内部资料

新一代钢铁材料的重大基础研究

国外文献汇编

新一代钢铁材料的重大基础研究项目组

2001年11月，北京

国家重点基础研究发展规划项目

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— *Review* —

Prospect for Innovative Steel-making Process in the Forth-coming Century

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Currently, there is a strong demand for development of innovative steel-making processes, because the energy saving is a key issue for global environment and sustainable development of human society. In order to match such a demand, we should grasp the problems and issues on the current processes without any prejudice. In this paper, we review process elements available for such innovative steel-making processes and discuss the process images.

KEY WORDS: steel-making, swirling motion, efficient mixing and separation, flow control, potential energy.

1. Introduction

The promotion of productivity in the steel-making processes is an everlasting research target and it is also required for the energy saving from the viewpoint of global environment. In order to meet such a demand, we should grasp problems and issues on the current processes without any prejudice. From the analysis, we can know that it is the most essential issue how to increase the interfacial area for reactions as much as possible during the reaction stage and also to decrease it as soon as possible, after the reaction completed. By efficiently and skillfully incorporating these new options into highly-efficient mixing/separation technologies which have been devised and accumulated, the technologies will be considered to have proven its benefits early in the 21st century and also may enable the steel-making processes to move in a new direction. On those problems, we review issues here and consider some problems on development of such innovative processes.

2. Research strategy on innovative steel-making process

The innovative process should carry the following features.

1) Cost reduction with higher productivity, energy saving and improvement in yield.
2) Higher refinability for sulfur, phosphor, oxygen, nitrogen to obtain highly qualified ingots.
3) Environmental conservation by less or no emission for CO_2, NO_x, SO_x and other toxic substances, and minimizing waste slag and solubilization out of fluorine ion from the slag.

In order to realize such innovative steel-making processes, key issues are to develop highly efficient mixing, separation and flow control technologies for metallurgical reactors.

3. Elements for the innovative process

For the achievement of these objects mentioned in the preceding section, elements required for innovation are tightly related to refining issues as shown in **Table 1.**

Table 1 Elements for innovation and refining issues

Refining issue	Element of innovation
• Speedup	• Efficient mixing method
• Higher efficiency	• Efficient separation method
• Resource and environment-friendly	• Efficient flow control method

Up to now, many types of mixing and separation methods have been used and proposed in the practical steel-making process as in **Table 2** and **3.**

Table 2 Efficient mixing methods

Mixing phase	Method	Process
Solid/Liquid	• Pulverized Injection • KR stirring • Ravlenchev's mixer[1] • Swirling flow mixer • Electromagnetic stirring entrapment	De-P, De-S, De-Si
Gas/Liquid	• Gas injection • Swirling flow mixer • Electromagnetic stirring Entrapment	Removal of non-metallic inclusion De-gassing

Liquid/Liquid	• Counter flow mixer • Swirling flow mixer • Ravlenchev's mixer[1)] • Electromagnetic • stirring entrapment	Entertainment of non-metallic inclusion De-P, De-S, De-Si

Table 3 Efficient separation methods

Property, used	Method
Difference of specific gravity	• Skimmer in runner • Darts and top in ladle and converter • Teapot type separator • Centrifugal force separator
Buoyancy	• Gas bubbling • Electromagnetic micro-bubble
Electromagnetic	• Electromagnetic azimuthal pinch force • Detection of metal/slag interface

4. Overview of the current processes for the innovation

We briefly discuss here the advantages and disadvantages for each site in transfer path or in vessel at the current process route, if it is used as a reaction site for hot metal treatment. It is also notified below, which sites may progress for success by the further innovation.

4.1. In Trough (Runner) in casting bed

Advantage: a) available potential energy, b) possibility of continuous process, c) utilization of skinner for slag-metal separation, d) utilization of the travelling step for refining,

Disadvantage: a) unstable blast furnace operation, b) damage of runner's refractory.

Objective: desiliconization, dephosphorization, and desulfurization.

Prospect: promising further subject for the innovation by renovation of casting bed and change in tapping method.

Issues for innovation:

- compromise with blast furnace operation
- highly effective mixing method of refining reagents with hot metal.

4.2. Runner to Torpedo via Tilting runner

Advantage: a) available potential energy, b) possibility of continuous process, c) utilization of travelling step for refining.

Disadvantage: a) unstable blast furnace operation, b) difficulty of slag-metal separation, c) damage of runner's refractory, d) difficult to large scale refining.

Objective: desiliconization, desulfurization.

Prospect: promising future subject.

Issues for innovation:

- compromise with blast furnace operation
- effective mixing method of refining reagent with hot metals
- new method for slag- metal separation.

4.3. In Torpedo

Advantage: a) a site possible for a fierce refining in its nearly closed space, b) utilization of transportation vessel.

Disadvantage: a) instability of blast furnace operation, b) difficulty of slag-metal separation.

Objective: desiliconization, dephosphorization, desulfurization.

Prospect: A great leap can not be expected from present situation.

4.4. Torpedo to Ladle

Advantage: a) available potential energy, b) refining in travelling step.

Disadvantage: a) difficulty of slag-metal separation, b) dust collection, c) difficulty of large scale refining.

Objective: desiliconization, desulfurization.

Prospect: promising further subject.

Issues for innovation:

- effective mixing method of refining reagents with hot metal
- new method for slag-metal separation.

4.5. In Ladle

Advantage: a) use of the transportation vessel.

Disadvantage: a) difficulty of slag-metal separation and slag discharge, b) difficulty of big-scale refining because of less free reaction volume.

Objective: desiliconization, dephosphirization, desulfurization.

Prospect: little leap from this situation.

4.6. Ladle to Converter

Advantage: a) availability of potential energy, b) use of transportation vessel, c) refining in travelling step.

Disadvantage: a) difficulty of slag-metal separation, b) dust collection, c) impossibility of large-scale refining, d) difficulty of positioning of reaction vessel.

Objective: desiliconization, desulfurization.

Prospect: future issue.

Issues for innovation:

- effective mixing method of refining reagents with hot metals
- positioning of reaction vessels.

