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PROBLEMS OF QUALITY IN STEEL PRODUCTION

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Summary

Quality of steel is not a precisely definable attribute since it measures fitness for purpose in comparison with competing materials. It is, therefore, possible only to discuss the difficulties in controlling, during steelmaking, those aspects that determine the suitability of a batch of steel for its end use.

The paper discusses the problems of ensuring correct composition, the origin and avoidance of contamination by undesirable elements, the occurrence and overcoming of segregation, the sources of exogenous and indigenous inclusions and the ingot defects that can arise as a result of casting conditions.

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1. Before discussing the problems of quality that arise in steel production, it is probably as well to state that the word "quality" in this connexion has no precise meaning. It is impossible to say that one sample of steel is of better quality than another unless we specify the use to which it is to be put. In fact, quality means merely suitability for purpose at a cost that is economic in comparison with other materials. Thus we could say that Thomas steel was not of good enough quality for the making of engine crankshafts yet it is a good material for the machining of spark plug bodies. For this latter purpose, the steel is of high quality.

2. We can, therefore, discuss only those problems that occur in steel-making in the control of composition, undesirable elements, homogeneity, non-metallic inclusions and ingot defects, all or any of which may affect the mechanical properties, fabricating characteristics, and service performance. The control may be exercised during the steelmaking process itself, during the transfer from the furnace to the casting bay, during teeming, or finally during solidification to ingots.

3. By <u>composition</u>, reference is intended to the proportions of carbon, manganese, silicon, chromium, nickel, etc., that have to be held within specified limits in order that the resulting finished product may have the mechanical properties and service performance appropriate to the end use envisaged. Such elements as sulphur, phosphorus, nitrogen and hydrogen are dealt with later.

4. As far as composition is concerned, all existing methods of steelmaking, open-hearth, electric arc and converter, are capable of making almost any steel, though practically and economically some are far less suitable than others. This does not, of course, mean that even with the most suitable there are no problems in making a steel to a desired composition; this is witnessed by the number of "off-heats" that arise in any melting shop. Although such "off-heats" may be diverted to other uses, it is more likely that they will have to be down-graded and sold at a lower price or, worst of all, scrapped and used for re-melting.

5. Steelmaking is a process by which undesirable constituents of the charge are removed by oxidation into a slag. Unfortunately, the desirable elements are not immune to this oxidation process and we cannot, therefore, choose our starting materials correctly, remove what is not wanted and then tap the furnace. The extent to which the various elements are removed is variable. Thus silicon is oxidized almost

completely under any oxidizing conditions, whereas nickel and molybdenum are not affected to any appreciable extent. Manganese, chromium and iron itself are partly oxidized and carbon is removed, as carbon monoxide, to an extent depending on how far the oxidation is carried. The slagging of any element is a function also of the composition of the slag and the temperature of the bath. But the slag composition and bath temperature change as refining proceeds and it is extremely difficult to predict the extent to which all the simultaneous oxidation reactions will have proceeded at any time. A decision has to be made whether (a) to leave out some element from the charge and add it when the refining reactions have been completed, (b) to accept that it will be oxidized and attempt, at a cost, to reduce it back from the slag at the end of the process, or (c) to remove the material with the slag and add the necessary amounts as virgin alloys. This decision will be decided by the cost of the element as alloy or in the raw material, or by its mode of occurrence. Thus if stainless steel is being made from mild steel scrap, we should adopt the first method. If stainless steel scrap were available, the second method would be used. Manganese and silicon are allowed to oxidize into the slag and any residual amounts are made up to the specified level by addition of ferro-manganese and ferro-silicon, i.e. the third method is used.

6. How does the steelmaker cope with these problems so as to arrive at a given composition? Firstly, he must aim at consistency in raw materials and methods of working, allied with careful observation of the changes in composition that occur during operation. This will enable him to build up a knowledge of how the various reactions proceed and of the extent to which different elements have been removed by the end of the process, judged for example by carbon content or final temperature. He will also be able to observe the effect of unplanned variations in raw materials or operation and thus decide whether these variations are desirable and to be regarded as good practice or deleterious and to be avoided in future. Deliberately planned variations may also be introduced in an effort to discover a better method of working or to use a cheaper raw material. These will be assessed in the same way as chance variations but should be planned in the light of knowledge of the physical chemistry of slag-metal systems. This kind of experience has already been largely acquired in developed steelmaking countries and can, to some extent, be taught to newcomers to steelmaking, but it is best and most quickly gained during actual furnace operation.

7. Nevertheless, there arise occasions when even this knowledge is not adequate, particularly when variations arise over which the steelmaker has insufficient or no control. Thus, for example, when aiming at a given carbon content in the open-hearth process, the melter will have followed the carbon drop by periodic sampling and analysis. But sampling and analysis take time and the melter must prepare to tap on the assumption that the carbon content of several minutes previously will have dropped to the required value by the time the tap-hole has been opened. The problem is aggravated by the fact that opening the tap-hole may take a variable length of time and that the carbon added, as impurity in the ferro-alloys, will contribute in an unknown way to the final carbon in the ladle.

