Iron Making and Steel Making

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Module – 09
Lecture – 43
Cored wire Injection – Modeling, melting sequence, effect of operating parameters

There are two techniques for injecting the reactive and volatile calcium powder into the liquid melt. One is powder injection through submerge lance, which we have already discussed in the last lecture. In this lecture we will discuss submerged calcium injection using cored wire technique.

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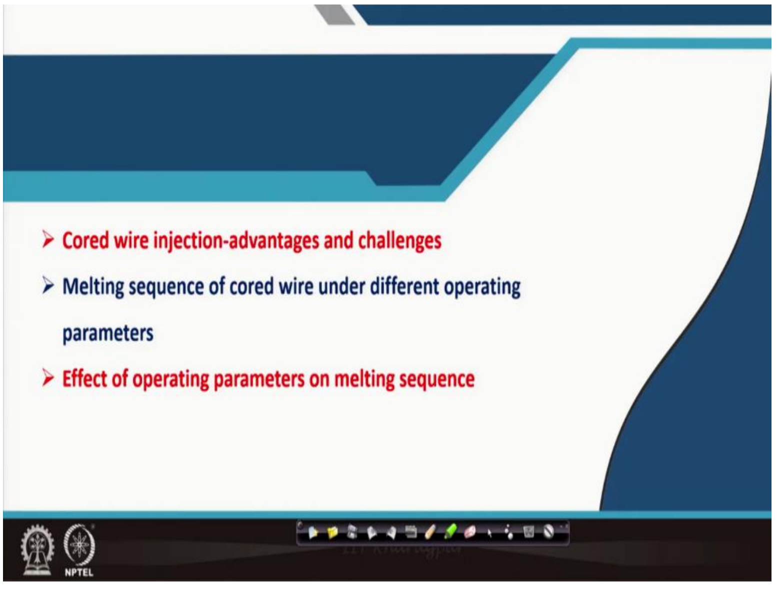

Topics covered will include brief introduction about the cored wire, , melting sequence of the cored wire under different operating parameters, and effect of operating parameters on melting sequence.

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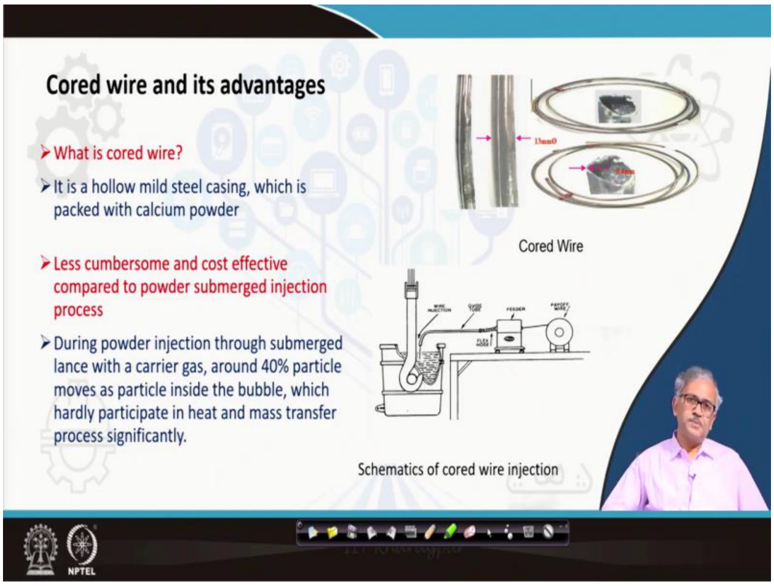

Cored wire is a hollow mild steel cylindrical casing that is packed with calcium powder. It appears like a wire, and called the cored wire (see Figure 43.1).

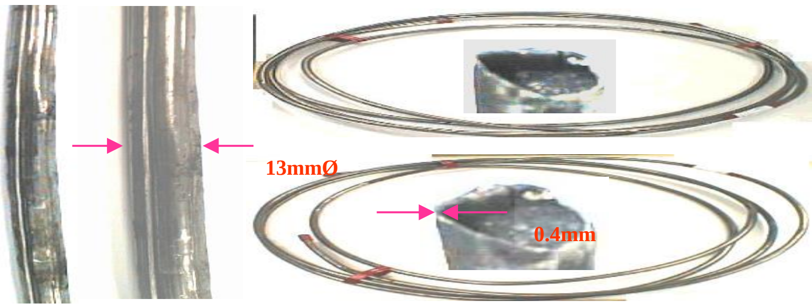

Figure 43.1: Schematics of cored wire

The typical outer diameter and casing thickness of cored wire are 13 mm, and 0.4 mm, respectively. The cored wire is injected into the steel melt using mechanical devices as shown in Figure 43.2.

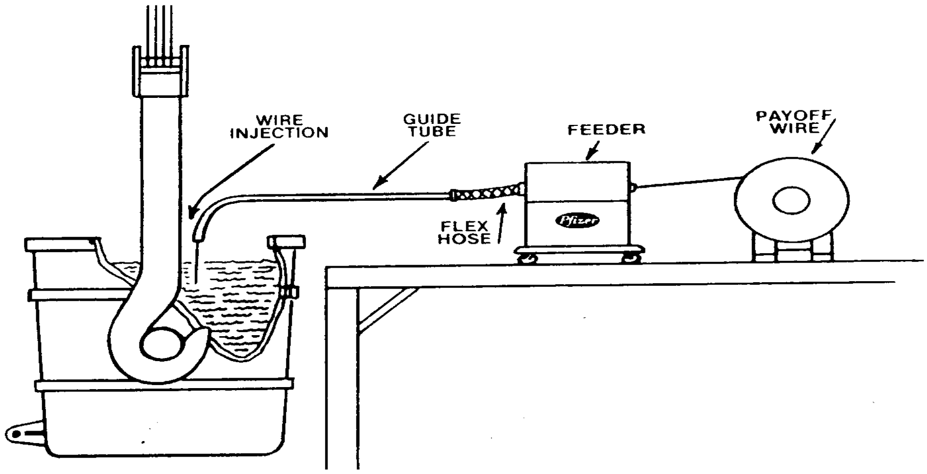

Figure 43.2: Schematics of mechanical device for injecting cored wire in liquid melt

After travelling through liquid when the casing of the wire melts, the powder get released. Obviously, wire injection is much less cumbersome process compared to the submerged lance injection of powder using carrier gas.

Besides, during powder injection through submerged lance around 40 percent of the powder rise as particle inside the bubble without participating much in the mass transfer process, decreasing the yield of the process.

