TECHNICAL SESSION NO. 8

(RAPPORTEUR'S SUMMARY)

R.M. Iyengar

Mr. Chairman, distinguished members of the Panel, distinguished delegates, ladies and gentlemen,

For the last three days, we have been looking at the modern developments in steelmaking and this afternoon you saw a very interesting film and a new theory on the solidification phenomenon. To distinguish this series of lectures from what you heard in the early morning, let me recall to you an old adage which was taught to me by an old steelmaker. He said: You make steel in furnaces, you make gold in ladles and scrap in moulds and that is what we are going to be talking about in the next few papers because the effect introduced in the moulds continues to remain through out the solid state, gets aggravated and causes loss in yield, loss in property and also loss in profits. So I have taken the papers in an order slightly different than what is given in the text here. The broad approach, I am taking here, is after having completed the refining reaction with respect to sulphur, phosphorus, removal of silicon, carbon, etc., the one element that remains behind in liquid steel which causes many problems is oxygen content and understanding the behaviour of this oxygen - what it does through inclusion, is the first paper by Dr. A. Ghosh and co-workers from I.I.T., Kanpur, on aspects of 'Thermodynamics of deoxidation of molten steel with manganese, silicon and aluminium'. The production of clean steel is intimately connected with the control of oxygen dissolved in the molten steel all the way from the finishing stage of the heat in the furnace to the mould which requires the adoption of a correct deoxidation practice. In order to exploit the available scientific knowledge, Dr. A. Ghosh and co-workers recommend that we take the following three steps: (1) Thermodynamics and kinetics data available be fully exploited to understand the various mechanisms, behaviour and equilibrium conditions with respect to oxygen; (2) The use of immersion oxygen sensors based on solid electrolyte to get more quantitative data on the said oxidation of metals and (3) To develop more reliable sampling and analysis methods for the determination of total oxygen. The authors also go on to say that the precision or the accuracy of the thermodynamic calculations depends strongly on the precision of the available thermodynamic data. In the paper, they have made two calculations: (i) with the simple binary aluminium - oxygen system using the available interaction co-efficient between the various solutes and in the calculation, they show that the difference among various sets of data available is around 15% for the deoxidation of aluminium as only at a higher level of aluminium and manganese there is a deviation in the calculations based on the various data. However, coming to the ternary system consisting of manganese, silicon and aluminium, the authors started from the activity of the solutes in the slag-base as given by the Japanese workers, developed a method of calculation and then predicted the oxygen level with respect to various solute levels. They have shown that with this approach, using the data available in the literature their calculations differed significantly from that of the Japanese workers from which they started their calculations. They also show that if they had used the interaction co-efficients as given by the Japanese then the calculations agree. What the authors have shown is that now we have a powerful mathematical way of calculating the activity of oxygen in steel where manganese, silicon and aluminium are present and the effort now is to screen-out the available thermodynamic data and find out the most reliable one and to use them. The authors have also found that carbon has a significant influence on the activity of oxygen and in the paper, they have shown this effect of carbon on dissolved oxygen.

The second paper, which now I would like to take, is 'The recent development in calcium alloy cored wire in steel production' and the reason I am taking this up is to link up the theoretical calculations with the practical application of the oxidation control. In this paper, the authors have said that the mechanisms of ladle injection are now well-established, as you all have heard early in the morning. However, there are certain limitations to the injection technique which I would bring again to your attention. The first is that this technique requires large tonnage applications to be economical. Secondly, the technique is more suitably adopted to 15-20 tonne and higher sizes of ladle and thirdly, it requires the use of basic lining and also relatively higher gas volume. In order to overcome these limitations, the authors have developed a calcium cored wire which appears to be a simple technique to control the inclusions. This development of cored wire was made (1) to use industrial powders of calcium alloys, (2) to suppress fumes and splashes that are produced during injection of powders, (3) to have a maximum content of silicon and calcium per meter of the wire and the most important to ensure a precise control of inclusions in the production of special steel as well as carbon steel cast in small billet castors to replace the aluminium wire in the mould. The flux cored wire is produced by a continuous process and is usually available in the sizes of 11 to 22 millimeters for injection into ladles and 5 to 6 mm of diameter for injection into small ladles and tundishes. The biggest spool till now contained 400 to 500 Kg. of powder, i.e. about 850 to 900 Kg. of wire. There are two machines to inject these powdered wires. For the 12 mm wire, the machine is made up of a wire reel, a capstan and an output guide. The feeding is by pushing down the wire when the machine is located above the ladle. For the 5 to 6 mm wire the machine is again made of a wire reel, wire feed rolls for pulling the wires and an output guide. The metallurgical results that were obtained in the industrial practice with this wire-feeding device consisted of inclusion control. Here the aim was to replace the two slag practice in the electric arc furnace with a single slag practice to eliminate the alumina stringers, to globularise sulphides in the range of 0.015 to 0.030% and to achieve a partial desulphurisation in the ladle. The results, that the authors have obtained, show that time saving in the electric arc furnace was 30 minutes in the refining period. They have obtained 30 to 40% desulphurisation in the ladle and most important, the control of inclusions, such as alumina inclusions were replaced by aluminates rich in calcium surrounded by manganese - calcium sulphides and also the rate of globularisation for sulphur was high and they have obtained good isotropy in the steel properties. The second application that they made was in continuous casting and here the ladle addition of silicon-calcium cored wire enabled them to cast aluminium killed steel with aluminium level greater than 0.015%. They also were able to use a single slag practice with wire addition of 1.5 Kg/ton. They were able to cast 103 mm core section billets with open nozzle having a diameter of 14 mm and were able to completely eliminate the aluminium wire addition in the mould. The results show that they got excellent fluidity of the steel even with this high aluminium level. Thirdly, there was complete disappearance of sub-surface blow-holes and pin-holes. Another application, the authors made, was in the tundishes. Here they were able to improve the castability and cleanliness of steel cast with submerged shrouded nozzles with the wire addition of 1 Kg/tonne which completely got rid of the clogging of nozzles.