8. More rapid methods of analysis will minimize these difficulties because the composition can be known almost at the instant of tapping. Such rapid methods are now available and it is possible, with relatively untrained personnel, to obtain on the shop floor results of carbon analysis in less than four minutes. If the results of carbon analysis are plotted against time, the melter is in a far better position to predict the changes that will occur between last analysis and tap-hole opening.

9. The problem is different when the bath is "blocked" by the addition of reducing agents, in the electric arc furnace or converter where the heat can be tapped quickly, but even so rapid analysis will assist in closer control.

10. With top-blown converters, the problem assumes a different aspect. Repeated sampling is not possible but by careful adherence to operating schedules, the amount of oxygen to be blown to reduce a carbon content, determined at an intermediate turn-down, to a desired final figure can be predicted.

11. Control of manganese presents difficulties after the steel has been made. During the later stages of refining there is not much change in manganese content of the melt. Ferro-manganese has to be added in the furnace or the ladle. If it is added in the furnace, the oxidizing conditions will tend to remove it into the slag and the longer it takes to tap the furnace the lower will the manganese content be. One successful method of overcoming this is to analyse the slag for iron, add an appropriate amount of ferro-manganese to the furnace and a variable amount to the ladle after it is half-full. Working charts showing the relationship between slag iron, time to ladle half-full and the amounts of ferro-manganese to be added to give a desired manganese content, have been worked out by statistical examination of past records and are convenient for use on the shop floor. No technique is, however, fully reliable because the final manganese content will vary with the extent to which the

steel is churned up with the oxidizing slag during tapping. The solution of this dilemma must be in obtaining constant tapping conditions and holding back slag until late in the tapping; devices such as jet tappers can help in this respect.

12. One problem common to all procedures in which additions are made to the otherwise finished steel is that the precise weight of the steel in the furnace or ladle is not known. It is only by careful weighing of input and adopting constant operating conditions that the former can be reliably estimated and only by ensuring that all the steel in the furnace or other vessel is tapped that this estimate can be used to calculate ladle additions.

13. <u>Undesirable Elements</u> The undesirable elements may be divided into two classes. There are those impurities, like sulphur, phosphorus, nitrogen and hydrogen, that arise from any normal raw materials or from contamination during processing and those, known as residual or tramp elements, like copper, nickel, cobalt, arsenic, antimony, tungsten, molybdenum, lead and tin, that arise in unknown amounts from commercial scrap. The elements in the first class are generally regarded as deleterious to performance and steel specifications usually lay down maximum limits. The members of the latter group are generally not so specified but if present in more than minimal amounts may render the steel unfit for certain purposes. It must not be overlooked that some of these "undesirable" elements are often beneficial. Thus sulphur and lead may be deliberately added to improve machinability, copper and phosphorus added to improve corrosion resistance or to impart extra stiffness to sheet.

14. <u>Sulphur</u> is found in practically all the raw materials used for steelmaking; pig iron, scrap, fuel oil and even lime. From whichever source it arises, when the charge is molten the sulphur burdon in the steelmaking unit will be distributed between the slag and the metal. The steelmaker must then endeavour to improve this distribution. Although it is desired to keep this paper as simple as possible it is necessary to consider the factors that control the distribution. The chemical reaction involved can be written as:

Sulphur (in metal) + Basic Oxide (in slag)= Sulphide (in slag) + Oxygen (in metal).

This shows that a first requisite for low sulphur in steel is low sulphur burden. Every effort should be made to obtain pig iron and scrap of the lowest sulphur content, even if this means that the hot metal from the blast furnace has to be treated with soda ash or injected lime. High sulphur fuel oil should also be avoided for it has been shown that 25% of the sulphur contained in the oil burned during melting down in an open-hearth furnace can be absorbed by the charge. The second requisite is a high concentration of basic oxide in the slag. Care should be taken that, in calculating charge and feed materials, sufficient lime is employed to give a 2:1 to 3:1 lime: acids ratio. The final factor is the concentration of oxygen in the metal. Here it is that the problem really occurs. In steel refining by oxidation, it is necessary to establish conditions for the removal of phosphorus and carbon that inevitably lead to oxidation of the metal and in spite of all the precautions to maintain a high basicity, the partition coefficient between slag and metal never reaches a high value. It is under these circumstances that the careful choice or treatment of raw materials and the use of low sulphur fuel are of advantage. On the other hand, converter steelmaking does not use fuel oil, so this source of contamination is avoided. Nevertheless, since it is essentially an oxidizing process, it is not capable of very much sulphur removal, though there is evidence that it is superior to the open-hearth in that some of the sulphur introduced with the charge is burned away in the very oxidizing conditions of top-blowing. For very low sulphur content in steel, the electric arc furnace is superior. There is no contamination from fuel, the best type of slag can be produced and by adding reducing agents and closing the furnace doors the concentration of oxygen in the steel may be brought to a very low level. In this way, sulphur contents of 0.01 and below can be achieved.

11. Phosphorus, unless required at very low level, is generally not troublesome provided the slag is sufficiently basic and oxidizing. When, however, high phosphorus iron is used as the charge, the slag-metal distribution obtainable without excessive oxidation of iron (and thus unacceptable loss of yield) is not sufficiently high to produce phosphorus contents low enough for some applications. It is necessary, therefore, either to avoid high phosphorus charges (as is the case in fixed open-hearth furnaces) or to work a multi-slag process, in which the major proportion of the phosphorus is caused to pass into a slag which is then removed. The formation of a new slag and prolonged refining will then reduce the phosphorus down to the desired level. This is the process used in tilting open-hearth furnaces and LD-AC and OLP vessels.