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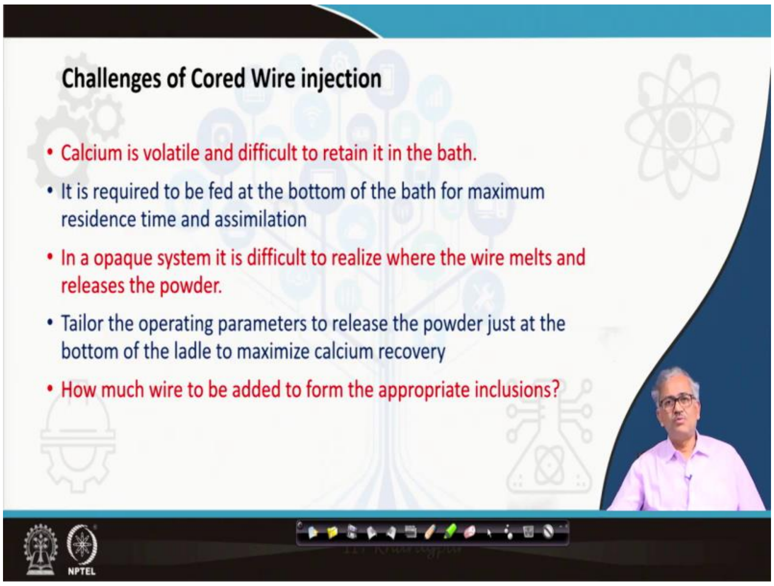

Let us first discuss the challenges of cored wire injection. As we have mentioned that calcium is volatile and very reactive and therefore poor recovery of calcium in liquid melt is an issue. To enhance calcium recovery, calcium is usually injected as calcium alloy like calcium silicide, where activity of calcium decreases and consequently its vapour pressure decreases. Another way is to release the powder at the bottom of the bed where pressure is comparatively high and it also allows the maximum residence time of calcium in the melt during its rise, either as bubble or liquid droplet. Challenge during cored wire injection is to ensure that the casing melts just at the bottom of the vessel and releases the powder there. Since liquid steel is opaque, it is very difficult to visualize where the wire melts and releases the powder. So, after entering the bath, the powder can be released in the midway, it can be released at the bottom, and the wire may not melt even after reaching the bottom. So, all possibilities are there; and at the same time you cannot see where the wire is melting. This is the challenge. So, mathematical modelling can be helpful from this point of view to predict the distance traversed by the wire before it melts and releases powder.

And, then it could be possible to optimize the parameters, like bath superheat, wire speed such that the wire melts just at the bottom of the bath. Another important parameter is that how much the wire has to be added? In other words, how much calcium is needed in the bath to form the appropriate inclusion, which will be discussed in the next lecture.

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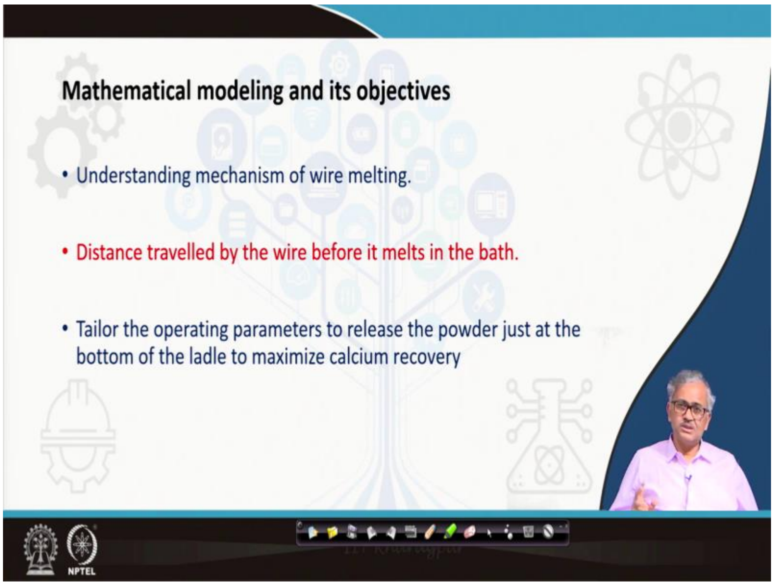

Mathematical model: A mathematical model has been reported in literature that identified four routes of melting and capable of predicting the distance traversed by the wire before it melts [1]. Let have a brief description of the model.

When the wire enters into the bath, a steel shell forms on the wire surface due to localized cooling. Then the steel shell melts back, casing melts, and finally, the powder is released.

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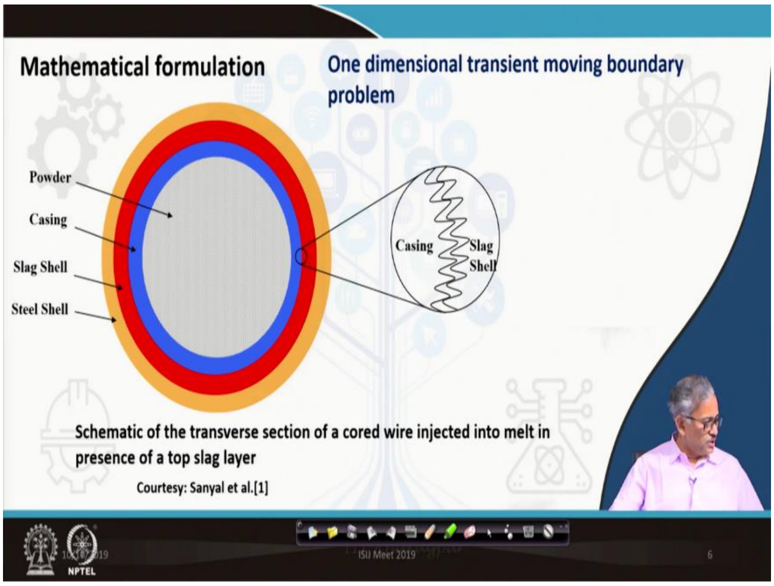

The reported model is an one-dimensional transient moving boundary problem. It is one-dimensional, because wire is a long cylinder where heat crosses across the radial distance only. It is transient with respect to an observer moving with the wire. It is also a moving boundary problem because solidification and melting of the shell over the wire changes it apparent outer diameter with time. Figure 43.3 shows the cross section of the wire at any instance after it has been immersed through an overlaying slag layer. Just above the casing there is a slag shell because wire has first entered through the slag. And then over the slag shell, there exists a metal shell. So, it looks like a composite structure.