Having seen the problems of oxygen level in the steel and how one can go about controlling it, the next topic that I would like to take up is a very vital topic called 'the reoxidation of steel' and here the problem of steelmakers starts. The paper on 'Reoxidation of Steel' was given by A. McLean and Sommerville of Toronto University. Reoxidation is the result of oxygen pick up by the de-oxidised steel either from atmospheric oxygen or - and this is very important - by the chemical erosion of siliceous refractories. Reoxidation products are usually very much larger than the de-oxidation products and tend to be richer in weaker oxide forming elements. Generally they are about a 100 microns in diameter or larger. Reoxidation by erosion of ladles, nozzles, stopper rods and refractories is a very serious source of inclusion in steel. The inclusions are created just prior to the solidification when the possibilities of their escaping is minimal. Detailed study of air entrapment using water-modelling techniques were carried out by the authors. The variables that they studied were nozzle diameter, height of fall, discharge rate, turbulence level of the steel and the effect of each of these variables on the jet distintegration. The authors have concluded that turbulence or surface roughness is the most important parameter. While the jet becomes turbulent, the indication on the surface at the point of impact becomes highly irregular in form due to rough jet periphery. Ambient air is entrapped by the surface. This air is then carried as bubbles by the flow of the jet within the pool and distributed throughout the submerged aerated region. The distribution of air in the aerated region is highly dependent on the turbulence level of the impacting jet. The authors experimented to investigate factors affecting the pickup of oxygen, nitrogen and hydrogen from air of controlled humidity. The molten steel droplets in contact with air for only 0.25 seconds were able to pickup an oxygen level of as high as 700 ppm, the nitrogen absorption rate was very much lower than the absorption of oxygen. As sulphur content in the steel decreased, the nitrogen absorption rate also increased and this is a very important surface active phenomenon which the authors have further stressed. Hydrogen absorption is also observed and they found that when very clean steels are produced particularly for the thick plate applications, there is a tendency of hydrogen pickup and damage due to hydrogen flaking. The chemical reactions between the stream and the atmosphere which results, as I mentioned, in the absorption of oxygen, nitrogen and hydrogen, requires certain protective measures. These oxidation reactions contribute to the formation of iron oxide in the slag layer even when the stream is led from furnace to ladle. The interaction between this high iron oxide bearing slag and the refractory will produce an iron-oxide rich phase which will be transferred to the steel in the subsequent heat. This is a phenomenon, which I think, the author has brought out very strongly in the paper. The first re-oxidation product consists of large alumina grains and with continued re-oxidation the inclusion-forms contain decreasing amount of aluminium and increasing amount of manganese and silicon. The factors which influence the absorption of these gases, such as nitrogen, can be controlled by working on a higher sulphur level as it was shown that sulphur is a surface-active element and retards the reaction of nitrogen with the stream and, therefore, one can minimise nitrogen pick-up. Control and improvement of stream stability can be achieved in tundishes or pouring boxes by the use of castellated nozzles. Method of stream compaction reduces the extent of disintegration and hence the surface area of the steel exposed to the air. Stream protection is by shielding the stream from atmosphere either physically or by the use of gaseous shrouds. In case of argon-shrouding, attention should be paid to the impact zone more than the stream itself. The authors have shown that it is the impact zone that causes more re-oxidation than the steam itself. There is benefit with respect to alloy recovery, product qualities, metal yield and energy efficiency when appropriate measures are taken to improve pouring stream characteristics and to eliminate entrainment.