16. While some <u>nitrogen</u> is contained in pig iron and scrap, the boil during carbon removal is sufficient to lower it to acceptable values. However, if the purging action of the boil subsides, contact with nitrogenous gases will cause the content to rise again, often to undesirable levels. For this reason, air-blown Thomas steel is higher in nitrogen than open-hearth steel, and steel finished under reducing conditions in the electric arc furnace, particularly if the reducing period is prolonged, is also high in nitrogen. For very low nitrogen steels it is advisable to avoid contact altogether with nitrogen or air and to use processes like steam-oxygen or carbon dioxide-oxygen bottom-blowing or oxygen top-blowing.

17. <u>Hydrogen</u> enters steel when it comes in contact with the gas or with substances containing it. Hydrogen may also be transferred to the metal by a slag which, in turn, absorbs it from the water vapour in the air. Fortunately, the purging action of the carbon boil will generally overcome any transfer from the slag but once the boil has ended conditions are right for hydrogen pick-up. Any additions made to the furnace should be well dried and the steel should not be tapped into damp ladle or teemed into moulds that are damp or have improperly dried hot tops. Even in spite of all these counter measures, hydrogen contents in the steel may be excessive and recourse may be needed to auxiliary treatment. Of these, inert gas flushing is easily carried out and can be quite effective. Undoubtedly, vacuum treatment in some form is the most effective and stream degassing into the mould or vacuum treatment of the contents of the ladle are now becoming routine operations for hydrogen removal.

18. <u>The residual or tramp elements</u> entering the steelmaking furnace in the pig iron or scrap can be divided into two groups. There are those that are fully oxidized during refining (and do not present any real problems) and those that are little affected and remain dissolved in the steel. The elements mentioned in paragraph 14 belong to this group. Since they are not removed in steelmaking there is no remedy but to choose raw materials carefully when low-residual steel is needed. The tramp element content of pig iron is generally low, though if scrap is used in the blast furnace some may be present. Steel made from pig iron will also be low in residuals and works' scrap is therefore a suitable charge material. Purchased scrap, however, is a potent source of tramp elements because even with the best arrangements it is not possible to guarantee complete separation from non-ferrous materials. For low residual contents,

pig iron and works' own scrap should be employed. Prompt analysis for tramp elements at melt out should also be performed so that if any are too high the heat may be diverted to a less critical order. By a like token, if a heat made from purchased scrap should prove to be low in residuals, it can be diverted to a suitable application.

19. Homogeneity In order to ensure that a batch of steel is consistently of the desired quality, every billet, bar or sheet rolled from it should have the same composition, within the limits laid down by the relevant specification. Although there may be variations of composition (because of stratification) in the furnace, it may be assumed that the turbulence at tapping will result in a homogeneous liquid charge in the ladle.

20. During the cooling that takes place in the ingot mould, the steel will, of course, be subject to the laws governing the solidification of solutions. Segregation will occur as a result of phenomena which cause the first solid to separate to be of a higher purity than the liquid and for the various components of the steel having the lowest freezing points to concentrate in the parts of the ingot last to solidify. The result is that certain regions contain more and others less of a given element than the average composition of the ingot as a whole. To a first approximation, it may be said that solidification takes place from the sides and bottom of the ingot so that major segregation occurs near the top of the ingot.

21. Carbon, sulphur and phosphorus are the elements most prone to segregation and though the steel can be made sufficiently low in sulphur and phosphorus that even if segregation does take place, the concentration of these elements is nowhere above specification limits, carbon has generally to be held within certain narrow ranges and measures have to be taken to eliminate segregation. Fig. 1. indicates the type of segregation referred to. The shaded area represents the region in which porosity occurs. A first step will be to make the ingot shape such that solidification takes place as rapidly as possible; the cross section of the mould should be as small as possible, for this will make the average solidification rate high, always subject to the proviso that the ingot can be given sufficient mechanical working to produce the full mechanical properties in the finished product.

22. Advantage may also be taken of the fact that segregation tends to be concentrated towards the top of the ingot, by providing the mould with a hot-top or feeder head. This will maintain the steel at the top of the ingot in the liquid state and allow the segregated impurities to rise into the head and so give an acceptably low discard on

cropping. But with all these counter-measures it must be accepted that, when making large ingots, segregation will occur. When a user demands finished products that can be made only from large ingots, he must be prepared to relax composition specification limits if the steelmaker is to be able to make material economically.

23. However, for many products, there is an answer to the problem of segregation. Small cross sectional dimensions and rapid solidification are possible by continuous casting. Other speakers will be describing the process so it will suffice here to state that continuously cast ingots are essentially free from segregation both in cross-section and longitudinally and, with less mechanical working than is given to conventional ingots, produce finished materials fully in conformity with current specifications.