4.7. In Basic Oxygen Converter

Advantage: nearly closed vessel, suitable for a fierce refining.

Disadvantage: difficulty of slag-metal separation and slag discharge.

Objective: decarbonization, dephosphorization, desulfurization.

Prospect: main vessel required for further innovation

Issues for innovation:

- pursuit of faster refining
- closed refining vessel for recovery of highly pure CO gas as a resource, and for preliminary deoxidization by using a reduced pressure or slags,
- method for oxygen supply,
- development of equipment.

4.8. Converter to Ladle

Advantage: a) availability of potential energy, b) utilization of travelling step for refining.
Disadvantage: a) slag-metal separation, b) dust collection, c) impossibility of large-scale refining, d) hard control in the atmosphere, e) corrosion control of tapping hole.
Objective: deoxidization, desulfurization. degassing.
Prospect: important future issue.
Issues for innovation:

- further development of slag-metal separation,
- method of increase in reaction interface for the acceleration,
- new shielded tapping method as bottom tapping to avoid hydrogen and nitrogen pickup from ambience
- new equipment.

4.9. In Ladle (secondary refining)

Advantage: use of transportation vessel.
Disadvantage: a) difficulty of separate and discharge slag, b) temperature drop (increase in cost), c) reoxidation by air, slag and refractory.
Objective: deoxidization, removal of deoxidation product, decarburization, desulfurization.
Prospect: further development for higher quality of ingot.
Issues for innovation:

- rapid treatment,
- ultra-clean steel,
- process integration with a simple production line,
- new method as powder injection under vacuum,
- application of electromagnetic metallurgy,
- new technology for clean steel without Ca treatment,
- slag reforming and the utilization.

4.10. Ladle to Tundish

Disadvantage: a) difficult to slag-metal separation, b) difficulty of strict atmospheric control.
Objective: prevention of reoxidation, removal of deoxidizing product, degassing.
Prospect: future subject.
Issues for innovation:

- innovative method for slag-metal separation
- discovery of new seeds as electromagnetic metallurgy and swirling flow,
- new sliding valve system to avoid air leakage during teeming.

4.11. In Tundish

Advantage: use of transportation step.
Disadvantage: a) entrapment of carry-over slag, b) requirement of strict control on ambience, c) temperature adjustment suitable to high throughput casting.
Objective: Prevention of reoxidation, Removal of inclusion by floatation, Degassing.
Prospect: still important issue to be resolved in the future.
Issues for innovation:

- method for forced floatation of nonmetallic inclusion
- innovation of turndish shape
- application of electromagnetic metallurgy,
- removal of nonmetallic inclusion assisted by fine bubbles,
- temperature control method,
- composition control technology,
- new technological seeds.

4.12. Tundish to Mold.

Disadvantage: a) clogging of submerged entry nozzle, b) entrapment of carry-over slag at initial and terminal stage of teeming, c) air leakage via sliding valve during teeming, d) entrapment of argon bubbles.
Objective: Prevention of reoxidation, Removal of inclusion by floatation, Prevention of nozzle clogging.
Prospect: important issue.
Issues for innovation:

- new removal method of non-metallic inclusion during the teeming of hot metal,
- application of electromagnetic metallurgy,
- new submerged entry nozzle with swirling blade,
- quit of argon gas flowing into hot metals.

From this overview, it is recognized that two types of reaction sites may be available for the innovative refining; (1) inside of stationary spaces, such as in blast furnace trough, torpedo, ladle, basic converter, tundish, etc., and (2) transitory space during the teeming of hot metals from vessel to vessel in which potential energy caused by height difference between two vessels may be available for the refining. One of the key issues for the innovation is use of this potential energy, and the other is to development a new method for effective mixing of hot metals with reactants and to separate the reaction products from the metal rapidly after the reaction has terminated.

5. Some examples on utilization of the potential energy for innovative refining

5.1 Desiliconization of molten iron

Molten iron tapped off from the blast furnace transfers to a torpedo though a runner in the cast house floor as shown in **Fig.1**.

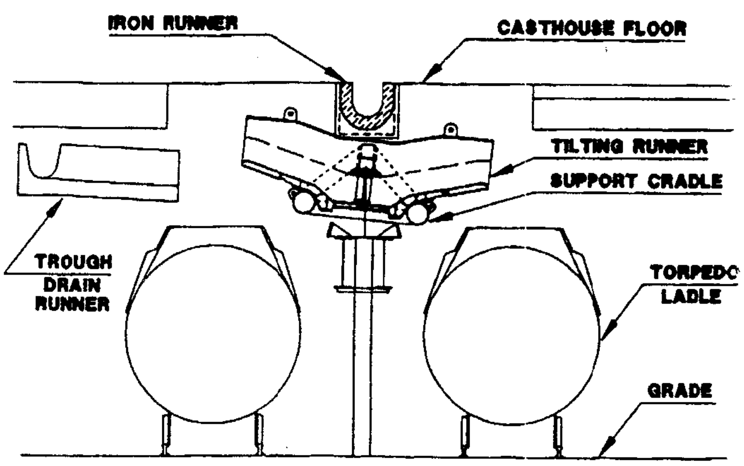

Fig.1 Installation of runner, tilting runner and torpedo.

During this path, there are many trials for desiliconization of hot metal, for example; injection of oxidizer into a metal bath in the runner, charging the oxidizer on the metal flow from runner to torpedo via tilting runner, etc. In the cases, slag sometimes foams uncontrollably and the forming jammed the further furnace operation. It is caused by CO gas evolved from oxidation of carbon in metal phase after lowering the content of silicon at the metal-oxidant interface by retardation of silicon transfer to the interface. To avoid such CO gas evolution during the disiliconization, the key is how to keep the interfacial area larger to shorten the transfer path of silicon to the reaction site. Potential energy between the runner and the torpedo may be available to realize a new desiliconization process without slag foaming. **Figure 2** shows schematics for the reactor[2].

