batch addition provides the control over the opening temperature as well as slag volume.

To obtain the desired tapping condition, the heat balance was maintained by reducing the scrap charge. The usage of sinter has importance as replacement of iron ore when lump ore gets wet and hence becomes difficult to handle in BOF batching systems.

A comparison of BOF operating data is shown in Table 2. During tapping bath C ~ 0.03% and P ~ 0.01% is required. Improved opening phosphorus has resulted in elimination of reblows for phosphorus correction. Only 50-150Nm<sup>3</sup> oxygen is blown to lower bath C below 0.03% before heat is tapped. Improvements were also observed in the blowing process with respect to slag formation, spitting, lance skulling, hood jamming etc and hence to shop productivity.

**Secondary steel refining** The existing practice of ladle addition during tapping was not altered, with around 200kg of SiMn added during tapping. Vacuum treatment with oxygen blowing is standard practice to control the gaseous content of steel and to further reduce steel carbon (<0.025%) which ensures C < 0.003% in the final product after decarb-annealing.

Some modifications in secondary refining practice were necessary to achieve improved desulphurisation, given the high tap S compared to the aims required in the product.

Desulphurisation depends largely on the fluidity and composition of slag made after de-oxidation and alloying.

The equilibria for the reaction [4] can be expressed as  

$$\text{CaO} + \text{S} = \text{CaS} + \text{O} \dots\dots\dots (1)$$

...and the equilibrium constant is expressed by

$$K_{\text{CaO}} = h_{\text{O}} a_{\text{CaS}} / h_{\text{S}} a_{\text{CaO}} \dots\dots\dots (2)$$

The value of K at 1,600°C is 4 x 10<sup>-2</sup>. The value of K decreases with increasing temperature; therefore, making desulphurisation less favourable, however, kinetic factors are favoured by high temperature and this may be more

BOF variable	Without sinter addition	With iron ore / sinter addition
Hot metal charge, Kg/t crude steel (tcs)	1,076.9	1,090.8
Scrap charge, Kg/tcs	110.9	88.5
Iron ore or sinter addition	No addition	2-4 batches of 50-100kg
Lime, Kg/tcs	63.7	64.5
Dolomet, Kg/tcs	15.4	13.7
Oxygen consumption, Nm <sup>3</sup> /tcs	52.5 (2.3)	54.1 (2.9)
First turn down Temp, °C	1,626 (19.3)	1,621 (27)
First turn down analysis, wt%		
C	0.044 (0.014)	0.042 (0.013)
Mn	0.021 (0.004)	0.016 (0.007)
P	0.015 (0.005)	0.010 (0.003)
S	0.057 (0.012)	0.053 (0.012)
Slag composition, wt%		
FeO	28.6 (0.96)	27.0 (1.44)
SiO <sub>2</sub>	10.3 (0.40)	10.3 (0.72)
CaO	46.8 (2.16)	47.0 (1.09)
MgO	3.9 (1.64)	3.6 (0.68)
Al <sub>2</sub> O <sub>3</sub>	0.7 (0.36)	0.5 (0.11)
TiO <sub>2</sub>	0.7 (0.15)	0.8 (0.11)
P <sub>2</sub> O <sub>5</sub>	2.4 (0.25)	2.4 (0.14)
S	0.17 (0.06)	0.17 (0.01)

Table 2 Comparison of BOF operating data with and without sinter (s.d.)

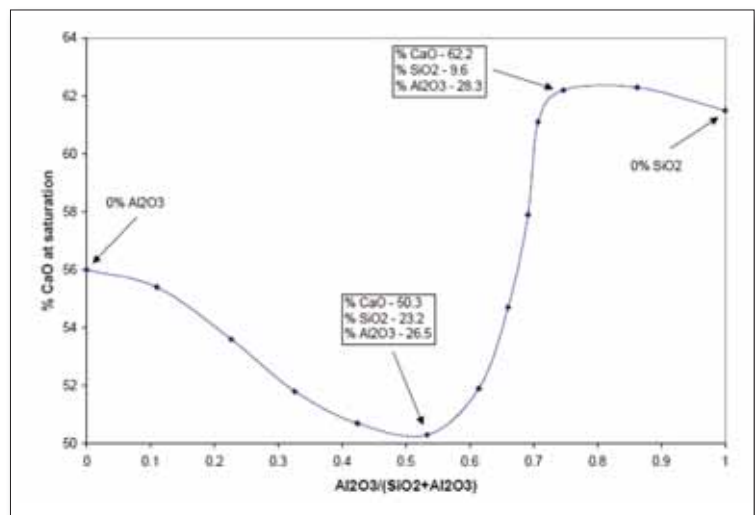


Fig 5 The solubility of CaO as Al<sub>2</sub>O<sub>3</sub> replaces SiO<sub>2</sub> at 1,600°C