24. Non-metallic Inclusions In spite of all the care devoted to obtaining correct composition, absence of undesirable elements and to reducing segregation, another source of "impurities" is indissolubly linked with ingot making. I refer to non-metallic inclusions, predominantly oxides or compounds of oxides of aluminium, silicon, manganese and iron, which constitute sources of inferior mechanical properties. They may arise in two ways; from reactions taking place within the bulk of the steel or by reactions between the steel and the refractories with which it comes in contact. The full extent to which inclusions arise from refractories is not yet clear, in spite of many researches that have been carried out. Examples have been found of embedded particles that obviously came from broken refractory gaining access to the steel in its passage to the ingot mould. Such defects can be prevented by strict attention to cleanliness in the setting of ingot moulds and runners and the choice of bricks of adequate strength. There is evidence, however, that some steels can, during their passage over or through refractories, react with and dissolve the material. Some of this eroded material may remain entrapped within the ingot. The occurrence of this type of inclusion is somewhat sporadic, so that it cannot be said with any certainty whether the tests conducted to determine how far refractories do contribute to non-metallic inclusions lead to positive conclusions.

25. The major source of inclusions is, undoubtedly, deoxidation practice. Almost all steels when ready for tapping contain a concentration of oxygen such that, during cooling and solidification, it will react with carbon to evolve carbon monoxide and thus to uncontrolled turbulence and blow-hole formation. Before the steel is allowed to

... it is, therefore, treated with deoxidants such as ferromanganese, ferrosilicon, ...inium, etc., to lower the oxygen content so that no carbon monoxide gas formation is ...ossible (killed steels) or that the correct amount is produced at the right time (... ing and balanced steels).

... The oxides formed by the action of the deoxidants are insoluble in steel and it is clear that the remedy is to be sought in providing conditions in which they can escape before the steel solidifies. For this reason, the deoxidation is preferably conducted in the furnace or ladle, where the steel remains molten, and time is allowed for inclusions to rise into the supernatant slag layer.

... Each deoxidant gives different levels of dissolved oxygen and inclusion content at the various stages after tapping. Fig. 2 taken from the work of Plöckinger[1] shows this. Since the solubility of oxygen in solid steel is extremely small, it can be taken that the total oxygen content of a solid sample represents the sum of the inclusion that were present before sampling and those that will form during solidification.

2... It will be observed that silico-manganese additions to the ladle result in lower total oxygen after 8-12 minutes waiting time than do silicon or calcium silicide but ... zirconium, titanium, and aluminium are superior. It will be observed that ...minium causes a rapid fall during tapping of the furnace, no change during the ...ing time and another decrease during ingot teeming. This suggests that the alumina ...ticles are removed rapidly only when the metal is agitated but do not have a high ... of rise through quiescent metal. This may be attributable to the fact that when ...ought by agitation to an interface, with either slag or air, they are absorbed ...ly by the slag or remain at the air-metal interface. Since it is difficult under practical conditions to ensure absence of slag, the first explanation is considered ... likely. The superiority of aluminium as a deoxidant for producing cleaner steel ...s been verified in works' practice.

... There is, however, one deoxidant that gives rise to a product that very readily escapes from steel. This is carbon, though when used under normal conditions, it is not an efficient deoxidizer. Although carbon will react with oxygen during solidification ... perform some deoxidation, it will produce carbon monoxide blowholes and in any case ... residual oxygen will be sufficient to interact with elements having greater oxygen ...inity to produce non-metallic inclusions. However, the deoxidizing power of carbon

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[1] Plöckinger ..., Influence of deoxidation practice on cleanness of steel, Journal Iron ... Steel Institute, 876-881 (July 1963)

is very much increased if ambient pressure is lowered and by subjecting the steel as a batch or continuously to high vacuum, very low residual oxygen and thus low inclusion contents can be obtained. This technique is now being applied increasingly not only for removal of hydrogen as mentioned in paragraph 21, but also for deoxidation. It has the great advantage that if the treatment is given before addition of alloys, there is no oxygen to react wastefully therewith and alloy recovery is higher.

30. Ingot Defects Many a satisfactory batch of steel has been made of reduced value because of defects arising during the actual ingot making. These defects may not even be apparent at the ingot stage but only after rolling or forging and hence additional wastage of time, effort, and money. It is not possible here to describe the many ingot defects that can arise and reference should be made to Special Report No.63 of the Iron and Steel Institute, but examples may be quoted to indicate the cause and remedy of some of them.

31. The most obvious defects are perhaps cracks. Hanger cracks can occur when the ingot is suspended in the mould because of a badly worn or ill-fitting hot-top or to overfilling of the mould. These are generally horizontal cracks. Vertical fin cracks arise when the contraction of the ingot skin is prevented by metal having frozen in an open crevice in the mould. Fins or flashes between mould and bottom plate can cause basal cracks. The remedies are obvious; moulds should be rejected when cracked and the fitting of hot-tops and setting on stools should be carefully checked.

32. Cracks can be associated with surface irregularities which restrict contraction. Thus double skin (see later) can cause transverse, longitudinal and oblique cracks. There are also cracks not accompanied by surface irregularities nor caused by obvious restriction. These are usually described by direction and position as transverse or longitudinal facial cracks, transverse or longitudinal corner cracks or basal cracks. Their cause is not fully understood but the following are known to be contributing factors:

a. Inability of the skin to withstand the stresses resulting from ferrostatic pressure exerted by the liquid steel.

b. Too high teeming temperature.

c. Too high teeming rate.

d. Too high mould temperature.

e. Too large corner radius on ingot.

f. Too small flute depth on ingot.

g. Steel entering mould towards one side instead of centrally.

