Iron Making and Steel Making
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Module – 09
Lecture – 44
IM: Cored wire injection: Industrial implications

On the last lecture, we discussed about a literature reported mathematical model of cored wire injection in steel melt. Four routes of wire melting have been discussed along with effect of operating parameters on the predicted distance traversed by the wire before it melts and releases powder. The model demonstrated it capability to predict the point of release of powder into the liquid melt.

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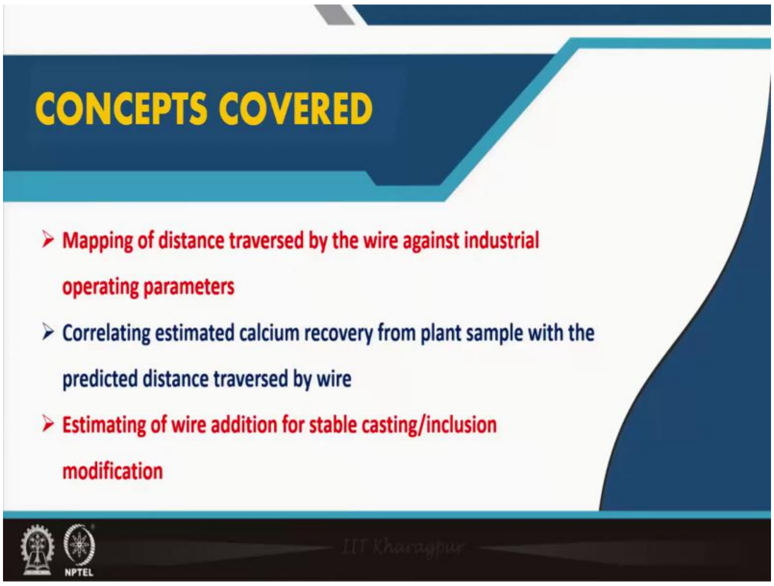

In this lecture, industrial application the model has been demonstrated. Topics covered in this lecture includes mapping of the distance traversed by the wire against widely varied industrial operating conditions, correlation of calcium recovery against the predicted distance traversed by the wire, and finally predicting the optimum wire addition for development of proper inclusion. All the data presented in this lecture from our published research, which are given in the reference slide.

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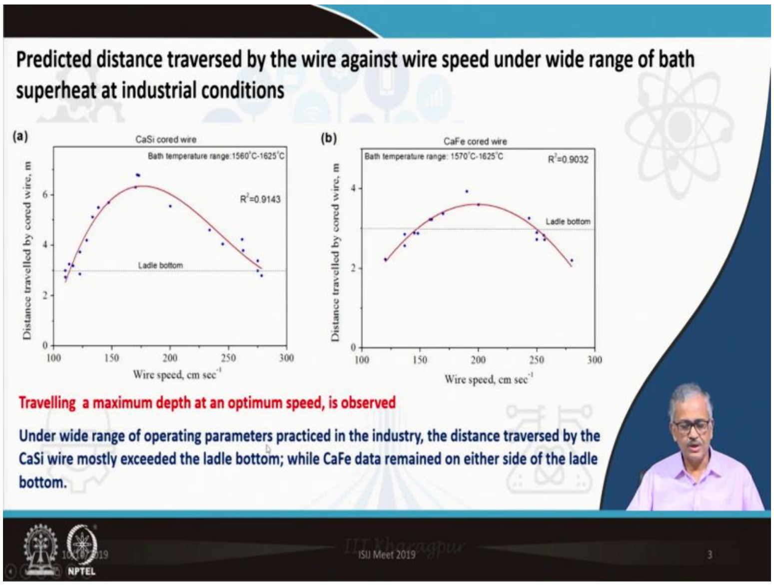

Here we have calculated the distance traversed by the wire in actual industrial melt against the range of values of wire speed (100 to 300 cm/sec) and bath superheat (1560 to 1625ºC) under actual industrial operation.

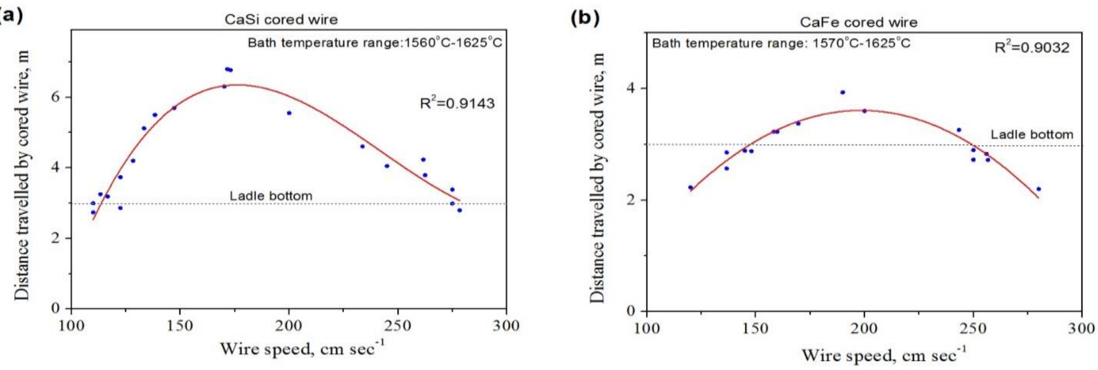

Figure 24.1: Mapping of predicted distance traversed by the wire in actual industrial liquid bath against widely varied wire speeds for a range of bath superheats under industrial operating conditions: (a) for calcium silicide (Ca-Si), (b) for Ca-Fe.