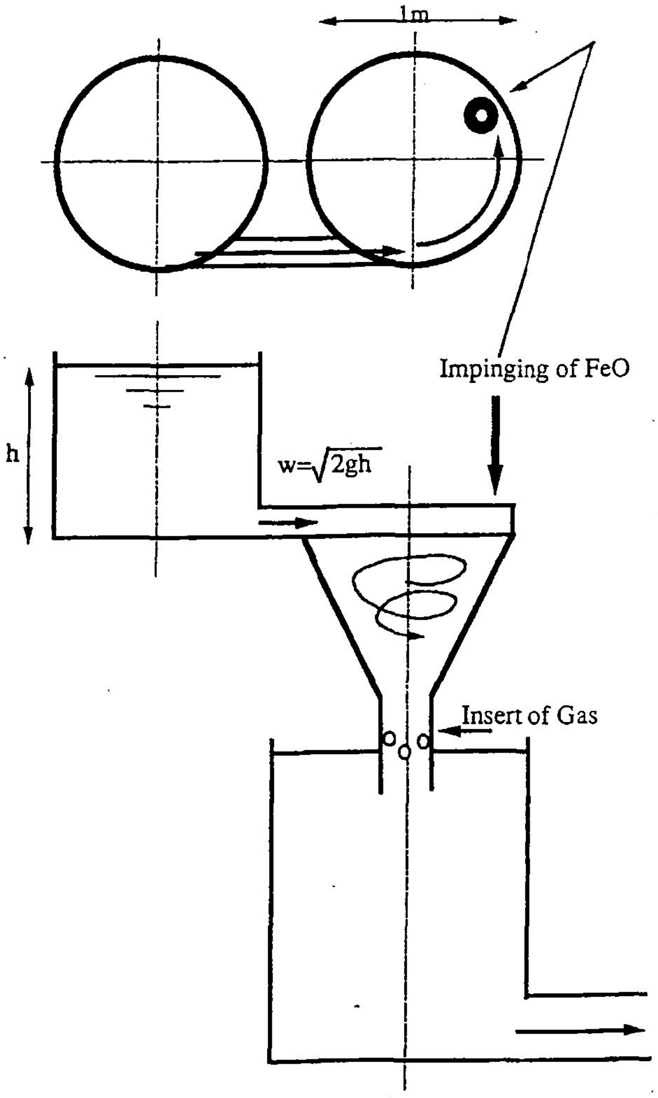

Fig.2 Image of new reactor for the desiliconization

The metal flow created by the head, h runs horizontally into the funnel to form a vortex and drains off downward. During the process, insoluble additives are easily mixed with liquid. **Photo 1** shows examples of the perfect mixing for polyethylene particle-water system obtained by using this type reactor [3]. If the horizontal flow rate is 2m/s in the inlet (which corresponds to the case of the head h=1m for molten iron, 1m of diameter of the funnel and 1/3m of the stem already shown in **Fig.2**), the flow accelerates to be 3.6-4.0m/s in the stem as shown in **Fig.3**[3]. This swirling motion also creates a suitable condition to insert fine bubble into the stream. It means that it is possible to use carbon dioxide as a desiliconization reagent of molten iron[1], effectively. According to current research on fine bubbles formation of metal bath by swirling motion, fine gaseous bubbles penetrate easily from a gas delivery hole set on a container wall to a mercury bath by addition of the swirling motion, which creates a centrifugal force[2].

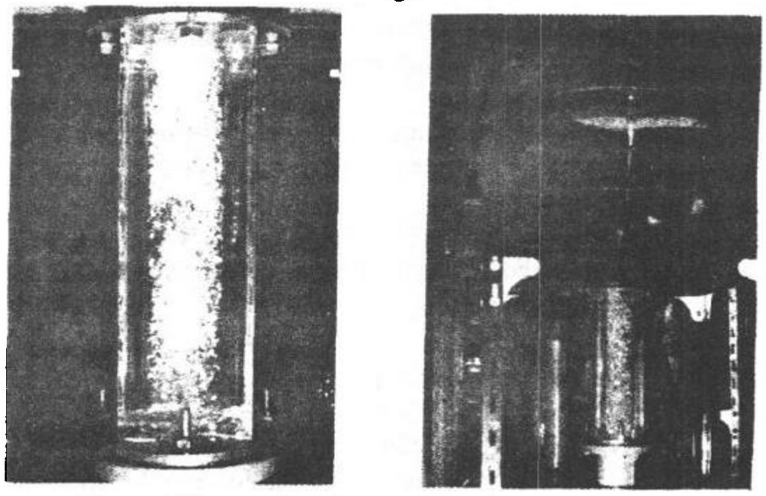

Photo 1 Views of perfect mixing of polyethylene Particles in water by the funnel type mixer.

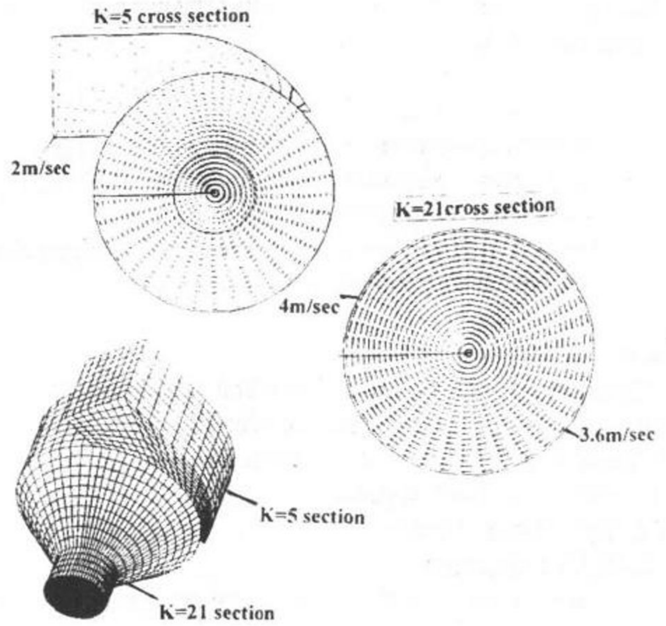

Fig.3 Flow pattern of the funnel type reactor

Yokoya et al.[2] suggest that the diameter of bubbles, B can be computed by the following equation,

$$\mathbf{B=(1/2)^{1/3}(1/W)(2R\,\sigma\,/\,\rho\,)^{1/2}} \qquad \mathbf{(1)}$$

in which W, R, σ and ρ are tangential velocity of the liquid in the container, the radius, surface tension and density of the liquid, respectively. If the equation (1) is applied to a reactor of 1m in radius for molten iron, it is calculated that the tangential velocity required for creation of 4mm bubbles on diameter in molten iron is about 2.7m/s. As shown in **Fig.3**, this tangential velocity is not so difficult to be realized by using the potential energy and a funnel type reactor.