Once again the remedies can be seen from the above. Some cracks occur within the ingot itself and have been attributed to the presence of high proportions of aluminium and nitrogen which reduce the strength of the steel so that it cannot withstand the solidification stresses.

33. Double skin may result from splash of steel on to mould walls at the start of the teeming. The use of splash cans or pads is to be recommended. Double skin can also arise at the top of an ingot, e.g. with effervescing steel a shell of metal may be formed as a result of the metal level falling rapidly when the mould is filled. This shell will give rise to double skin if teeming is resumed.

34. Lap marks may result from slowing down or interrupting the teeming if this gives part of the top surface a chance to solidify. Very slow teeming or too low a teeming temperature may cause pronounced ripple.

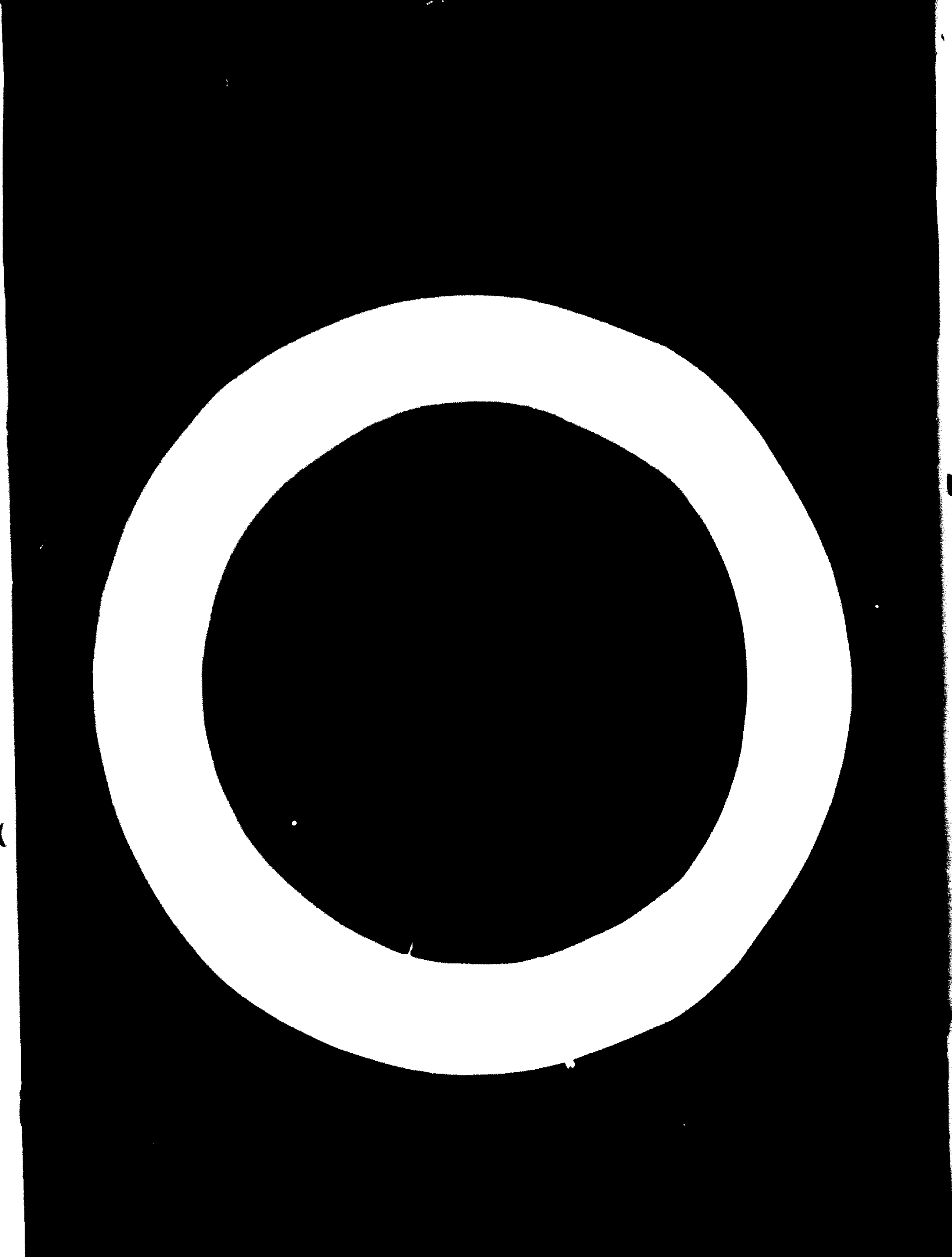
35. Subcutaneous blow holes and segregates have been known to occur when an insufficiently deoxidized steel has been teemed into dirty moulds. The iron oxide in the dirt can react locally with the carbon in the steel to produce small blowholes that infill fully or partly with impure liquid from the still liquid part of the ingot.