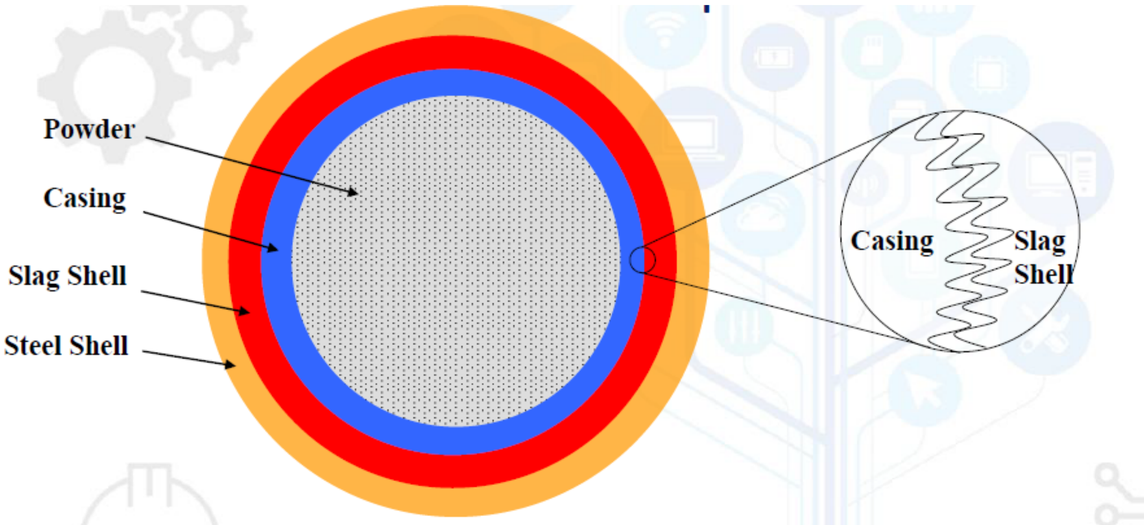

Figure 43.3: Schematics of core wire inserted into liquid metal at certain instent of time.

So, moving outward from center of the wire, there exists the powder, then casing, then slag shell, and finally the metal shell. So, the time instant indicated represents the event when the shells are developing. Thereafter, the metal shell will dissolve, followed by the slag shell and casing, and then finally the powder will released. It may be noted that a contact resistance at the casing-slag shell interface has been considered to represent the lack of wetting of casing surface by solidified slag shell. The flux continuity at this interface has been made using the concept of heat transfer coefficient at the slag-casing interface. All other interface are considered smooth and simple heat continuity has been maintained by applying Fourier law of heat conduction on either side of the interface.

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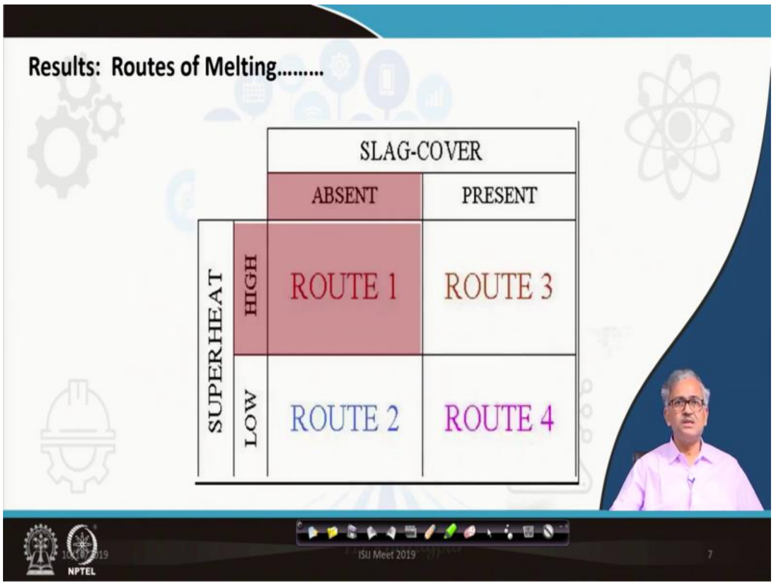

Four wire melting routes has been identified based on bath superheat and presence and absence of overlaying slag layer.

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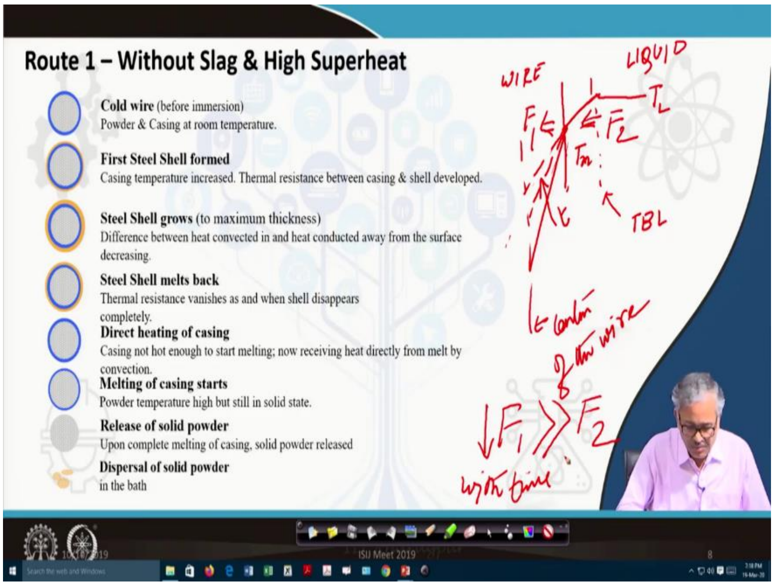

First route of melting: without slag and high superheat: As soon as the wire enters the liquid melt a solid steel shell forms. Steel shell forms due to imbalance between the heat flux reaching the solid-liquid interface from bulk liquid (F_1) and the heat flux that is entering the cored wire (F_2). F_1 and F_2 can be represented as:

$$F_1 = h(T_b - T_m)$$

(43.1)

$$F_2 = \frac{K_P(T_m - T_p)}{R}$$

(43.2)

Where, h represents the heat transfer coefficient at the solid-liquid interface. K_p represents the thermal conductivity of the powder, T_p represent the temperature at the enter of powder bed. T_m and T_b represent the melting and bulk temperature of the liquid steel.

T_m for mild steel is say 1300°C. Initially Tp is 30°C. So the temperature difference for F_2 is very large compared to that of F_1, which is the bath superheat, say 100°C. Considering h, Kp are of same order, F_2 should be much higher than F_1 and (F_1-F_2) becomes negative, which means shortage of heat supply to the wire surface, giving rise to undercooling and solidification of steel shell.