5.2 Process from ladle to mold via. tundish

Molten steel is transferred to a tundish for casting into a CC mold, after the degassing and final adjustment of the composition. Typical transfer paths of molten steel to the CC mold are shown in **Figure 4**.

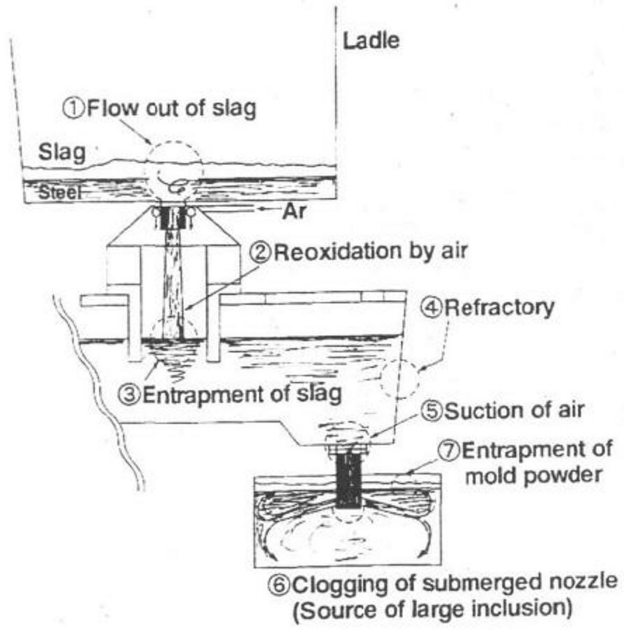

Fig.4 Origin of inclusion increase during CC operation.

During the path, contamination of molten steel is sometimes occurred by (1) reactions with carry-over slag, (2) re-oxidation by air-leakage, (3) entrapment of carryover slag, (4) reactions with refractory, (5) re-oxidation by air-suction, (6) clogging of submerged entry nozzle, (7) entrapment of mold powder and so on. In order to avoid the contamination during the path, flow control of molten metal by utilization of potential energy is very useful.

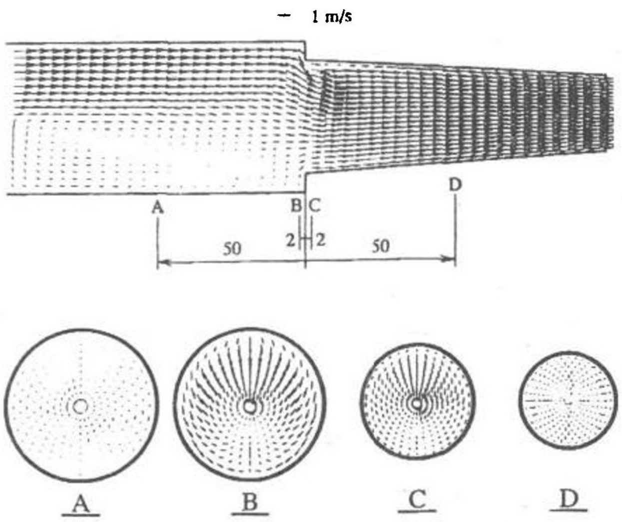

Fig.5 Flow pattern of contraction nozzle with step in case of 40mm and 20mm for the inlet and outlet diameter, 5.15mm for the step and 30 deg. of sliding opening.

A new type nozzle proposed by Yokoya et al. [5, 6] is a typical example of the application. They considered that the air contamination originates from a negative pressure induced by a biased flow inside the nozzle, after passing through a sliding gate. Accordingly, the step and the contracted outlet in the nozzle as shown in **Fig.5** rectifies the biased flow and creates a new flow pattern in molten metal which works for suppression of the leakage.

Another example is usage of fine bubbles for removal of small non-metallic inclusions. The process concept is shown in **Fig.6**. During a transfer path of molten metal as submerged immersion nozzle, bubble accumulated zone; namely bubble curtain can be established by imposing a swirling motion in it which creates a centrifugal force for the bubble-injection. According to the equation (1), the tangential velocity of 15m/s is required to inject bubbles of bubbles 5mm in diameter from the wall of a 100mm in diameter tube.

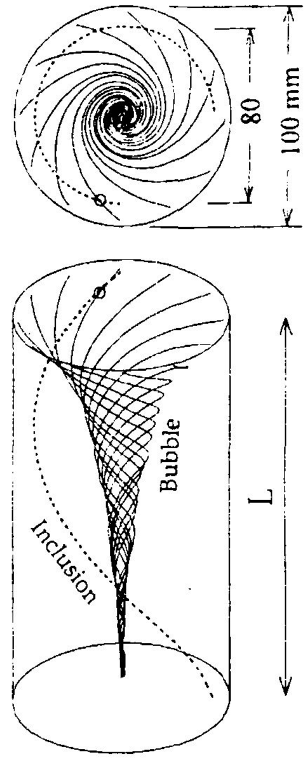

Fig.6 Bubble curtain created by swirling motion and trajectory of inclusions (axial and swirling velocity are both 1m/s, and diameter of bubbles and particle are 10mm and 50 μ m, respectively)

6. Conclusion

Now the global environment and depletion of resource as well as production cost and quality on steel require for innovation of the steelmaking process. It is notified that new technology for highly efficient mixing and separation of slag-metal system is a key for the innovation. In order to achieve the target, electromagnetic and ultrasonic application technologies are important, however, we should pay more attention to utilize potential energy which has not positively be used yet in the process. Although we have already used the gravitational force to transfer molten steel between two vessels at the different altitude, it can create swirling motion inside the melt as shown here. This swirling motion works not only to realize a highly effective condition for mixing or separation in solid-liquid system and gas-liquid systems, but also to create a well-controlled flow of molten steel inside the CC mold. At April 2000, the High Temperature Process Division in the ISIJ started a new research committee on "Development of Innovative Reactor with Highly-Efficient Mixing and Separate Abilities" and works for 3 years. One of the target is to utilize the potential energy, because it has a big advantage of no requirement on extra equipment.