36. Some of these ingot defects may disappear on rolling or forging or at least necessitate merely ingot scarfing, but others may cause so many consequent defects in the rolled or forged product that part or all of a cast has to be scrapped. It is clear then that as much care must be taken at the ingot making as at any other stage to ensure that teeming temperature and rate are correct for the steel being cast, that bottom plates and hot-tops are well fitted and that splashing or overfilling of the moulds are avoided. Moulds should be strictly examined for cracks, properly cleaned and used only at the correct temperature. No hard and fast rules can be laid down; experience must be the guide to correct practice for each grade of steel and each ingot shape and size.

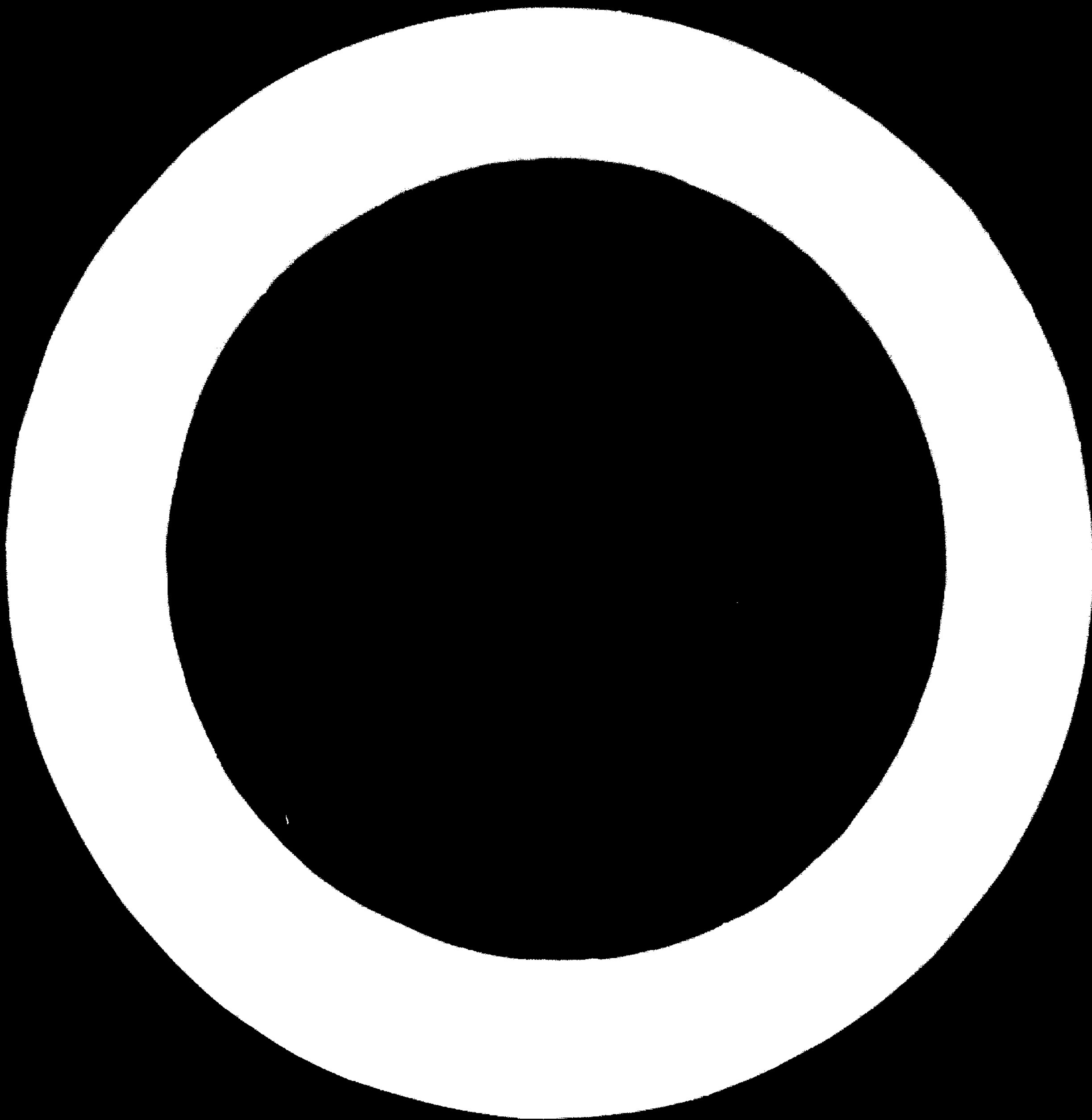
37. In paragraph 29 it was indicated that continuous casting could overcome the problem of segregation. Although ingot defects do arise in continuous casting, the process generally gives far less trouble in this respect than does conventional casting.