Moving from re-oxidation now we proceed along chronology of steelmaking towards the mould. The paper by Mr. Bloodworth and Mr. Harvey - 'Hot tops for steel ingots - their developments as influenced by solidification patterns begins by saying that the shrinkage of steel during solidification is the reason why hot-tops are required. They have shown that the losses from the melt can be considered as three vectors - one in the lateral direction towards the mould wall - one on the top of the mould towards the atmosphere and one heat vector into the body of the melt. The authors state that the solidification profile will be normal to the resultant of these three vectors. So, by making the vector vertical as much as possible, the solidification profile can be made as much horizontal as possible. This is the principle on which the authors have developed their hot-topping practice. They have then gone through the various developments which have taken place, beginning with the use of refractories as early as 1950 and then changing over to sideliners. By reducing the heat losses through the sideliners and the top cover they were able to obtain better shrinkage characteristics. The most early feeder heads either extended the mould by glazing on a heavy frame lined with refractory base or raised onto the top of the mould. Sideliners with low density, which meant reduced heat demand and improved insulation, began to be used in the late 50s. The heat loss from the top of the ingots, which cannot be covered, have been estimated to be 25 to 30% of the total heat loss. In the earliest hot topping they used covering with a layer of vermiculite. The use of antipiping compound began in the early 50s. These are powders - the compositions possessing an exothermic material or component which by rapidly raising the product's temperature ensures low initial heat demand or chilling effect. On cessation of the exothermic reaction, the insulating residue remains and provides further barrier to heat-transfer. The first stage APC compounds were low-efficiency materials whereas the second generation of anti-piping compounds incorporated spinel forming ingradients. These materials were still dense. Third generation of these products emerged with light weight fillers into the composition and an improvement in insulation performance. These were overtaken by expanding products during the exothermic reaction to give a light weight residue better in insulation performance than any of the previous generation APC compounds. There is certain inter-dependence between the development of side-liners and the hot-top and to understand these relationships and to design a better hot-top, the authors have developed in their laboratory an instrument capable of providing information on the comparative thermal performance of side-liners and top-cover products. The instrument comprises an insulated furnace, heated by electrical elements and a silicon-carbide test plate is fitted in the upper surface to accept the specimens. The test plate is maintained at a constant temperature. The instrument meters the electric inputs required to maintain this constant temperature and this input electric power is plotted continuously during the test. This instrument can be used as a comparator giving information on the relative thermal efficiency of the hot topping side-liners or hot-topping compounds. Specifically it can evaluate the chilling effect of the sample, the insulation properties of the sample, the duration and the nature of exothermic reaction. Continuing their efforts to understand what happens during the last stages of solidification, the authors have developed a computer-aided mathematical model to understand the behaviour of ingot solidification. This model predicts mathematically the optimum feeder head shape and volume for any given ingot and it also predicts the ingot feed and primary segregation profile for a given heading system. In this system account is taken of the thermal efficiency of the hot-top material, the ingot configuration, steel quality and casting parameters. A typical comparison between the predicted and measured feed profile shows the accuracy of the model that they have developed. The more recent developments in this area are the super-light weight insulators of density of half that of conventional insulators. They have also developed superlight weight exothermic products with a new super-light weight product. The advantage of these two products is that the heat capacity is lower and the exothermic reaction produces a super-light weight strong residue with insulating properties considerably better than those of conventional side liners.

Coming to the last two papers which have a direct bearing on the key-note address, one is by Prof. Beach and Dr. Davies on "Current Researches into fundamental aspects of ingot structure". Prof. Beach states that the irregularities such as ripples and laps on the surface of cast ingots are due to the various conditions during solidification. Experimental ingots were produced using an up-hill teeming technique. The mould consisted of the faces in contact with the melt machined to different roughness levels - the first one was grooved, the second one was with vertical lines, the third one was with horizontal lines and the fourth one was ground to good finish. The results from these ingot surface observations show that the face (a) reproduces the lines and no ripples are produced when the surface is rough. In the case of (b) & (c), the lines were not produced but ripples were found and these ripples were most severe in the corners. In case of (d) with a ground finish surface the most severe rippling was observed and this was more so with water cooler copper. They also found that carbon black reduced rippling during teeming. They also observed that the severity of the surface rippling decreased as the carbon content increased. The melt superheat also decreased the tendency to ripple and finally the authors concluded that the presence of a shrinkage force is not an essential pre-requisite for the ripple formation.