The shell forms as long as flux difference is negative. With increase in time, F_2 will decrease as the powder gets preheated and the difference between F_1 and F_2 will decrease; thereafter it will become zero. At that stage the shell will get the maximum thickness; because beyond that time F_1 will exceed the F_2 and the difference become positive, meaning surplus heat at the interface that will melt the solidified shell. So with progress of time the solidified metal shell will completely melt and the casing will be exposed to the liquid bath. When the steel casing will attend attain it melting temperature it will start melting and finally preheated powder will be released. Since the bath superheat is higher, F_1 is higher and consequently shell thickness will be small and total time of shell formation and subsequent wire melting time will be less. As a result the powder will be preheated but might not melt and released as preheated solid powder as represented by model prediction in the figure 43.4.

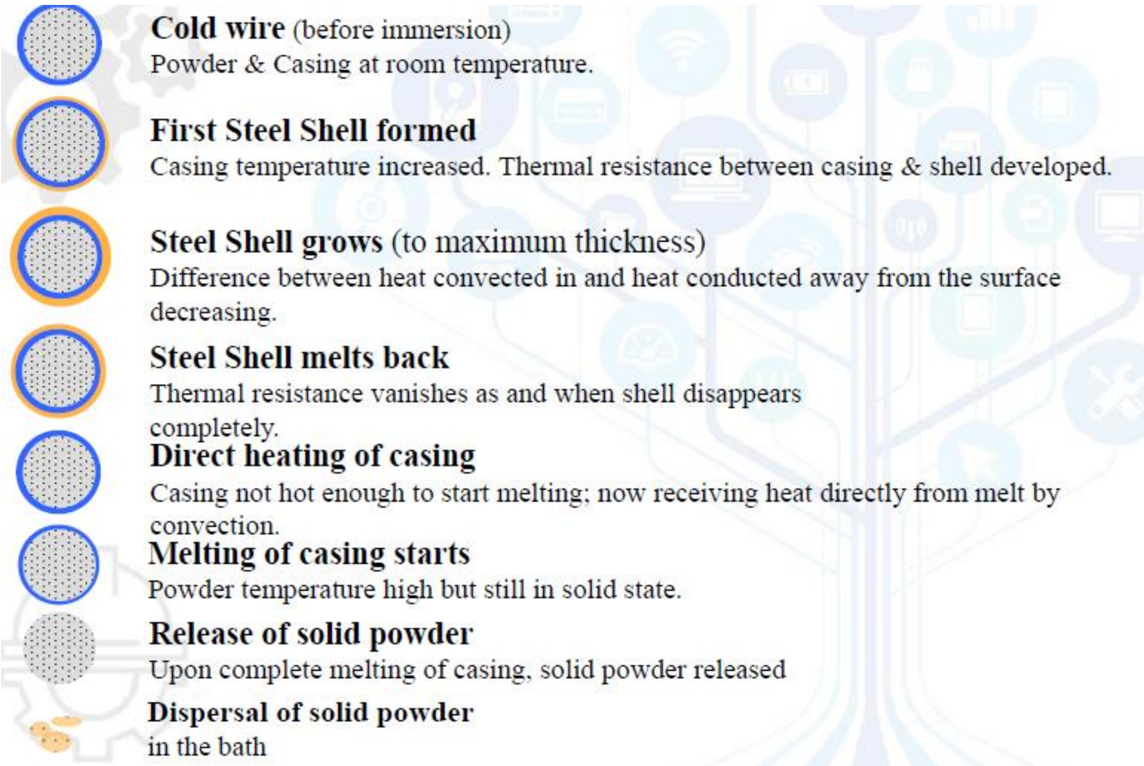

Figure 43.4: Sequence of wire melting for route 1 (High super heat and in absence of slag)

Second route of melting: Low superheat and in absence of slag: Similar sequence events follows as in the first route of melting (Figure 43.5). However, the shell thickness become higher than the first route of melting; because bath superheat and F_1 are lower that allows more time for F_1 to exceed F_2. Consequently total time of wire melting becomes higher and powder get preheated to molten state during prolong heating of the wire in the second route of melting.

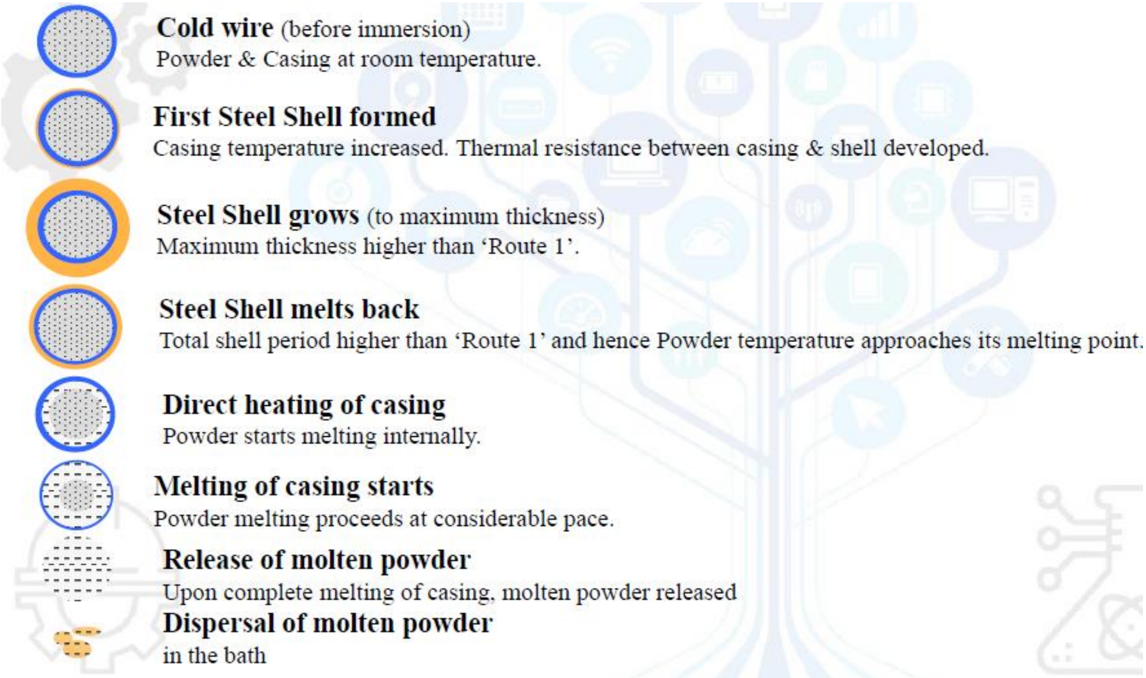

Figure 43.5: Sequence of wire melting during second route of melting (Low superheat & absence of slag)

Third route of melting: High superheat and in presence of slag: In this case as the wire first passes through an overlaying slag layer, a slag shell forms first followed by a steel shell and subsequently both the shells melt, casing melts, and powder is released (Figure 43.6). Since two shells form and melt, time required for melting is comparatively higher than route one but much less than route two because of higher bath superheat. As a result, powder is released as solid preheated powder as in the first case.

