Steel Production and Refining

The production of steel and its subsequent refining before casting is a subject of enduring interest due to the extreme difficulties that are encountered in the production of a high tonnage, ultra pure material at high temperature. Recent trends in process development have been focused upon reduction of processing cost, improvement of quality, and issues of sustainability. The production route is complicated by the balance between the integrated processing route, where iron ore is reduced using coke to a liquid iron carbon alloy and subsequently refined and alloyed, and the recycling route where scrap is melted, refined, and alloyed. These two routes have significantly different technological issues. The purpose of this section is to discuss recent trends and developments in steel production, to highlight future areas for technological progress, and to discuss the recent trend towards sustainable developments in liquid steel production.

1. *Background*

Steel production has become an internationally competitive industry where multinational companies have become more prominent as the industry has been rationalized. Large steel companies that cross international borders are becoming more common. For example, Ispat International, which is headquartered in London, has production facilities in Kazakstan, Indonesia, Mexico, Canada, USA, Germany, and France. This trend to globalization has lead to global pricing of raw materials, strategic steel deployment into chosen markets and steel products becoming international commodities. This trend towards the global steel market has also led to significant levels of imported steel in North America where 38 million tons were imported in 2000. This resulted in a short-term crisis for the local producers due to an over abundant supply of imported low cost steel.

Regardless of the impact of the worldwide consolidation of steel production, it is clear that there is a growing ability for any steel grade to be produced anywhere in the world. Thus producers must ensure that their technological solution is not only able to produce the necessary grade and quality but is also cost competitive in the world market. Thus to survive in today's steel market one must be able to compete with all producers of steel in price and differentiate oneself in the marketplace by quality. Thus the production of liquid steel has become an area where it is necessary to produce a basic liquid steel chemistry very cheaply and to develop highly sophisticated ladle metallurgy procedures in order to ensure quality.

There are two major sources of liquid steel: the blast furnace where iron ore is reduced by carbon to form "hot metal" (a liquid iron–carbon alloy containing silicon) and the electric arc furnace where steel scrap is melted and alloyed to produce a liquid steel of defined carbon content. The hot metal from the blast furnace is refined in an oxygen converter to a liquid steel of defined carbon content so that the output of the integrated route is similar to that of the recycling route. Once tapped from these furnaces the liquid steel goes through a series of processing steps aimed at either chemical refining or temperature control.

2. *Technological Issues in Steel Production and Refining*

A complete discussion and road map for technological development in the steel industry can be found on the American Iron and Steel Industry web site (http://www.steel.org/mt/roadmap/roadmap.htm) where a DOE sponsored road map for technological development is documented. Issues documented in this section are abridged from this road map.

Issues in iron and steel production are as follows.

2.1 *Ironmaking*

There are three major methods of producing iron: the blast furnace, direct reduction and smelting.

Of these three technologies the blast furnace produces the majority of the iron that is produced from ore. The total quantity of iron produced from the blast furnace is predicted to decrease in the first 15 years of the twenty-first century from 55 million tons to 44 million tons. Productivity in the remaining furnaces is expected to increase markedly in the same time frame. Technological challenges will be in decreasing the coke rate by increasing the coal injection rate, developing an economic process to produce partially reduced pellets or sinter, developing a comprehensive fundamentally based control model of the blast furnace, and developing the requisite sensors to allow optimized operation.

Direct reduction is defined as a process that produces a solid iron product from iron ore using natural gas or a carbon based reductant. It is anticipated that in the first 15 years of the twenty-first century direct reduction technologies will supply 20% of domestic iron requirements. Technological challenges will be in developing technologies of sufficient productivity to be commercially successful, in controlling off-gases to avoid pollution, and in developing effective procedures to separate gangue material from the reduced iron.

Smelting technologies have long been seen as potential solutions to the environmental problems associated with coke production. Apart from COREX, commercialization is not thought to be likely until 2005 at the earliest, although Japanese developments at the end of the twentieth century appear promising. Technological challenges are as follows: heat transfer efficiency from combusted off gases must be improved, long life containers must be developed, cost effective hot-metal desulfurization technologies must be developed, and environmental issues in off-gas treatment must be addressed.