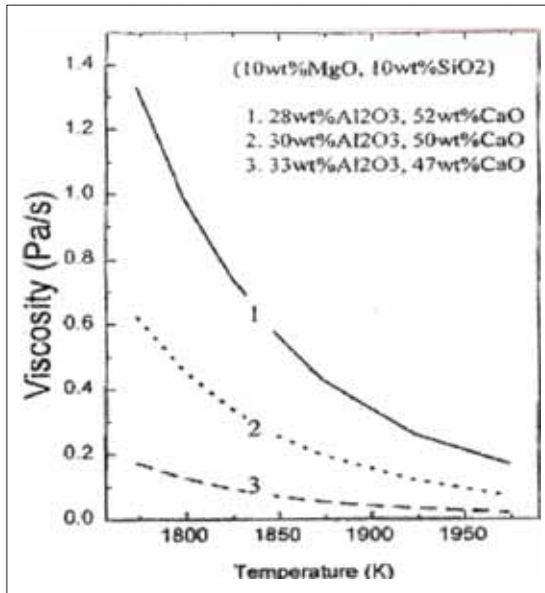


Fig 6 Effect of alumina on slag viscosity

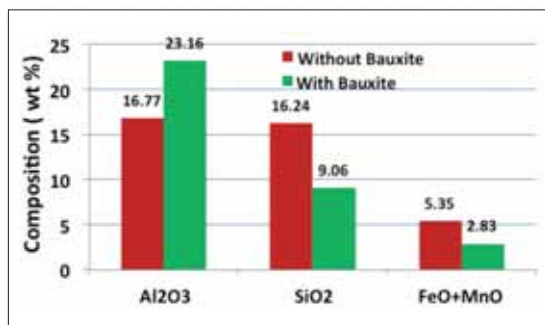


Fig 7 Slag chemistry in base heats and trial heats

important. Several important factors must be considered including slag composition, sulphide capacity, sulphur partition ratio, slag modifier, etc.

Sulphide capacity is the potential ability of a slag to remove sulphur during slag metal interaction. The basic requirement of desulphurisation is highly basic lime saturated slag. It is desirable that the slag should not contain more than 5% of easily reducible oxides like FeO and MnO.

The sulphide capacity of CaO-Al<sub>2</sub>O<sub>3</sub> slags is greater than for CaO-SiO<sub>2</sub> and increases with slag basicity. In simple silicate slags, the solubility of CaO is limited by the precipitation of the very stable phase, Ca<sub>2</sub>SiO<sub>4</sub> so the addition of any component to the slag that will dissolve (de-stabilise) Ca<sub>2</sub>SiO<sub>4</sub>, will increase the solubility of CaO in the slag.

Al<sub>2</sub>O<sub>3</sub> is the third 'best' component after B<sub>2</sub>O<sub>3</sub> and CaF<sub>2</sub> to destabilise Ca<sub>2</sub>SiO<sub>4</sub> and increase the solubility of CaO. A significant amount of Al<sub>2</sub>O<sub>3</sub> is required to result in an

increase in CaO solubility at 1,600°C. The increase in CaO solubility above the Al<sub>2</sub>O<sub>3</sub> threshold value is also linked to the SiO<sub>2</sub> content of the slag. B<sub>2</sub>O<sub>3</sub> and CaF<sub>2</sub> were not used because of environmental concerns and increased lining wear with these slag fluidisers/conditioners.

Figure 5 shows that in the CaO-Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub> (CAS) system [5], the replacement of SiO<sub>2</sub> with Al<sub>2</sub>O<sub>3</sub> will initially result in a decrease in CaO solubility. A large increase in CaO solubility only occurs when the Al<sub>2</sub>O<sub>3</sub> content of the slag exceeds 25% Al<sub>2</sub>O<sub>3</sub> and the SiO<sub>2</sub> content of the slag decreases from to less than 10% SiO<sub>2</sub>.

Al<sub>2</sub>O<sub>3</sub> could be utilised to increase the solubility of CaO in the slag. The required Al<sub>2</sub>O<sub>3</sub> levels should be greater than 25% Al<sub>2</sub>O<sub>3</sub> in order to generate slags with good fluidity at steelmaking temperatures. The MgO content of the slag is very important in this system and should be controlled in a very tight range of 8-10%. Figure 6 shows the effect of alumina on slag viscosity.