In Figure 24.1, these data representing the distance traversed by the wire in the industrial melt has been plotted against the wire speed. It is seen that the distance traversed by the wire against the wire speed passes through a maximum value. But, most interestingly it is observed that all the data points, representing distance traversed by the wire, lays above the ladle bottom as indicated by horizontal line in the figure. It means that the distance traversed by the wire in most of the industrials heats exceed the ladle bottom and in other words, it means that the wire does not melt even after reaching the bottom of the ladle. Under this condition, the un-melted wire may move up after hitting the bottom, or, may spiral at the bottom and move up. Whatever, may be the case it is likely to reduce the calcium recovery. Anyway we will correlate the distance traversed with the calcium recovery to see whether calcium recovery really decrease under this condition.

In Figure 24.1(b) shows a similar plots has been made for CaFe wire addition. In CaFe case, it is found that there are some cases where there is premature melting of wire before it reaches the ladle bottom; and in some cases wire does not melt even after reaching the ladle bottom.

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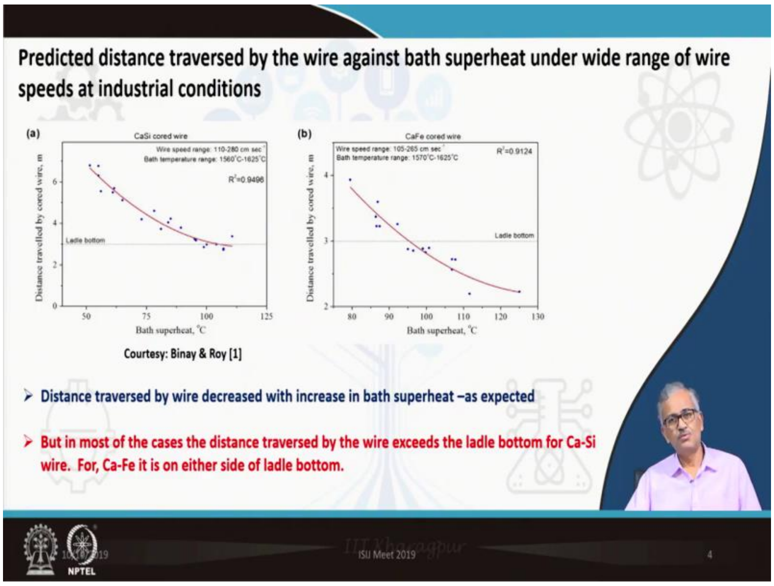

Figure 24.2 shows the similar plot where the same data representing predicted distance traversed by the wire in industrial melt has been plotted against the bath superheat. It is seen that distance traversed by the wire decreases with increase in bath superheat. Again it seen most of the data remains above the horizontal line representing ladle bottom, indicating distance traversed by the wire exceeds the ladle bottom in most of the cases and in few cases it is just at the bottom. In case of CaFe addition (Figure 24.2(b)) also a decrease in distance traversed by the wire is noted with increase in bath superheat. It is also seen that some of the CaFe wire melts prematurely while the others does not melt even after reaching the bottom.

Thus we see distance traversed by the wire in industrial melt follows the expected trend when plotted against the wire speed and bath superheat. It was more interesting to observe that for CaSi wire addition in most of the cases the wire did not melt even after reaching the ladle bottom and only in few cases wire melted just at the bottom. In case of CaFe injection, some premature melting of wire also indicated. Therefore, our next aim should be to correlate the calcium recovery with the distance traversed by the wire. Before doing that let us see how to measure calcium recovery in industrial melt.

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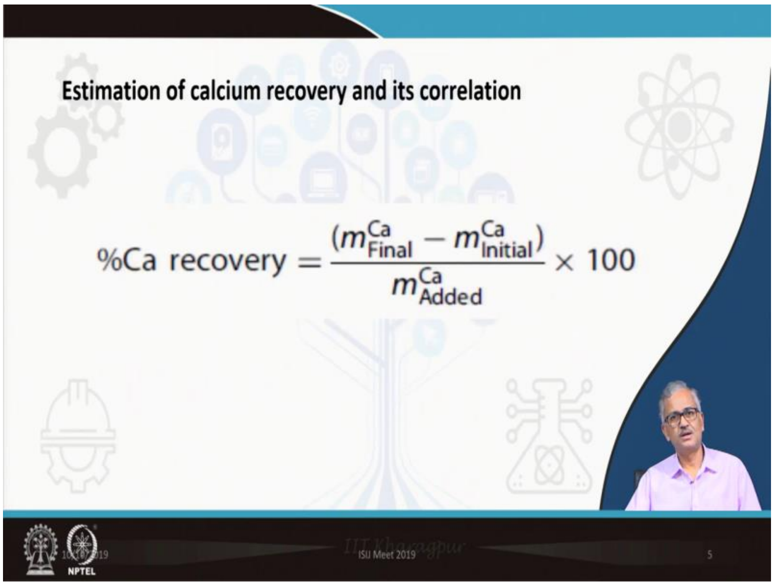

Calcium recovery maybe estimated by noting the calcium amount in liquid melt both before and after the calcium injection. % calcium recovery may be calculated as:

$$\%\text{Ca recovery} = \frac{(m^{Ca}_{Final} - m^{Ca}_{Initial})}{m^{Ca}_{Added}} \times 100 \tag{44.1}$$

Calcium added may be measured from the length of the wire added, powder composition and its bulk density in the cored wire.