Acknowledgement

We are acknowledged that this project was financially supported by the Iron and Steel Research Promotion Fund of ISIJ.

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ISIJ International, Vol. 41 (2001), Supplement, pp. S42-S46

Ideas for Process Control of Inclusion Characteristics During Steelmaking

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An optical emission spectroscopy (OES) method has been implemented for steel sample analysis in the steel plant at Ovako Steel. It makes it possible to receive feedback on oxygen content, inclusion size and inclusion composition within less than 10 minutes from sampling. A windows-based system has also been built to provide operators with easy access to the analysis data. A large number of production samples have been examined and evaluated using the new system. The information on inclusion size distribution and oxygen content in steel samples has been shown to correlate well with the oxygen content in rolled billet samples. It is therefore believed that actions taken during ladle refining to decrease the number of inclusions or the oxygen content can affect the steel cleanness in the finished material. Thus, it can be concluded that it is possible to obtain some control over inclusion characteristics during ladle refining.

KEY WORDS: inclusion characteristics; process control; steelmaking; microscopy; plant test.

1. Introduction

A major disadvantage during steelmaking is that no on-line feedback of inclusion characteristics is available, which makes process control impossible. At the same time, it is well known that inclusion characteristics affect the material properties of the finished steel product. Thus, there is a strong driving force to develop a means of obtaining information on existing inclusion types and contents during the different stages of steelmaking, which would make it possible to optimize steel production. Customer requirements regarding material properties could then better be fulfilled.

This report covers the use of an OES technique newly developed by Ovako Steel which provides feedback in the form of inclusion characteristics and the method's possible application in process control. In an earlier investigation, the effect of sampling design on the determination of inclusion characteristics was studied.[1)] It was found that analysis results of samples taken using a newly designed rapid solidification sampler were more consistent, judged by comparing the relative standard deviation, than results obtained from standard production sampling. In another report, the influence of top-slag composition on inclusion removal and inclusion characteristics during ladle treatment was studied.[2)] It was found that the top-slag composition affects the inclusion characteristics.

In this study, OES results from sampling during ladle refining were compared to results from oxygen content analyses performed on the finished material. The results are based on plant trials at Ovako Steel's plant in Hofors, Sweden. Based on that information, some ideas for process control are discussed. In the first part of the paper, the experimental procedure is presented. Thereafter, examples of inclusion characteristics determined using the OES method are given. Finally, the use of these results for process control are discussed.

2. Experimental Procedure

2.1 Plant Description

The production at Ovako Steel AB is scrap based. The scrap is melted in a 100-tonne oval bottom-tapped electric arc furnace. After adjusting the steel to desired phosphorous, carbon, and temperature levels, the steel is tapped into a ladle. The steel is then deslagged before transport to the ASEA-SKF ladle furnace. At the LF station a synthetic calcium-aluminate top slag is added. The secondary refining process mainly consists of three steps. First, induction stirring and heating with three electrodes is carried out during alloying and melting of the synthetic top slag. Second, vacuum degassing with gas stirring is applied to promote sulfur and hydrogen refining. Third, a final inductive stirring is once more utilized. During the third treatment step heating can also be used to ensure that the desired teeming temperature is achieved. After the ladle-furnace treatment is complete, the steel is teemed with uphill teeming into 24 ingots.

2.2 Plant Trials

Samples were taken from the liquid steel during the ASEA-SKF process using the automatic sampling system, which ensures that the sampling position is the same for all corresponding samples. The majority of the sampling was done at the ladle's arrival to the ladle furnace, before vacuum degassing and after vacuum degassing. A rapid solidification sampler was used in all plant trials.[3)] The samples were evaluated with the OES technique for oxygen content, inclusion size distribution and inclusion composition. Samples were also taken from a rolled product.

These samples were analyzed by melt extraction to determine oxygen content. The steel grade examined was a high-carbon chromium bearing steel (1% C, 1.4 % Cr).

2.3 Analyses

An optical emission spectroscopy method was developed by Ovako Steel during 1996-97 as a means of rapid determination of inclusion characteristics. An Applied Research Laboratories 3460 optical emission spectrometer was rebuilt by replacing the normal electronics to enable analysis of single discharges during the sparking sequence. An illustration of the method is shown in **Fig. 1**. The basic principle is that an electric discharge hits an inclusion in a steel sample which gives rise to a light intensity. These light pulses are broken up by a grating into their respective wavelengths and then detected by separate units for each element (Al, Mg, Ca, etc.). By analyzing the information from each spark, the size distribution and composition of inclusions can be determined. By analyzing the average information from a longer sparking sequence, the contents of the elements dissolved in the steel can also be determined. The lower part of **Fig. 1** shows the output signals from one of the detection units for a longer sparking sequence. The base line represents the dissolved content of the metal in the steel sample and the peaks correspond to the metal content in inclusions. More details regarding the analysis equipment, data acquisition and data processing can be found in earlier publications.[4,5]

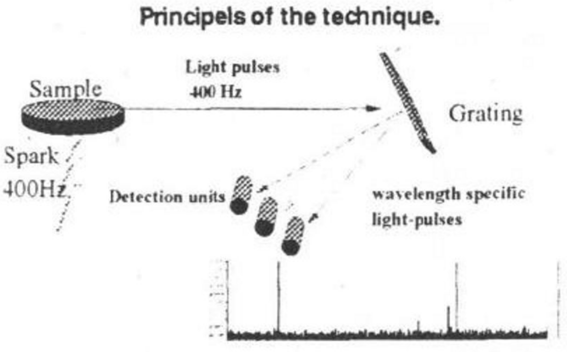

Fig. 1 Basic principles of the OES method.