Calcined bauxite is a suitable slag conditioner to suppress the formation of di-calcium silicate phase and to enhance flux dissolution and slag fluidity. Increasing lime in the slag increases the sulphide capacity of slag and calcined bauxite was added during vacuum treatment. The chemical composition of calcined bauxite received during the trial was: Al<sub>2</sub>O<sub>3</sub> 73%, MgO 4%, SiO<sub>2</sub> 15%, S 0.014%, LOI 1% max, and size 5-20mm

To keep the slag-lime saturated, the CaO content of the slag was kept at ~50% to ensure a high basicity of ~3.5-4.0 for better sulphur removal, higher slag deoxidation potential and thereby improved steel cleanliness. In order to achieve this condition, calcined bauxite along with calcined lime was added during secondary refining treatment in vacuum refining. The alumina and silica present in the bauxite helped to adjust the slag chemistry, and improved deoxidation practice helped reduce the level of FeO + MnO to <3% as compared to 6~8% in base heats (see Figure 7). A low level of FeO + MnO is favourable for desulphurisation.

Addition of lime in the vacuum degassing unit (VAD/VOD) was as normal, however, 180-200kg of calcined bauxite was added after 10-15 minutes of degassing. Other ferroalloys were added as required. Bath stirring for 15-20 minutes was done for efficient slag metal reaction to facilitate desulphurisation and inclusion absorption.

For improvement in desulphurisation it was ensured that the slag chemistry should fall in the desired range by adjustment in the ladle furnace by addition of further lime and calcined bauxite as required.

The modified slag has improved sulphur partition ratio and sulphide capacity which resulted in achieving the lower level of sulphur <0.015% in tundish. The percentage desulphurisation from steel ladle to tundish has also improved from 40% in base heats to 58% in trial heats.

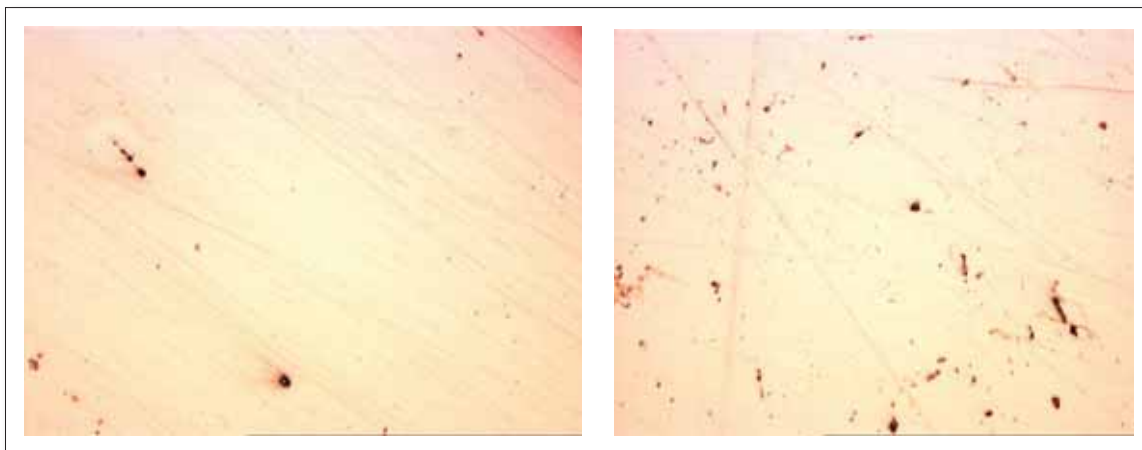


Fig 8 Inclusion volume analysis of CRNO M 36 & 43

## INCLUSION VOLUME ANALYSIS AND CORE LOSS VALUE

Final properties of CRNO are thoroughly tested for core loss value related to different grades. Electrical property varies according to quality of steel. A comparison of inclusion volume analysis of final product of CRNO M 36 & 43 is shown in *Figure 8*. Lower inclusion volume improves core loss value and thus steels with low core loss can be upgraded to higher value products. Classification of the product according to improved core loss value is shown in *Table 3*.

The overall efforts in each step of steelmaking and rolling has helped control CRNO steel quality and improved electrical properties. An improvement in upgrading of casts to a higher CRNO grade (52% to 60%) was achieved.

## CONCLUSIONS

The magnetic properties of CRNO steels are dependent on their chemical composition as well as other factors. To meet the stringent quality specification for these steel grades precise control of steelmaking operating parameters are required in each stage of its production, ie, BOF steelmaking, secondary refining and rolling process.

Improved BOF slag formation was achieved through modifications to the lance practice and additions of sinter to increase FeO content during the peak decarburisation period carried out to control turn-down steel quality. This led to lower and more consistent tap P contents.

Secondary refining practice was redesigned to improve deoxidation, desulphurisation and steel cleanliness by optimising the chemistry and fluidity of ladle top slag. The percentage desulphurisation from steel ladle to tundish improved from 40% in base case heats to 58% in trial heats, leading to more casts with <0.015% in the tundish.

This lower sulphur, coupled with improved steel cleanliness, helped improve core loss values for CRNO grades, resulting in the heat upgrading percentage increasing from 52 to 60. **MS**

CRNO grade	M47	M45	M43	M36
Core Loss Value (Avg), W/kg	5.50	4.85	3.71	3.35

Table 3 Core loss value for different CRNO grades

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