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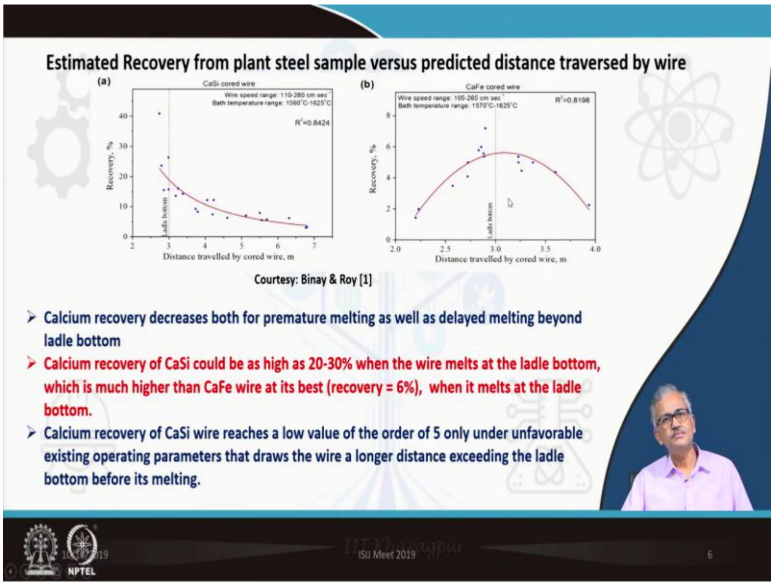

Calcium recovery has been estimated for all the heats considered in this study. Figure 44.3 shows a plot where recovery has been plotted against the distance traverse by the cored wire. Figure 44.3(a) for CaSi wire injection and 44.3(b) for the CaFe wire injection. From Fig. 44.3(a), it is seen that recovery is maximum when the wire melts near the ladle bottom (ladle bottom is indicated by a vertical line) and recovery decreases as the distance traversed by the wire increases beyond the ladle bottom. In case of CaFe wire, recovery is found to be maximum at the ladle bottom and less on either side of ladle bottom meaning when the wire melts prematurely or do not even melt after reaching the bottom.

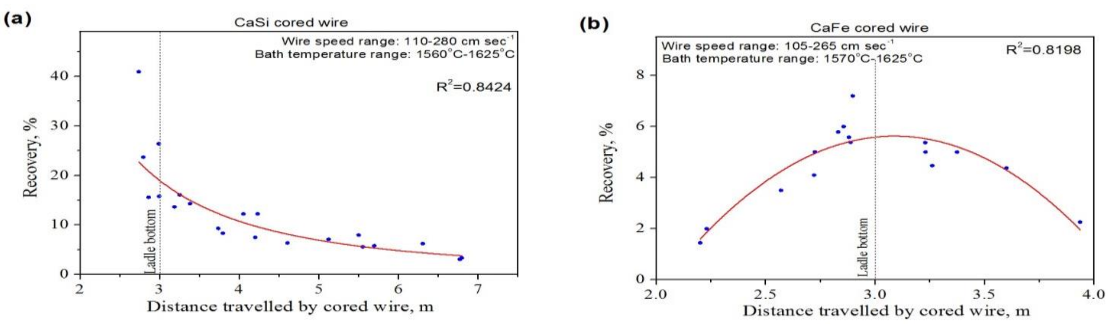

Figure 44.3: Estimated calcium recovery versus distance traversed by the wire in industrial melt: (a) for Ca-Si wire, (b) for CaFe wire.

It may further be noted that for CaSi, the maximum recovery is 20 to 30 percent when the wire melts at the ladle bottom and could be as low as 5%, when distance traversed exceeds 3 m from ladle bottom. In case of the CaFe, maximum recovery value is only 6 when wire melts at the bottom of the ladle and could be less than 2 either for premature melting or delayer melting after exceeding the ladle bottom.