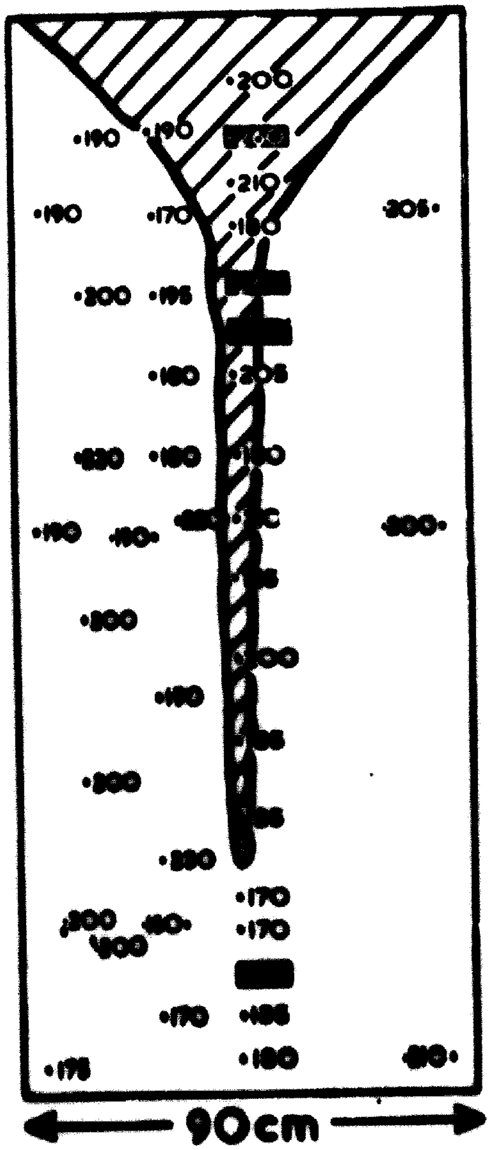
Provided the mould is designed correctly, steel is teemed at the appropriate rate, and the secondary cooling applied judiciously, external and internal ingot quality can be guaranteed. Because casting conditions can be and are maintained under much closer control than in a casting bay, continuous casting produces ingots consistently suitable for further processing.

53. <u>In conclusion</u>, to make steel of good quality, i.e. suitable for the purpose intended, close attention must be paid to choice of raw materials, methods of operation, deoxidation practice and, since a bad ingot wastes all the effort that has gone before, to the way in which the steel is converted to ingot form. Other quality-lowering defects can arise through wrong mechanical working or heat treatment procedures but these are not basically the concern of the steelmaker.