2.2 *Steelmaking*

There are two major steelmaking processes: oxygen based steelmaking that uses hot metal and scrap as feed materials and electric arc furnace steelmaking that uses scrap and direct reduced iron as feed materials.

(*a*) *Oxygen steelmaking*. Trends in this very mature technology are towards improved productivity and reduced operating costs. Technological developments in sensors and control are necessary.

(*b*) *Electric furnace steelmaking*. Although induction melting and plasma melting are commercial technologies electric arc furnace melting is the major commercial technology. Current furnace performance is of the order of two tons of steel per hour-MVA in top rated furnaces. Directions in furnace developments are towards more energy efficient processing to increase productivity. Since electric arc furnaces are scrap-based, raw material sources affect both efficiency and yield. Some clean iron units (free of residual elements, copper, tin and zinc) are necessary as a charge material in addition to scrap to offset residual element build-up by dilution. Clean iron units are either direct reduced iron, pig iron from a blast furnace, hot briquetted iron or iron carbide.

Directions in electric arc furnace steelmaking are towards increased clean iron unit usage, chemical upgrading of scrap to remove copper and zinc, cryogenic technologies to allow controlled scrap sizing, reduction of electrical energy usage by chemical energy input, improved practices for energy reduction, controlled tapping chemistry and improved refractory life.

2.3 *Ladle Refining*

Issues in ladle refining are related to productivity, yield, chemistry control, inclusion morphology, chemistry and size distribution, and container life.

Some specific trends include:

(i) Decreasing inclusion mass and size distribution

(ii) Increasing need for rapid and accurate determination of chemistry and inclusion content

(iii) Shorter processing times

(iv) Minimization of waste

At the beginning of the twenty-first century all steel ladle processes are limited to ppm levels of solute elements and to ppm levels of oxide inclusion contents. Future levels of solutes and inclusion contents will be driven to lower than ppm levels; however, the chemical analysis techniques and processing steps necessary for such developments are not yet developed.

In addition to decreasing the mass of inclusions there is an increasing body of literature that indicates that product properties such as fatigue life and processing issues such as die life are related, not only to the mass of inclusions but also to the chemistry and size distribution of inclusions. In addition, solidification initiation in the mold and solid state phase transformations are now understood to be related to the chemistry and distribution of inclusions formed in the liquid steel. Thus the future of ladle metallurgy will be towards strict chemistry control and to deoxidants other than aluminum. Thus the future of ladle metallurgy developments must be in the development of rapid sensors for:

(i) steel and slag chemistry and

(ii) inclusion chemistry, mass and size distribution determination.

These sensors would minimize time and increase the potential for highly accurate chemistry determination.

During recycling, unwanted residual elements are inadvertently added to the liquid steel. Future developments will be to actively control reactive residual elements such as calcium, aluminum, magnesium, and zirconium and to develop methods to minimize the effects of other nonreactive residuals.

Other challenges are as follows:

(*a*) *Slag control*, *manipulation and recycling*. Future developments in slag usage will be towards slag recycling within the steel plant and reuse. This will minimize waste. Reuse will mean that the slag must be removed from the ladle and treated before reuse. During use the slag must be monitored for chemistry and a continuous chemical sensor would allow active control of the process. Manipulation of slag viscosity and solidification characteristics will lead to slags that are not easily emulsified yet easy to remove from the ladle.

(*b*) *Inert or long life refractories*. Steel and slag interaction with container refractories remains a limitation of ladle processing.

(*c*) *Temperature control*. Techniques for team stream temperature prediction and control are necessary.