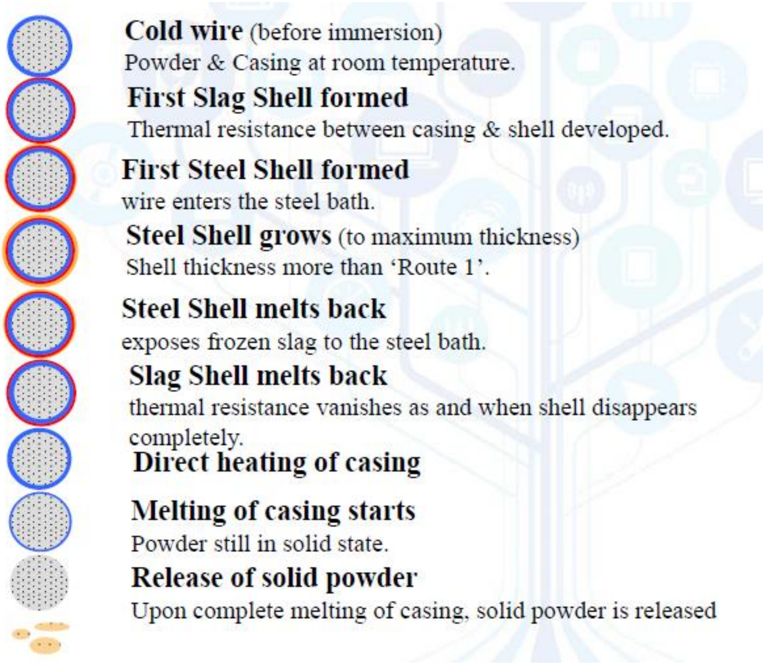

Figure 43.6: Sequence of wire melting for route 3 (high superheat and presence of slag)

Fourth route of melting: Low superheat and in presence of slag: This is the most interesting route of melting. In this case an especial phenomenon of secondary steel shell growth is observed. As overlaying slag is there, two shell forms and shell thickness becomes comparatively higher than case three due to lower bath superheat and lower F_1. During steel shell growth to maximum and subsequent melting, embedded slag shell gets preheated and before the steel shell completely melts back the slag shell melts. Once the slag shell melts, the contact resistance between slag-casing interface vanishes as the liquid slag completely wets the casing surface. Consequently, the flux towards the wire interior (F_2) increases suddenly, causing steel shell to grow again, called the secondary growth of steel shell. All these phenomena, increases the total melting time of the wire. Also the powder is released as liquid powder.

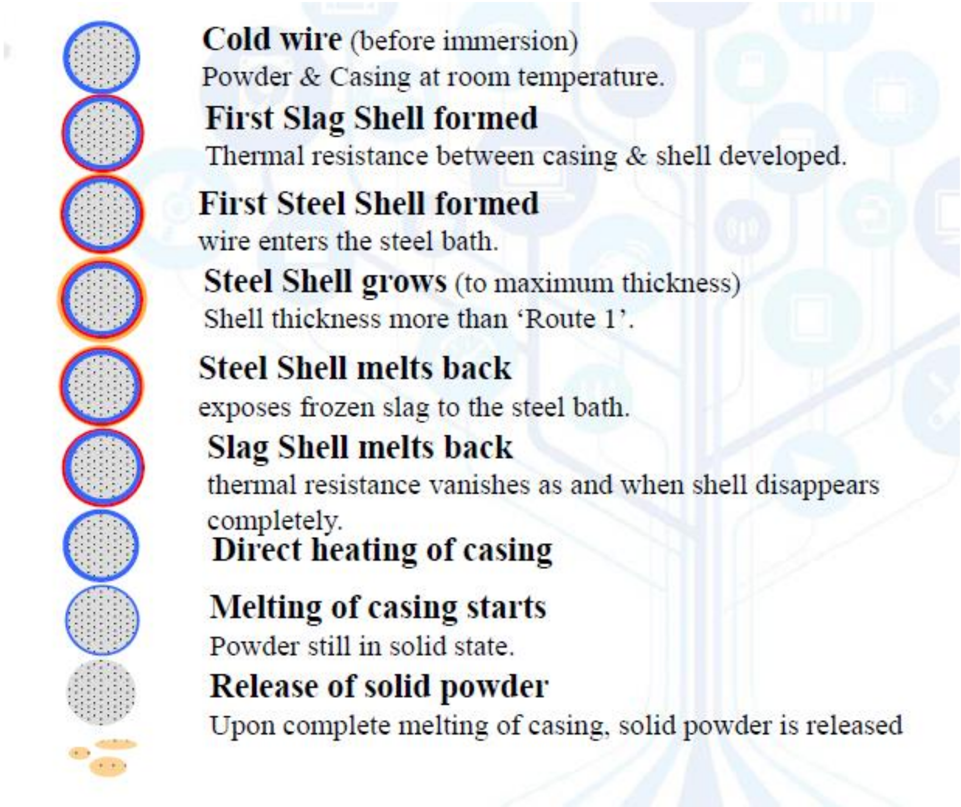

Figure 43.7: Sequence of wire melting for route 4 (low superheat and presence of slag)

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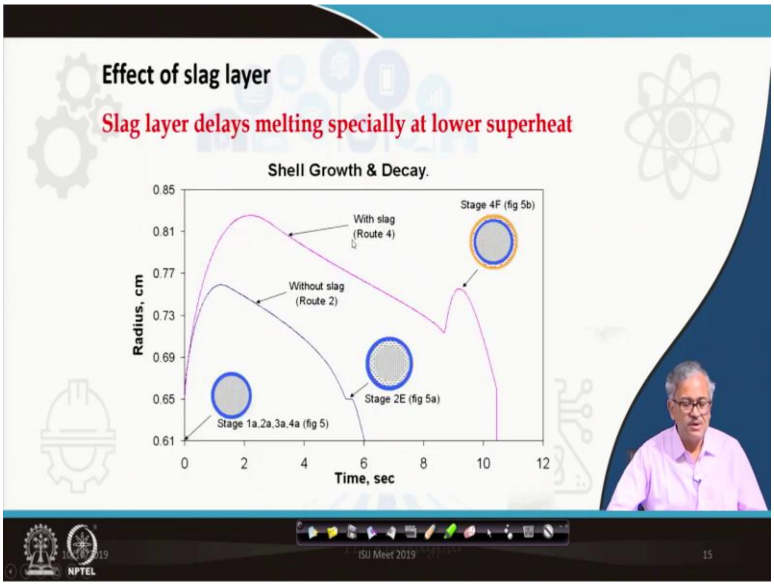