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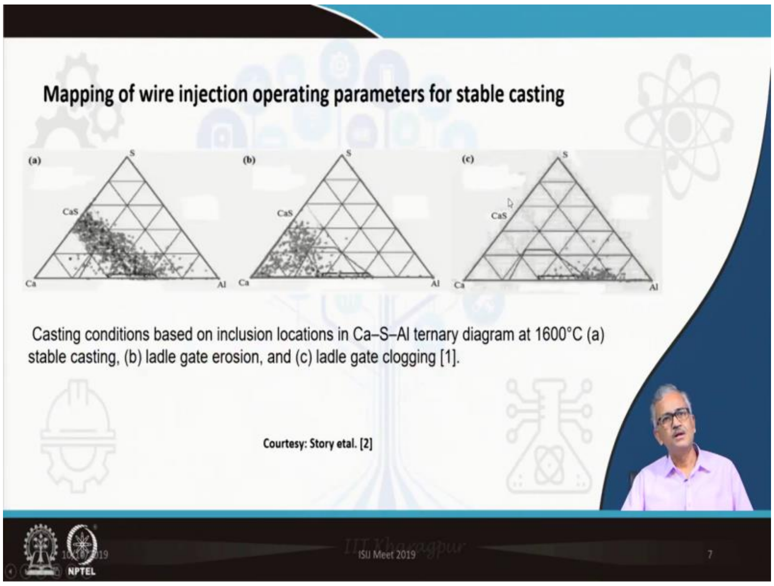

Calcium recovery is a major issue for calcium injection. The above discussion has demonstrated that calcium recovery become maximum when wire melts just at the bottom of the ladle and calcium recovery has been mapped against operating parameters under industrial conditions. Now let us evaluate two major objective of calcium injection. Stable casting, meaning no interruption during casting due to nozzle blockage by alumina network, in one major objective. Calcium injection in an optimum amount convert the networking alumina inclusions to liquid calcium aluminate that eliminate the problem of nozzle blocking. Second objective is inclusion modification, where deleterious inclusions like hard irregular alumina inclusion and soft elongated sulphide inclusiona are modified to harmless spherical deformable inclusion. Morphology of such inclusion shows central calcium aluminate covered by CaS and MnS. Here also calcium aluminate are required to be liquid at steelmaking temperature. So both the aims are served when calcium aluminate of particular composition is formed that are liquid at steelmaking temperature. Therefore, for developing desirable inclusion, Ca/Al ratio is an important parameter.

Therefore, stable casting may be mapped in a Ca-Al-S ternary map, or it can be mapped against Ca/Al ratio of the bath.

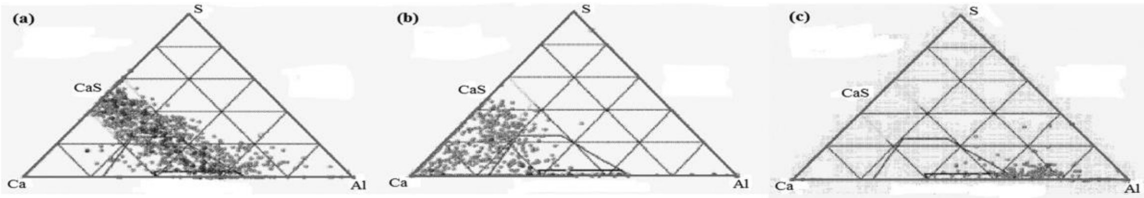

Figure 44.5: Casting conditions based on inclusion locations in Ca–S–Al ternary diagram at 1600°C (a) stable casting, (b) ladle gate erosion, and (c) ladle gate clogging [1].

From Figure 44.5, it is found that Ca rich inclusion will lead to erosion of ladle gate (44.5(b)), and Ca deficient inclusion will lead to nozzle clogging (44.5(c)) and when calcium is optimum, the liquid calcium aluminate will form to yield stable casting.

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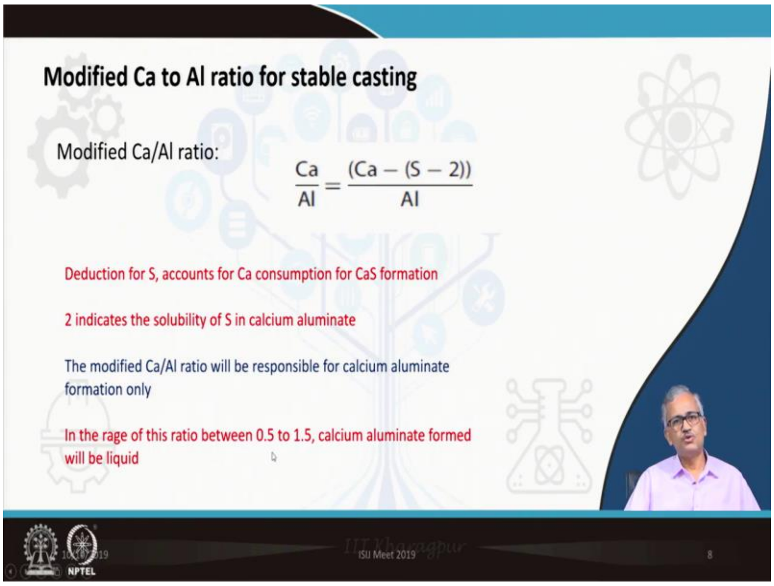

Stable casting can also be mapped against modified Ca/Al ratio, as defined by equation (44.2).

$$\frac{Ca}{Al} = \frac{(Ca - (S - 2))}{Al} \tag{44.2}$$

Deduction for S, accounts for Ca consumption for CaS formation. 2 indicates the solubility of S in calcium aluminate. The modified Ca/Al ratio will be responsible for calcium aluminate formation only. In the range of this ratio between 0.5 to 1.5, calcium aluminate formed will be liquid.