The oxygen analyses of the samples taken from the rolling mill were performed with the melt extraction technique using a Strölein ON-MAT 8500 instrument.

3. Results and Discussion

3.1 Inclusion Size Distribution

Fig. 2 shows how the inclusion size distribution varies during ladle refining for one heat. It can be seen that the number of inclusions for all three size classes is highest at the beginning of ladle treatment. Thereafter, it decreases throughout the process. The inclusion index corresponds to the number of inclusions detected per a fixed amount of sparks. The decrease in inclusions during ladle refining corresponds to those observed in earlier investigations at Ovako Steel.

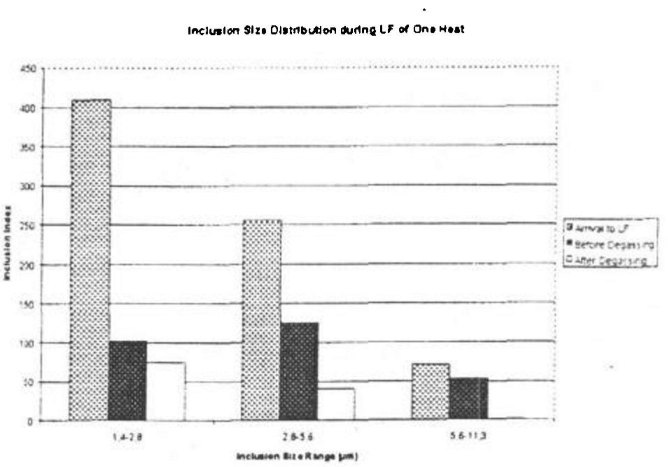

Fig. 2 Size distribution in samples taken during ladle refining for one heat

It should be noted that at this time the OES technique can only be used to detect inclusions from 1 to 11 μm.

3.2 Inclusion Composition

Fig. 3 illustrates how the average inclusion composition varies during ladle refining. The major constituent in the inclusions is alumina, which can be expected since aluminum is used as a deoxidizer. The increase in the fraction of magnesia in the inclusions, especially during vacuum treatment, is also to be expected. Earlier investigations at Ovako Steel have shown that the source of the magnesia is the refractory.[6,7] The MgO in the refractory is reduced by carbon at steelmaking temperatures during the vacuum treatment.

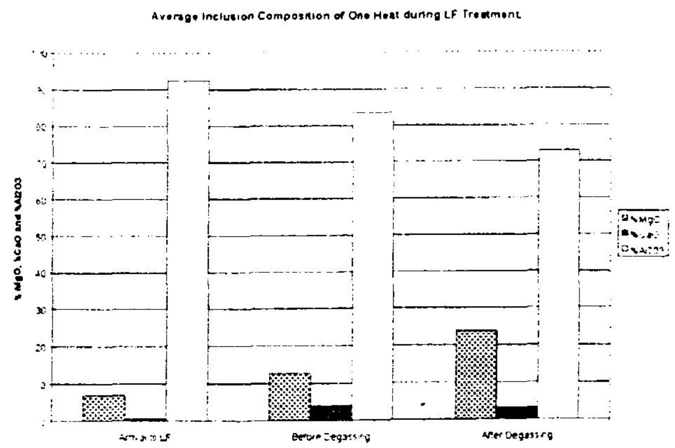

Fig. 3 Average inclusion composition in samples taken during ladle refining for one heat

3.3 Oxygen Content

The total oxygen content is often used as a measure of clean steel. It includes the oxygen dissolved in the steel, $\underline{O}$, and the oxygen bound as oxide in inclusions, O_{ox}:

$$O_{tot} = \underline{O} + O_{ox} \quad (1)$$

In an earlier investigation the oxygen content in finished bearing steel was determined both using the conventional melt extraction technique and the OES technique.[5] It was found that when the results were plotted against each other that a fairly straight line with a correlation coefficient (R^2) of 0.973 was obtained. In this study the oxygen content in a sample taken after vacuum degassing and analyzed using the OES method was plotted as a function of the oxygen content in the finished product analyzed with the melt extraction technique (**Fig. 4**). As can be seen, a high oxygen content in the steel after vacuum degassing tends to lead to a high value in the rolled billet.

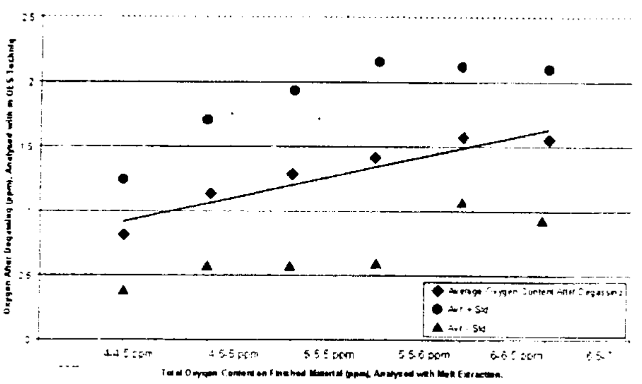

Fig. 4 Oxygen content after vacuum degassing determined using the OES method and plotted as a function of the oxygen content in rolled billets determined by melt extraction.