F I G U R E S



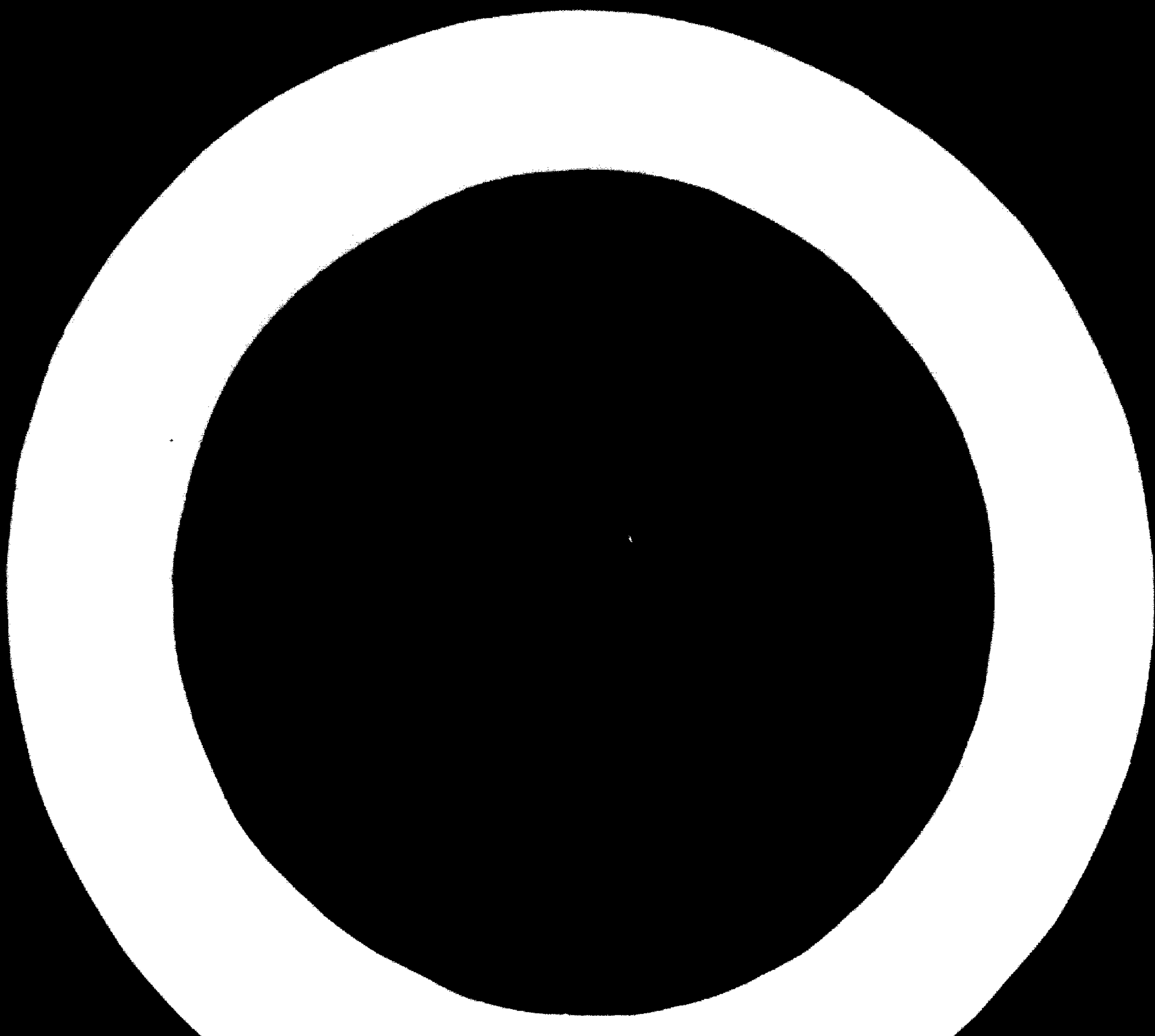


PIT ANALYSIS

C 0·190 %
S 0·037 %
P 0·011 %
Mn 0·67 %
Si 0·07 %

FIG. 1

CARBON SEGREGATION IN 17 TON LADLE BALANCED INGOT



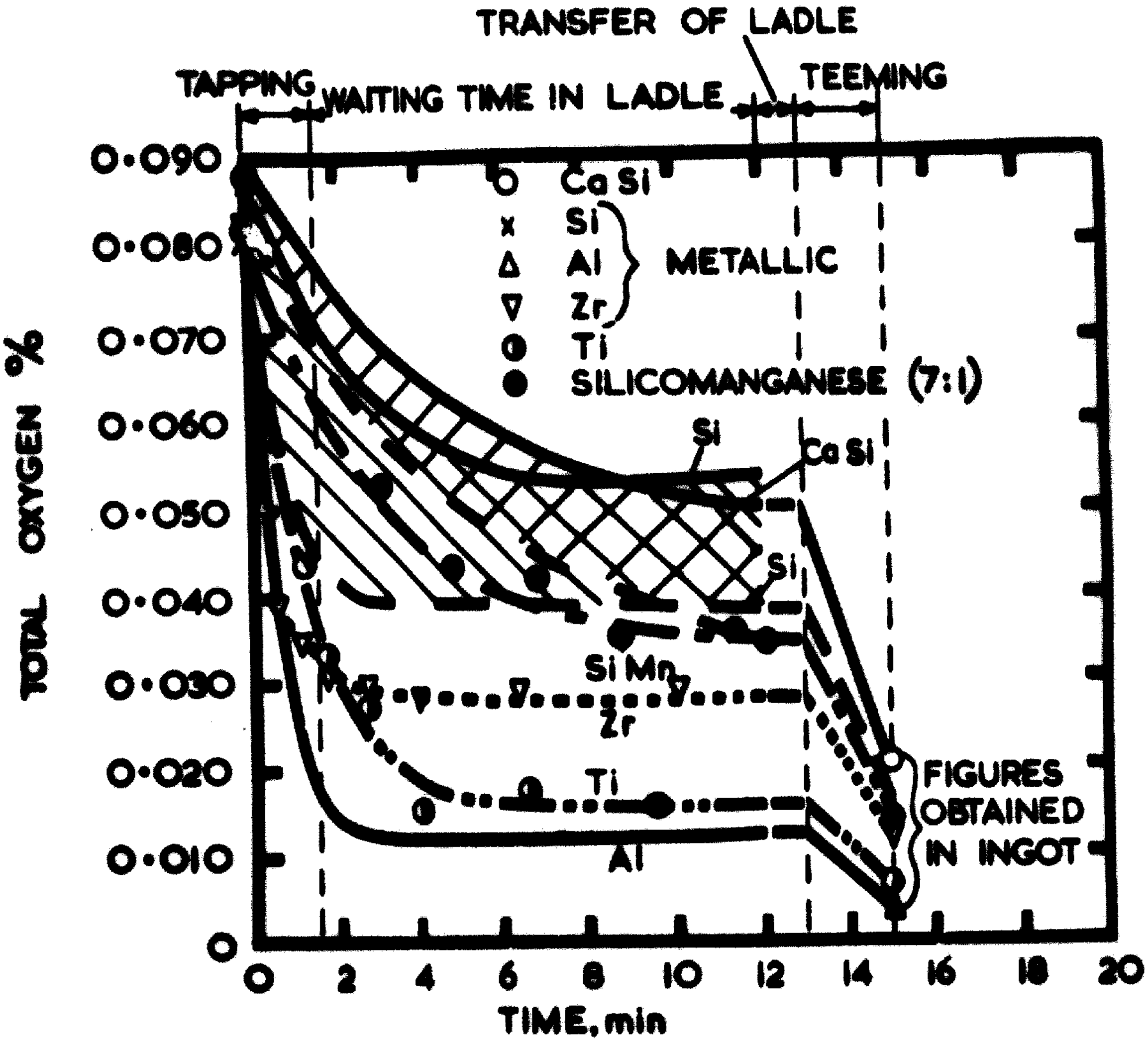

TRANSFER OF LADLE
TAPPING
WAITING TIME IN LADLE
TEEMING
0·090
0·080
0·070
0·060
0·050
0·040
0·030
0·020
0·010
0
TOTAL OXYGEN %
Ca Si
Si
Al
METALLIC
Zr
Ti
SILICOMANGANESE (7:1)
Si
Ca Si
Si
Si Mn
Zr
Ti
Al
FIGURES OBTAINED IN INGOT
0
2
4
6
8
10
12
14
16
18
20
TIME, min

FIG. 2

4. 4. 74