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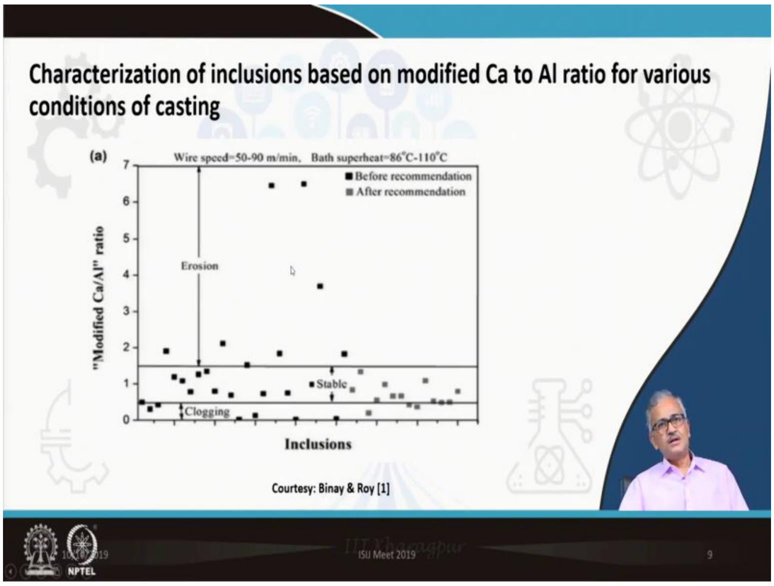

Figure 44.6 maps different inclusions against the modified Ca/Al ratio. Here before and after recommendation represents the original industrial data and data after some recommendation on the optimum length of wire addition calculated based on Ca-recovery and modified Ca/Al ratio under particular industrial operating conditions. It is found that original data are scattered in all three regions namely stable casting, erosion, and clogging and after recommendation the data confines more in the stable casting region.

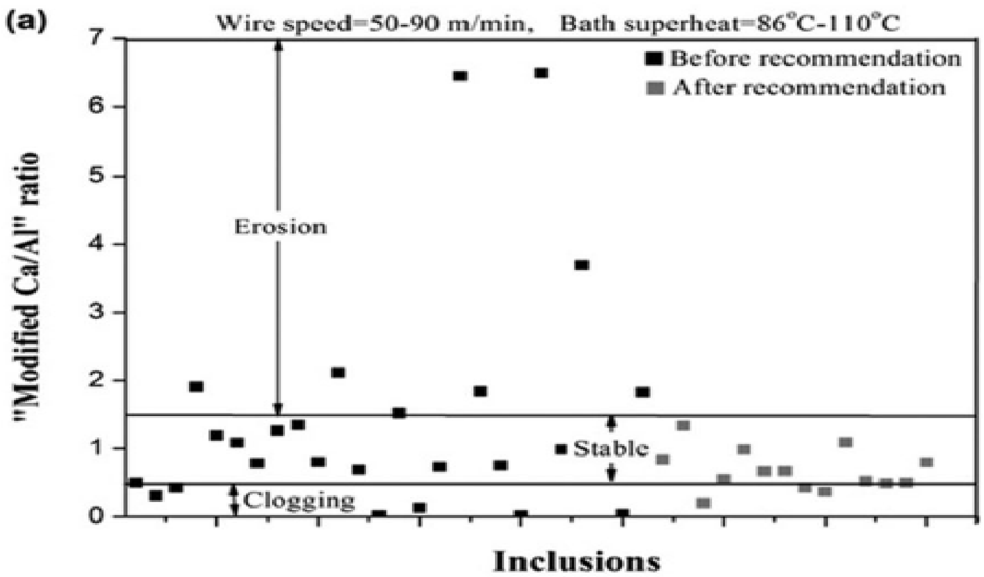

Figure 44.6: Mapping of inclusion against modified Ca/Al ratio in three zones-stable casting, clogging and erosion of ladle gate.

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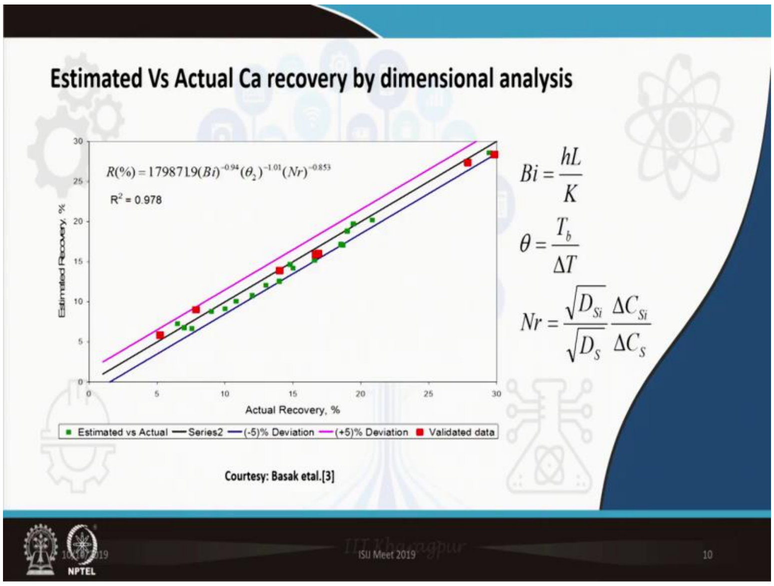