Effect of presence of slag on the wire melting:

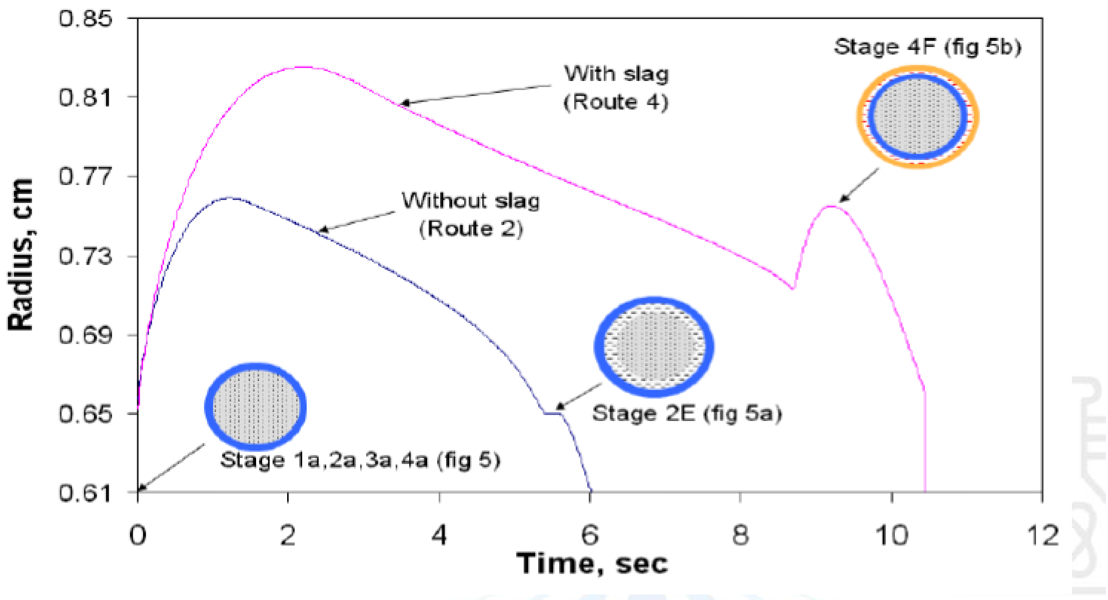

Figure 43.8: Variation of outer diameter of the wire against time for in presence and absence of slag

Figure 43.8 shows the effect of the presence of overlaying slag on the temporal evolution of external diameter of wire. It is seen external diameter increases (due to external shell growth), reaches maximum and then decreases (shell melting) and then it shows a plateau (indicating casing exposure before it melts) and then reduces to zero (complete wire melting). Both the case in presence and absence of overlaying slag are shown at low bath superheat. In presence of slag, secondary growth of steel shell is seen through a secondary hump; and no plateau indicating instantaneous melting of casing as it is exposed due to prolonged preheating. It is observed that total time of melting is increased in presence of slag (10.5 seconds, in comparison to 6 seconds in absence of slag). So presence of slag delays melting, especially in presence of overlaying slag.

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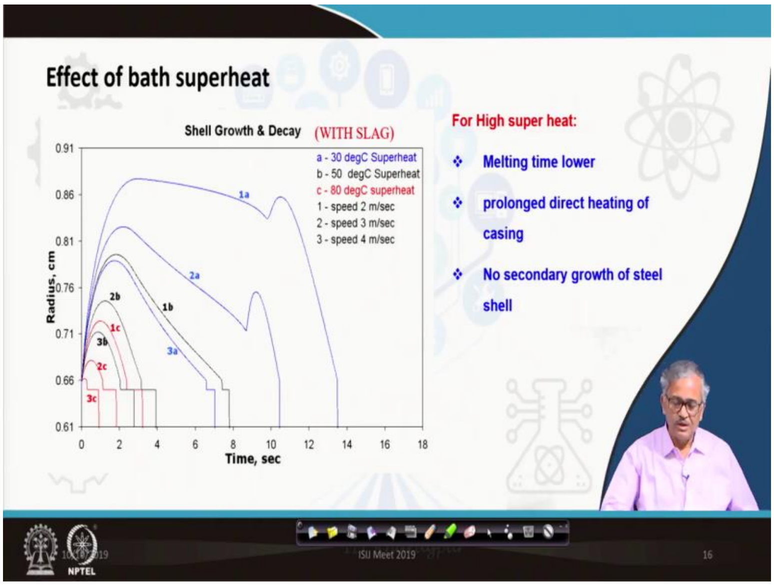

Figure 43.9 shows the effect of bath superheat and wire speed on the time of wire melting with overlaying slag.