From **Fig. 4** it is obvious that the total-oxygen-content values obtained with the OES method are lower than those from the melt extraction technique. This could be expected since the samples were not taken at the same sampling location and the steel can be reoxidized during ingot casting. However, our experience so far has been that if both methods are used to analyze samples taken during ladle treatment, the OES method always produces a lower value of the oxygen content. There are some possible explanations for this difference. First, the OES method cannot analyze inclusions larger than 11 μm and therefore these will not be included in the analysis results. Second, inclusions smaller than 1 μm also cannot be detected. These inclusions may be formed in connection with solidification of the steel sample. The reason is that at steelmaking temperatures steel contains a dissolved oxygen content which is determined by the following reaction when aluminum is used as a deoxidizer:

$$2\underline{Al} + 3\underline{O} = Al_2O_3 \quad (2)$$

This dissolved oxygen content is approximately 1 ppm at 1600 C. When steel solidifies, the dissolved oxygen reacts with aluminum and forms alumina according to reaction (2). It also reacts with other strong deoxidizers. The critical radius for the alumina inclusions formed is reported to be 6 to 32 Å.[8] It is also known that inclusions grow due to collisions.[9] However, the solidification time for a sample of 6-mm thickness and 35-mm diameter is only a few seconds when the time is estimated with calculations of Fouriers law. Therefore, it is likely that inclusions will not grow to a size of 1 μm and be able to be detected using the OES method. In titanium-deoxidized steel it has, for example, been shown that many fine oxides smaller than 1 μm precipitate and grow during rapid solidification of steel.[10] Therefore, some preliminary analyses of a steel sample in a transmission electron microscope (TEM) were done. The result was that inclusions of size 100 to 500 nm were present in the sample. This indicates that the 1 ppm oxygen which is dissolved in the steel sample might not be detected by the OES method because the inclusions are too small. However, a more in-depth study is necessary to confirm these findings.

A third possible reason that the determined oxygen content is lower when using the OES method compared to when using melt extraction is that oxygen present on the steel surface is more likely to affect the melt extraction analysis. This may lead to an overestimation of the oxygen content. Finally, it can be said that despite the fact that the OES technique does result in lower predictions of oxygen content in samples taken in liquid steel, it is still very useful. The main reason is that the oxygen content can be determined very quickly; feedback is obtained within less than 10 minutes from sampling in liquid steel.

3.4 Process Control

As previously mentioned, the modified OES technique is a technique for rapid determination of steel cleanness (oxygen content, inclusion size distribution and inclusion composition) of liquid steel samples. Less than 10 minutes is required from the time of sampling to the time the operators have the results. The question is whether or not these results provide relevant information on the cleanness of the finished product. It is shown in **Fig. 4** that there is a correlation between the oxygen content found in the steel after vacuum degassing and the oxygen content in the finished material. It is also a fact that for bearing steel a decrease of the oxygen content is beneficial for the important fatigue properties of the steel.[11-13] Therefore, determination of the oxygen content using the spark-inducing OES method can be used to indicate the status of the steel cleanness at this stage of the process. If the value is higher than the average value normally found for a specific steel grade, measures to decrease the oxygen content need to be taken, for example stirring to promote the growth and removal of inclusions, which would lead to a lowering of the oxygen content.

For bearing steel it is also known that not only lowering the oxygen content but also lowering the average inclusion size and number of inclusions will improve the fatigue properties of the steel.[14-16] Therefore, it is of interest to control the inclusion size distribution during ladle refining and to how and if it influences the cleanness in the rolled product. In **Fig. 5**, the average inclusion size distribution after degassing is plotted as a function of the oxygen content in the final product, determined by melt extraction. The inclusion size distributions for one heat with a oxygen content of 4.2 ppm and a heat with a oxygen content of 6.2 ppm in the rolled product are also plotted on the same diagram. It can be seen that there is a correlation between the inclusion size distribution during ladle treatment and the oxygen content in the finished product. If more inclusions of all sizes are found in the ladle sample, the oxygen content in the product will be higher. Therefore, a determination of the size distribution could be used to see if action needs to be taken to improve the cleanness in the rolled billet. If the number of inclusions of all sizes is more than what is normally found for the specific steel grade, action needs to be taken. Similar to what was suggested for the oxygen content, the measure taken could be stirring to promote inclusion growth and removal.

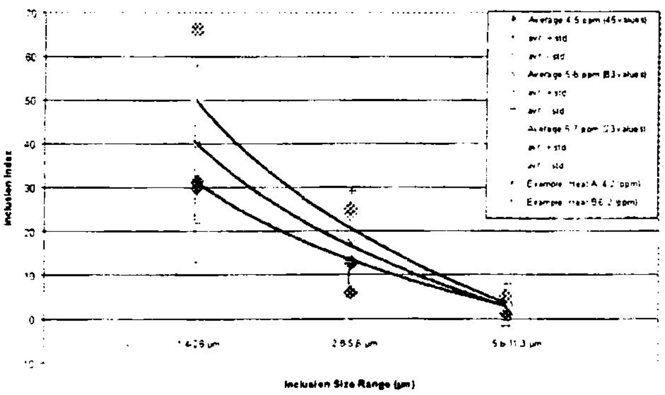

Fig. 5 The number of inclusions of different size classes in samples taken after vacuum degassing

It should be observed that the task of determining with great accuracy the length of time that the stirring needs to be prolonged and the stirring power required to remove inclusions is in itself quite difficult. One way is to mathematically model the inclusion growth and removal off-line. It has been shown recently that the concentration gradients of inclusions of different sizes can be modeled using fundamental computational fluid dynamics (CFD) models.[17] The average decrease in the number of inclusions resembles an exponential decrease. Therefore, off-line modeling of inclusion removal can be done for a certain number of stirring cases. Then, the stirring can be prolonged by x minutes using a y stirring power in order to bring down the size distribution and oxygen content for a steel grade to a level that is acceptable.

Material properties such as fatigue for bearing steel grades and other material properties which are important for other steel grades are also highly influenced by the composition of inclusions. Here, the OES technique could also be employed to determine the inclusion composition of alumina-based inclusions in samples taken during ladle treatment. However, it is not clear which specific inclusion compositions are most beneficial or most detrimental to material properties such as fatigue strength. Contrary to what was said for removing the inclusions by stirring, it is also less clear what action to take if the inclusions contain too much, for example, magnesia. Studies need to be carried out to find out how slag, refractory, atmosphere, etc. affect inclusion composition during ladle treatment.