In another publications we have also correlated calcium recovery against dimensionless operating parameters based on another (second) industrial data. Dimensionless numbers used are: (i) Biot number (Bi) that is the dimensionless heat transfer coefficient at the wire liquid interface. (ii) dimensionless temperature (θ), where ΔT represent the bath superheat (iii) relative rate of silicon to sulfur transfer, Nr (Equation 44.3).

$$Bi = \frac{hL}{K}$$
$$\theta = \frac{T_b}{\Delta T}$$
$$Nr = \frac{\sqrt{D_{Si}}}{\sqrt{D_S}} \frac{\Delta C_{Si}}{\Delta C_S} \tag{44.3}$$

ΔC represents the concentration difference across the concentration boundary layer at wire melt interface. D represents mass diffusivity of impurity. Subscript S and Si represent sulphur and silicon, respectively. The numerator of dimensionless term Nr gives the flux of silicon from the powdered surface to the bulk. Similarly, denominator represents the flux of the sulfur from the bulk to powder-liquid interface. If Nr is high, depletion of silicon or the transport of silicon from the interface to the bulk is much higher compared to the transfer of sulfur from the bulk to the interface. So in this case calcium gets depleted of silicon faster before it is captured by sulphur in the form of CaS. Therefore, a negative exponent for Nr is observed in the correlation. Exponent for Bi and θ are also negative because recovery decreases with increase in bulk liquid temperature and heat transfer coefficient.

Figure 44.7 represents the correlation of calcium recovery with the dimensionless numbers.

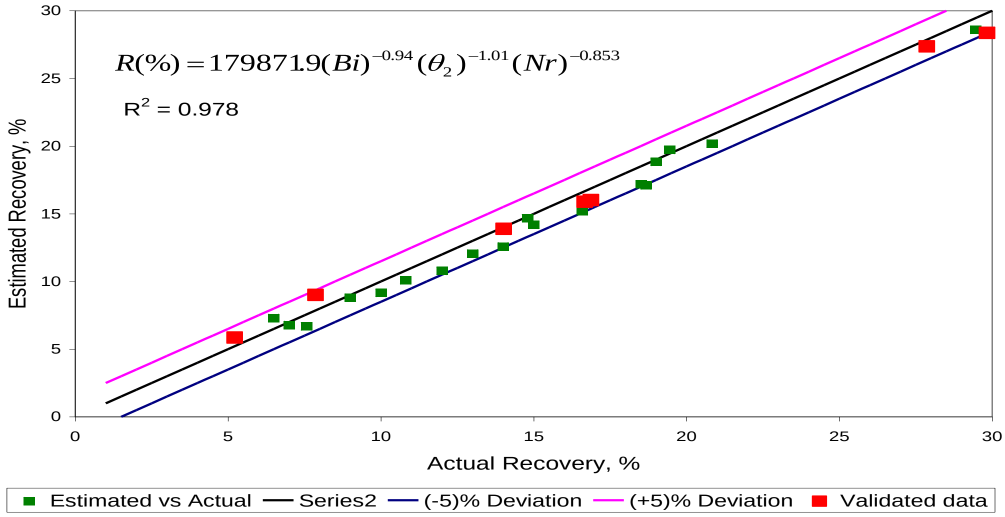

Figure 44.7 Dimensionless correlation between calcium recovery and dimensionless operating parameters.