The authors then have gone into a mathematical model to characterise and determine the severity of surface features of the ripple. They found that the skin thickness decreased as the superheat was increased. Rough surfaces produced less freezing over the meniscus and consequently fewer and shallower ripples were obtained. Freezing over the meniscus was at maximum at about 0.2% carbon. The meniscus freezing mechanism for the production of surface ripples and laps showed that shrinkage was not necessary. The model was able to predict most of the observations that they have made with their experiments. They have also said that the surface conditions can influence the formation of blow-holes. The gas content of the melt provides the driving force for the growth of the blow-holes. They found that the total gas content is more important than just the dissolved oxygen level and in order to find the total gas content the authors have developed a technique which was first used in the aluminium industry. This technique consists of pouring a sample of liquid steel into a crucible at a constant temperature and then evacuating the chamber. When the first bubble appears on the surface the pressure at the instant is observed. Gas content is then determined directly after suitable calibration. The experimental arrangement consists of an alumina crucible surrounded by a graphite placed into a larger alumina crucible. The entire assembly is put into an induction coil under vacuum. The contribution of nitrogen and hydrogen on blow-hole formation can be assessed by measuring the oxygen flow.

The third topic that the authors have covered is the formation of macrosegregates during solidification. Macrosegregates generally and channel segregates in particular are primarily the results of inter-dendritic fluid flow during solidification that Prof. Onho described earlier. The principal driving force for such fluid flow is the gravity acting on thermal density gradients in the musy zone. The experimental method allowed direct observation to be made on the solidification of a small sample of metal. The X-ray connected to a video tape-recorder allowed real time recordings of the experiment. These were then replayed and still photographs taken at regular time intervals. The authors concluded that the major channel segregates originate at irregularities on the growth front resulting in the entrapment of a significant pocket of liquid by the advancing front. Macro-segregation can be significantly affected by relatively small changes in solidification conditions. Only a few should grow and remain moving about in an adjusting shape during solidification. The channel formation can be controlled by increasing the rate to control the chemical composition which alters the composition of the interdentritic liquid in such a way that the decrease in density, which occurs during freezing, is minimized.

The last paper again on solidification is from Dr. Mukherjee, Mr. Maheswari and Dr. Irani on "Inclusion Distribution in Ingots - A Guide to Segregation mechanism". The authors contend that size, shape and distribution of inclusions and their melting points can give an indication of the mode of solidification and the mechanism of segregation. They have sectioned a large ingot and they have found that the negative segregation at the bottom end of the ingot was coincidental with the bottom cone of oxide inclusions. The oxide inclusions at the bottom end which formed the bottom cone were basically high melting point silicates with large volume of corundum sector precipitated in the central region of the inclusions. The volume fraction of the corundum in these critical areas was as high as - 67%. The sulphides in this region were basically of type 1 - although occasionally type 2 inclusions were also observed. The type 1 sulphides had manganese silicate in the centre with 43% MnO and 57% SiO_2. The presence of sulphide type 1 indicates concentration of dissolved oxygen in the liquid during the precipitation of the inclusions. They also observed first traces of alumina either present independently or along with sulphide inclusions. The melting point of silicates in this region, the authors contend, will be definitely lower. The sulphides at the top were mainly of type 3 with occasional occurrence of type 2. All the inclusions were present in the inter-dendritic region at the top end of the ingot, while at the bottom end of the ingot a large volume of oxide inclusions was present within the dendrite. Presence of type 3 sulphides indicate low concentration of oxygen in the liquid steel from which the sulphides precipitated on the top of the ingots. The inter-dendritic fluid and segregated liquid at the top end gets enriched in carbon, sulphur, phosphorus and denuded in oxygen. At the bottom of the ingots, the oxygen content was comparatively high leading to the precipitation of type 1 sulphides. The high melting point inclusions are present in the liquid at the end of pouring. This is the contention of the authors. The equi-axed grains entrap such inclusions either inside them or in between the dendrites. The equi-axed grains drop to the bottom of the ingots giving rise to the negative segregation and the cone of inclusion. This covers the six papers that are presented for this panel discussion.

Now just to conclude this Session here - these are very wide spectrum of papers, beginning with oxidation, reoxidation, hot - topping techniques and ending up with the various types of defects. The difference that I would like to point out in this particular area of steel-making which I still consider as a black magic is that lot of experimental and theoretical analysis is necessary to increase the knowledge. Until better and more information is available, we will not be able to control the fine quality of steel that can be made either with bottom-stirring or with vacuum metallurgy or powder injection. So with this, I turn over the Session to the Chairman.