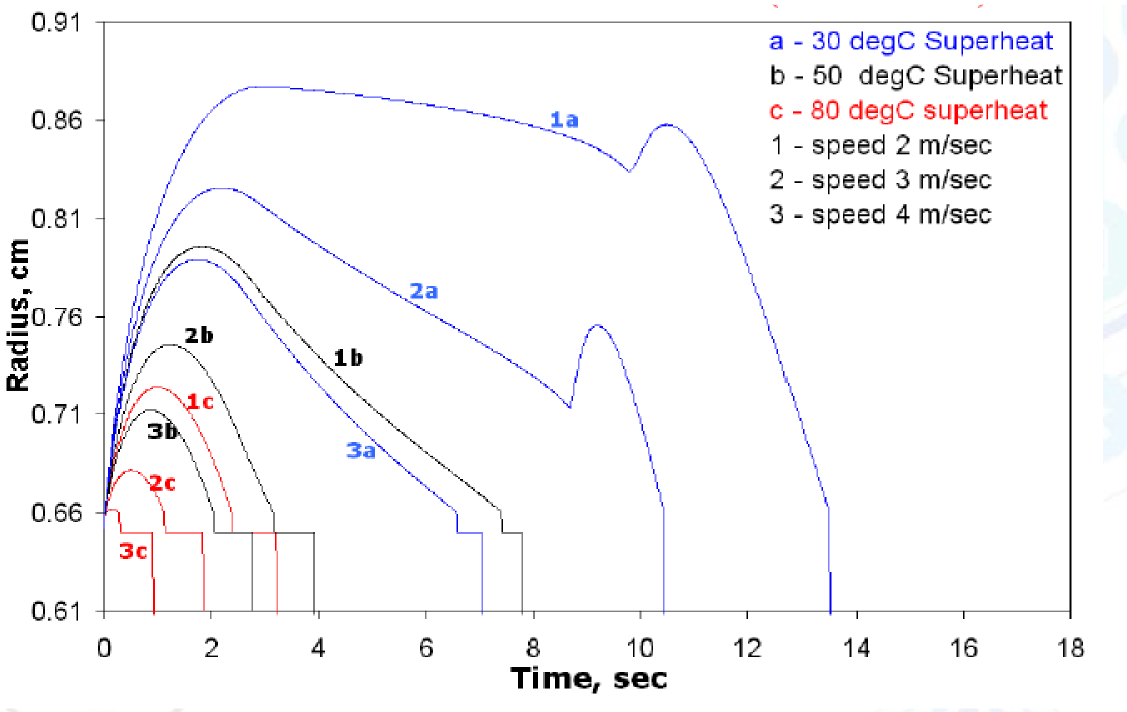

Figure 43.8: Variation of outer diameter of wire with time at different superheats and wire speed in presence of overlaying slag.

It is seen from Figure 43.8 that at higher superheat like 80ºC and 50ºC, no secondary growth of steel shell is observed and total time of melting are lower. At higher wire speed also the melting time decreases, because higher wire speed enhances the heat transfer across the wire. It may be observed that at maximum wire speed of 4m/sec and maximum bath superheat of 80^{o}C, the time of wire melting is minimum at 1 second only, compared to 13.8 seconds for the case with minimum wire speed at 1m/s and minimum bath superheat at 30^{o}C.

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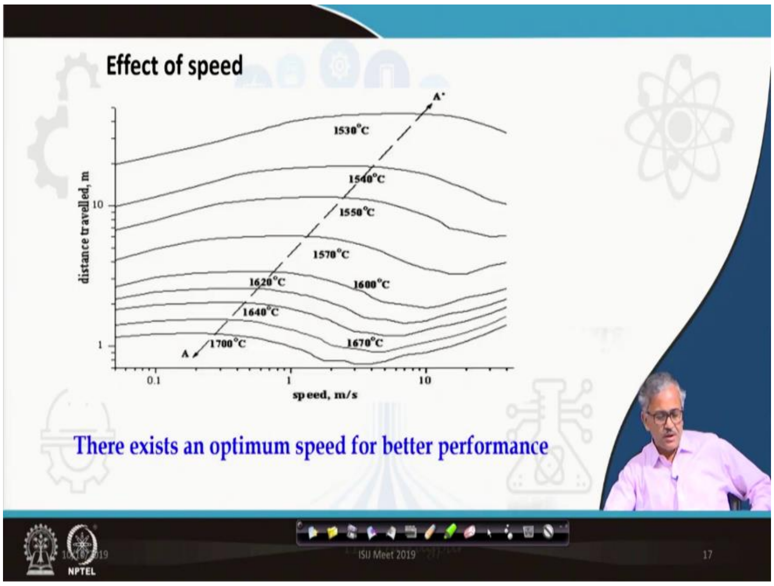

Effect of wire speed: The Figure 43.9 shows the effect of wire speed on the distance traversed by the wire before it melts in the liquid. Effect of wire speed this is a very unique phenomena. The general conviction is that at higher speed, wire will penetrate more. But actually another factor that comes into picture is that the heat transfer coefficient in the thermal boundary layer around the wire also increases with increase in wire velocity. This tries to melt the wire faster and lowers the distance traversed by the wire. So, these are two counteracting factor. Therefore, distance traversed by the wire sees an optimum value as the wire speed increases.

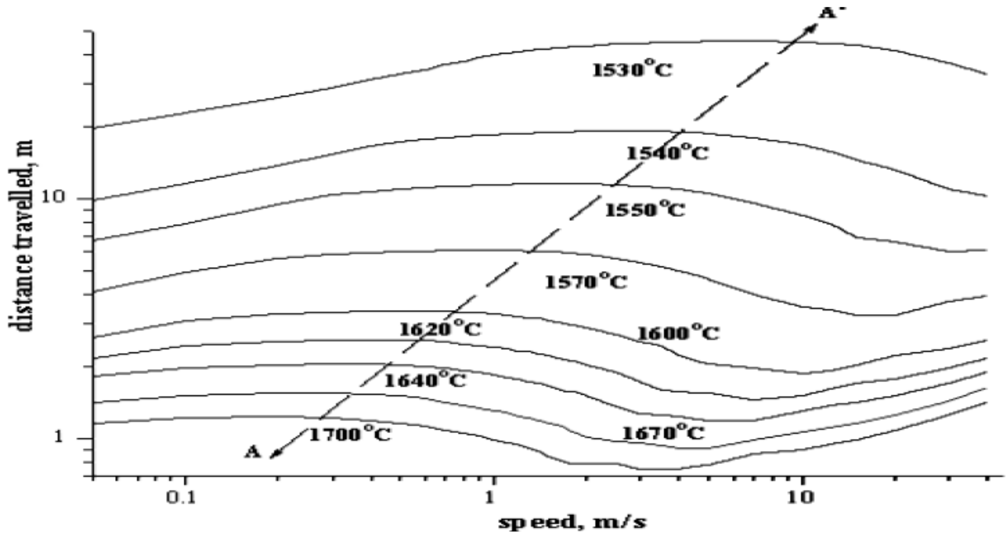

Figure 43.10: Distance traversed by wire as a function of wire speed.