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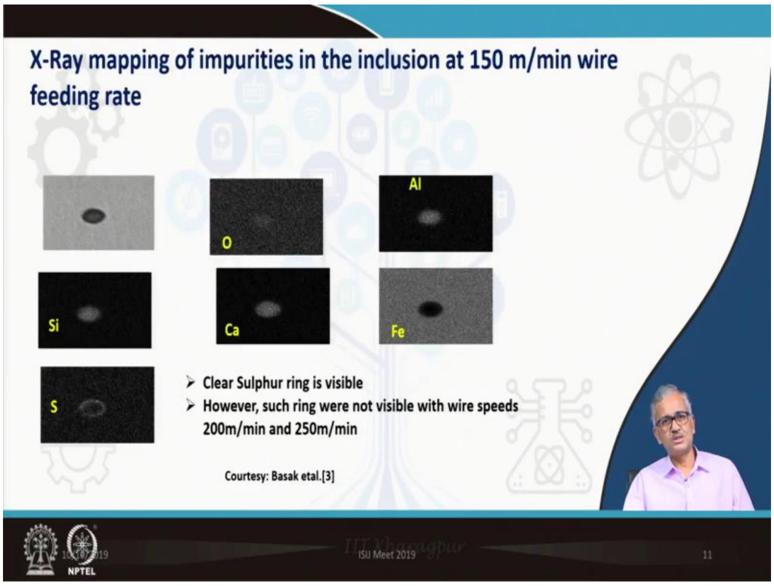
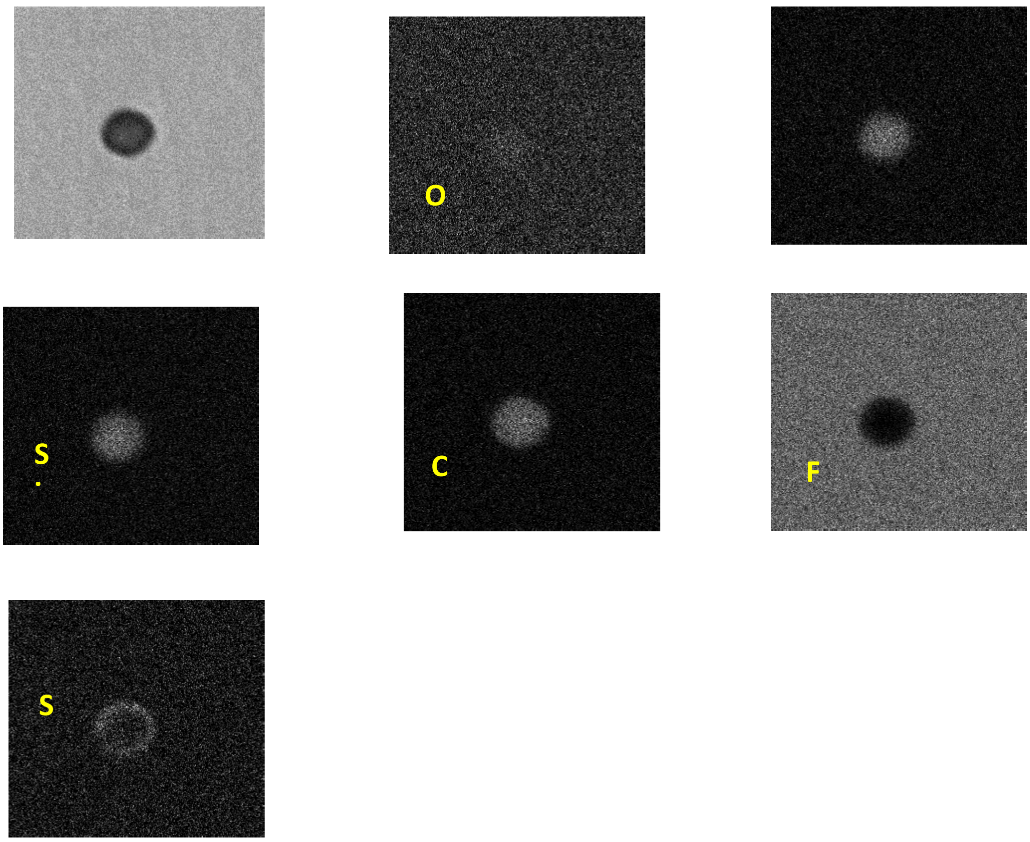


Now, we will show the evolution proper inclusion under optimum operating parameter based on another (second) industrial data. Elemental mapping of inclusions are done at various wire speeds, namely 150 meter per minute, 200 meter per minute, 250 meter per minute; but the best inclusion form only at 150 meter per minute. Figure 44.8 shows the elemental mapping of inclusion formed at wire speed of 150 m/min (250 cm/s).



Inside the inclusion strong presence of Ca, Al and O are observed indicating presence of calcium aluminate. Most interestingly, a nice sulfur ring can also be found.

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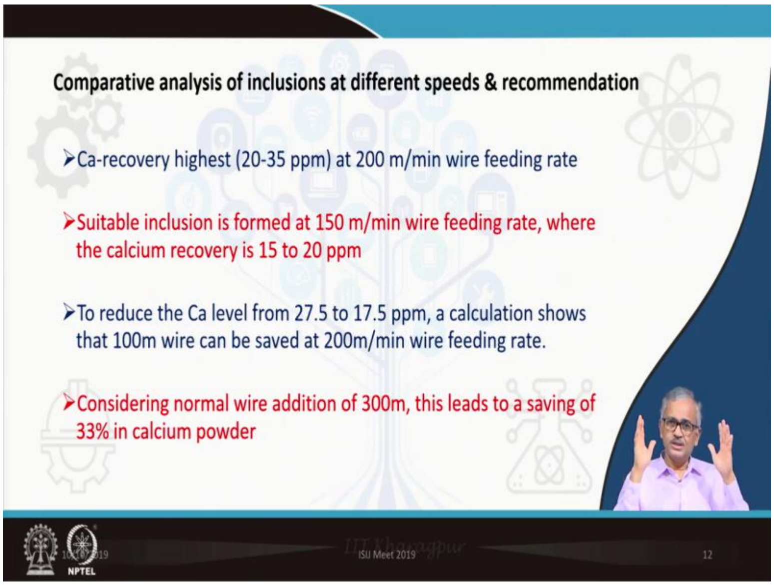

So, we can find at wire speed of 150 meter per minute, we can produce the best inclusion.

However, with this industrial data (second) maximum calcium recovery was recoded at 200 m/min (333 cm/s). It may be noted that this is in contrast to previously presented (first) industrial data, where optimum speed was found to be 200 cm/s, which might be due to different wire brand and range of operating parameters.

Anyway, the optimum speed for calcium recovery does not match with the optimum wire speed for proper inclusion development. It means that bath calcium and Ca/Al ratio is an important parameter for inclusion development. Therefore wire might be fed at optimum speed for maximum calcium recovery, but the length of wire addition could be changed for developing optimum Ca/Al ratio in the bath that yields proper inclusion.