In order to monitor inclusion characteristics during ladle refining in the ASEA-SKF ladle furnace at Ovako Steel, a windows-based system for handling information from OES analyses was developed. It was installed in the steel plant during 1999. An example layout of an output sheet is shown in **Fig. 6**. It has been designed in close cooperation with operators in order to make sure that it gives them maximum support in obtaining better control of the inclusion characteristics during ladle refining. The output sheet gives information on the heat and sample number, the oxygen content, average inclusion composition, and inclusion size distribution. The size distribution from the previous sample is also shown to allow for comparison. Thus, the operators can, for example, easily judge whether or not their use of stirring to promote inclusion growth and separation to decrease the number of inclusions was successful. The system also allows the operators to switch to another output sheet where historical data from previous heats are shown. In this way they can, for example, see what measures were previously taken for a specific steel grade and maybe take similar actions.

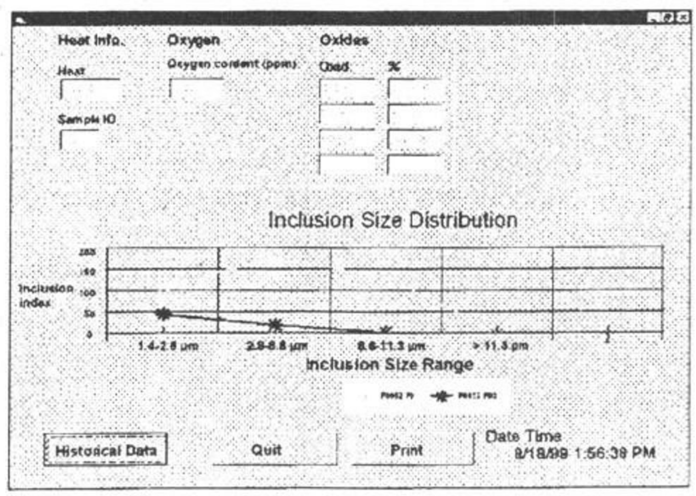

Fig. 6 Example of an output sheet providing information on inclusion characteristics, which have been analyzed with the OES technique

4. Conclusions

The OES method has been successfully implemented at Ovako Steel's steelworks in Hofors, Sweden. It can be used to provide feedback on micro-inclusion characteristics within 10 minutes from sampling the liquid steel, thus raising the possibility to, for the first time, monitor and control inclusion characteristics during ladle refining. A correlation has been shown to exist between the size distribution and oxygen content in liquid steel samples and the oxygen content in the finished steel. It is therefore possible to take measures during ladle refining to improve the end result. The operators at Ovako Steel have been are able to monitor inclusion characteristics through a windows-based system that has been developed and have begun to learn what actions are required and when they should be taken to improve steel cleanness.

The specific conclusions from this study are:

(1) A special system producing output sheets with information on inclusion characteristics determined by the OES method has been developed and installed at the ASEA-SKF ladle furnace station. The development was carried out in close cooperation with the operators.

(2) The information supplied by the OES technique can be used to optimize different parts of the ladle refining operation with respect to micro-inclusion characteristics.

(3) In the future it should be possible to optimize the micro-inclusion characteristics during steelmaking to be in accordance with the final-product demands of individual customers.

Acknowledgements

The authors wish to thank M. Hallberg and A. Lind of Ovako Steel and T. Sjöqvist of KTH for critically reviewing the manuscript.

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Swirling flow control in immersion nozzle for Continuous Casting process

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It has been acknowledged that swirling motion in the immersion nozzle is very effective to control the bulk mold flow. From the practical viewpoint, it is very reasonable for a swirling strength in the immersion nozzle to be as weak as possible while controlling the bulk mold flow. Here, a gradually diverging immersion nozzle is proposed and its characteristics and its effectiveness on controlling a bulk mold flow are investigated, using a water mold model. Using even considerably weak swirling velocity (0.24 m/s) in a immersion nozzle, maximum velocity at the outlet of the nozzle, surface flow on the meniscus and upward velocity near the narrow face were reduced. However a variation of velocity in those cases was observed.

KEY WORDS: Swirling flow control; diverging immersion nozzle; continuous casting process; bulk mold flow.

1. Introduction

With increasing casting speed in the conventional CC caster, critical problems such as meniscus turbulence, generation of longitudinal–vortex at the meniscus and generation of self–excitation–vibration in the bulk mold flow and biased flow from the outlets of the immersion nozzle have become remarkable.[1-5] Mold flux entrapment due to vortexing and shearing action from the oscillating surface waves have become of particular concern. Namely, many quality and productivity limitations of a CC caster are therefore fundamentally linked to metal delivery into the mold.

Recently, effects of swirling flow in the immersion nozzle have been considerably acknowledged: a quite uniform velocity distribution at the outlet of the divergent–immersion nozzle can be easily accomplished, the penetration depth of nozzle outlet flow is remarkably decreased and a uniform velocity distribution can be obtained within a very short distance from the outlet of the nozzle in the billet mold, separation along the wall of the immersion nozzle can be prevented, the divergent immersion nozzle with swirl is able to turn the flow radially outward without an opposite face on the end of the nozzle, stable flow pattern in the slab mold can be obtained and so forth.[1-9] The effectiveness of swirling flow in the immersion nozzle is in a trial stage for the practical application.

It is reasonable for a swirling velocity in the immersion nozzle to be as weak as possible, considering economic and simplicity. If a reasonable divergent angle with the diverging immersion nozzle is considered, it seems to be possible that not so large swirl velocity is required to prevent separation from the wall of the immersion nozzle, to control the flow pattern at the outlet of the immersion nozzle and in the bulk mold.

In this study, it is focused on the things that using a diverging immersion nozzle from the inlet to the nozzle-outlet both the mean velocity in the nozzle and the maximum velocity at the outlet are decreased and therefore the flow pattern in the mold is reasonably controlled.

2. Experimental Apparatus

Figures 1 and 2 show a schematic of the experimental apparatus. A scale factor of water model mold 1/2 was used considering a Froude-number of similarity which correspond to a through-put of 2.2 m/min in a real mold. A constant fluid velocity was obtained through the nozzle using an over flow tank. The desired swirl flow was established using a fixed swirl blade placed at the upstream end of the nozzle tube. The cross area of the immersion nozzle used in Fig. 1 is diverging in diameter from the upstream 40 mm to the exit 60 mm in the length, 300 mm.