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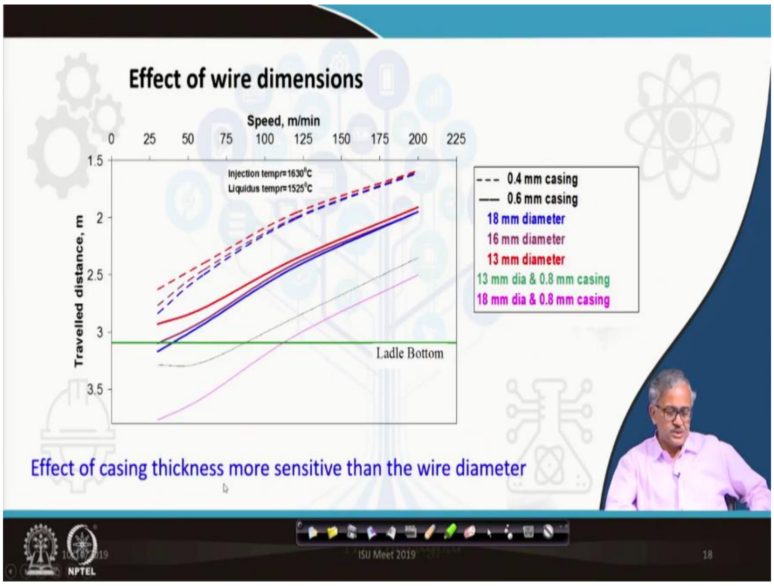

Effect of wire dimension:

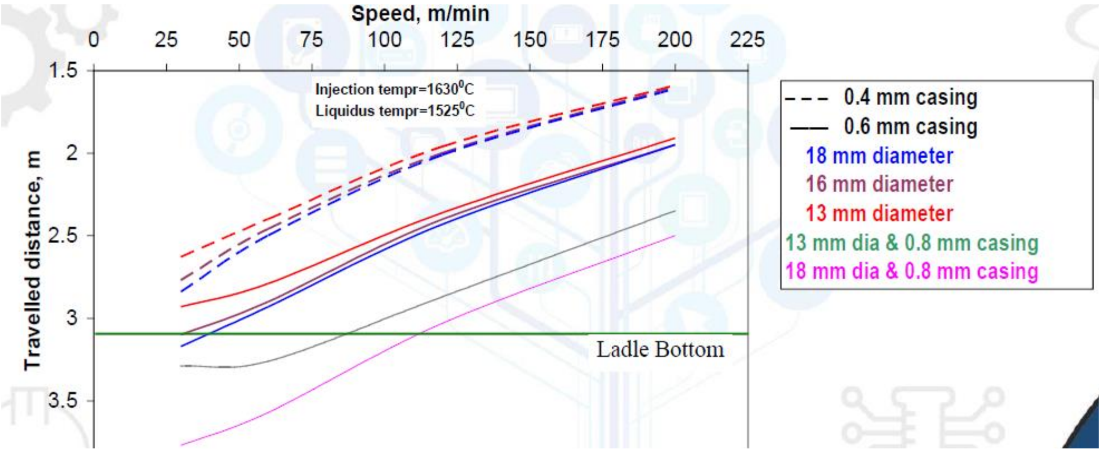

Figure 43.11: Effect of wire dimension on the evolution of the distance traversed by the wire with wire speed

The dotted line represent the wire with 0.4 thickness and solid line represents the wire with 0.6 mm casing thickness. Three different colours represent three different wire diameters (13, 16, 18mm). It is observed that major difference exists between the dotted and solid lines; while difference between solid lines of different colours are minimal. This trend is observed for wide range of wire speed. It means that casing thickness has more influence on distance traversed by the wire than that of wire diameter.

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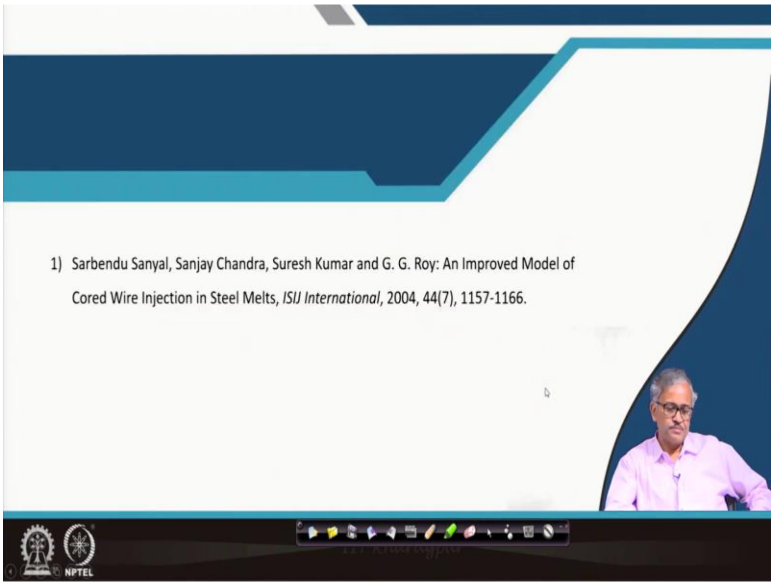

The above discussion is made on the published paper by Sarbendu Sanyal etal.,as mentioned in the slide above.

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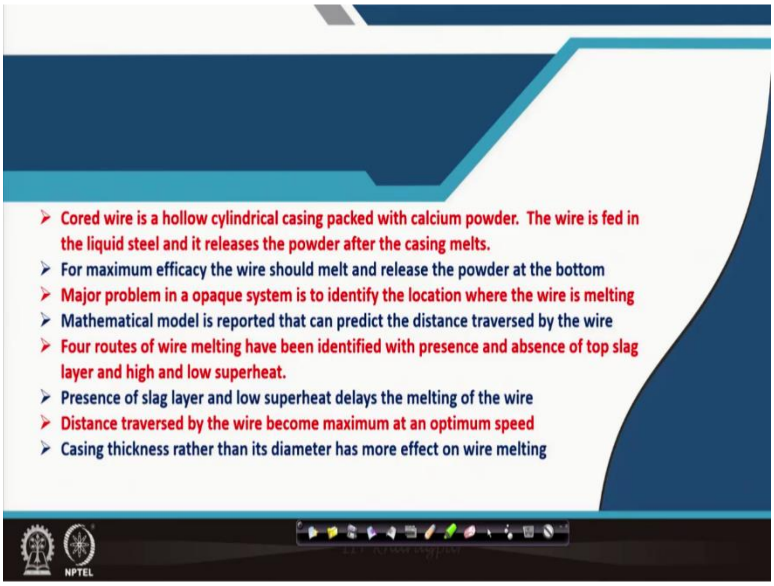

Conclusion: Cored wire injection is another yet more effective technique of submerged calcium powder injection. Cored wire is a hollow cylindrical casing packed with the calcium powder. For maximum efficacy, the wire should be inserted to the bottom of the ladle. Since in opaque steel melt wire could not be located, mathematical model is needed. So, a mathematical model is reported that has identified four routes of wire melting and is capable of predicting the distance traversed by the wire as a function of operating parameters.

The sequence of melting involves the formation of solidified shells (slag and metal shell) over the wire followed by their melting and then melting of casing and powder release. It has been found that in presence of overlaying slag and at low superheat, a unique phenomenon of secondary growth of steel shell occur that delays melting of wire. High superheat enhances the wire melting.

Distance traversed by the wire passes through an optimum with increase in wire velocity. Casing thickness has more influence on the distance traversed by the wire than that of wire diameter.