For this case maximum calcium recovery (with bath calcium in the range of 20 to 35 ppm) was found at wire speed of 200m/min against bath calcium development in the range of 15 to 20 ppm at wire speed of 150 m/min. Therefore if we need to push the wire at

200m/min to derive the benefit of maximum calcium recovery, calcium in the bath has to be reduced from an average level of 27.5 ppm to 17.5 ppm. Based on wire parameters, this could be achieved by reducing the wire length of 100m. Considering initial length of 300mm, this leads to reduction of wire length by 33%.

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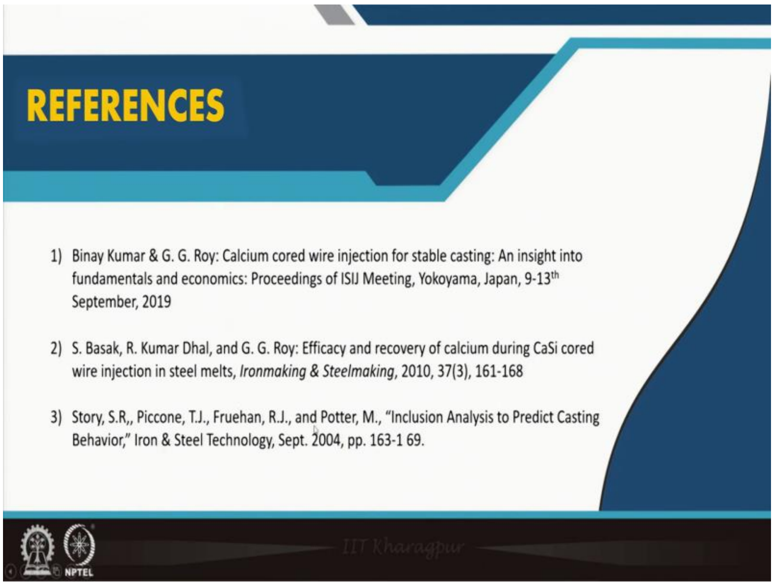

The slide above shows the three references, based on which above discussion has been made.

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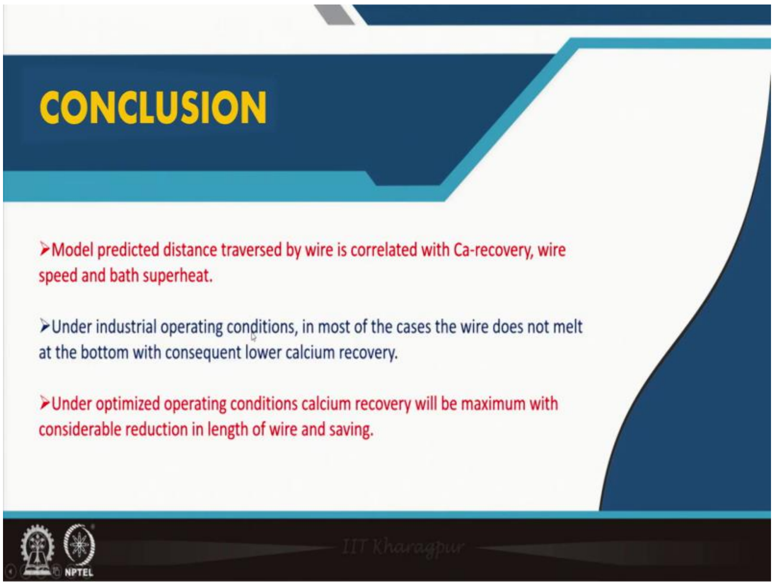

Conclusions: Model predicted distance traversed by the wire in actual industrial melt is correlated with the calcium recovery, wire speed and the bath superheat.

Distance traversed by the wire in actual industrial melt followed the expected correlation with wire speed and bath superheat. Distance traversed decreased monotonically with increase in bath superheat while it passed through a maximum with wire speed. Interestingly, it was observed that in most of the cases wire did not melt even after reaching the ladle bottom in case of Ca-Si powder addition and in case of CaFe addition, wire melted either prematurely or did not melt after reaching the bottom.

Calcium recovery in industrial melt was found to be maximum (20-30% in case of CaSi) when wire melted at the bottom and decreased progressively thereafter with delayed melting. In case of CaFe maximum recovery at 6% was observed when wire melted at the ladle bottom or decreased if the wire either melted prematurely and did not melt even crossing the bottom of the ladle.

It was found that stable casting depended on a particular Ca/Al ratio in the bath that develops liquid calcium aluminate at steel making temperature. Thereafter, based on calcium recovery at a particular set of operating parameters (wire speed and bath superheat), and required Ca/Al ratio for stable casting, the length of wire to be injected was calculated and recommended. After analyzing the revised industrial data it was possible to capture most of the inclusions in the stable range of casting.

In another experiment with second industrial data, a handy correlation for calcium recovery against dimensionless number has been established.

In this study, inclusion development was also studied under microscope. Optimum wire speed for developing proper inclusion (with a distinct Sulphur ring) were found to different to that for maximum calcium recovery. It was found that by injecting wire at optimum speed for maximum calcium recovery, wire addition could be reduced by 33%.