(*d*) *Modeling*. Coupled heat and mass transfer models are necessary to allow prediction of the effect of ladle metallurgy on chemistry and inclusion control. Current computational abilities exist that would enable a ladle model that would include heat transfer with the container and the slag, reaction between the steel and the slag, reheating, degassing, and refining. Such a model would also include free surface interaction at the slag–metal and slag–gas interface and the effect of gas injection on heat and mass transfer within the system. Slag emulsification phenomena must also be included.

(*e*) *Yield.* Ladle design and methods to prevent emulsification during ladle draining are necessary to increase yield from the ladle. Vortex prevention, development of repeatable free opening performance and slag design are key components of this technology.

(*f*) *Productivity.* Future developments in steel plant design will be to better match the steelmaking productivity with the productivity of the rolling mill. This suggests that ladle refining times in the future will be significantly less than in the past. Thus there will be an increased emphasis in rapid refining at the ladle metallurgy station. Thus new rapid chemical sensors must be developed.

3. *Technical Issues in Steel Production and Refining*

The science and technology of steel production is quite well developed as one would expect from a mature industry; however, the development of a complete understanding of the physical and chemical phenomena that govern steel production and refining is not yet complete. As a phenomenological model of the process is not complete, computer based modeling efforts on the process are also not complete and only a few truly first principle predictive models of the varying processes are available. Sensor technology is also limited due to the high temperature environment and, as a result, control of the process tends to be an inexact science. However, it is clear that the process requirements are becoming stricter as steel product development leads to new grades with lower solute levels and an increased need to control residuals.

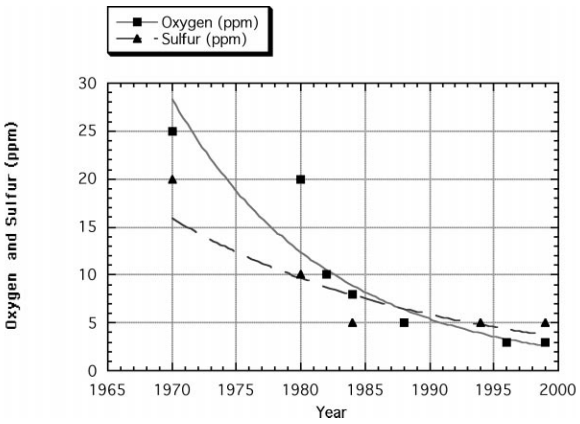

Figure 1
Trends in minimum oxygen and sulfur contents.

Future technical issues are not in metal production but in metal refining. For example, in Fig. 1, trends in the lowest possible oxygen and sulfur levels of bulk commercial steels are documented historically in steels treated with aluminum as a deoxidant.

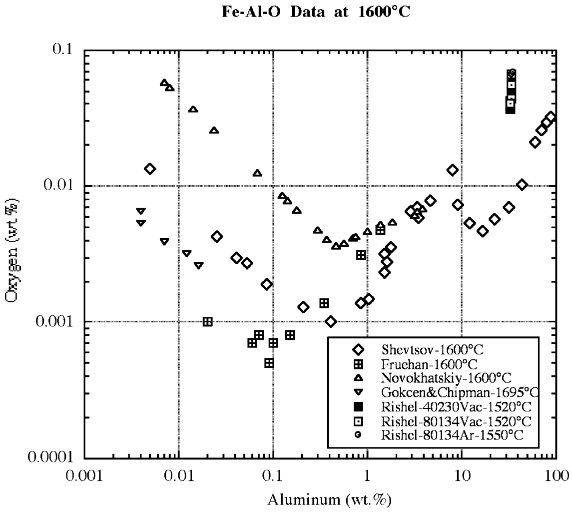

Figure 2
Equilibrium of oxygen with aluminum in liquid iron–aluminum alloys at 1600 °C.

However, as can be seen in Fig. 2, where the equilibrium oxygen content for the reaction between aluminum and oxygen is shown, there is a minimum achievable oxygen content in liquid iron at 1600 °C that limits refining (Shevtsov 1981, Fruehan 1970, Novokhatskiy and Belov 1969, d'Entremont *et al.* 1963). This limit is a function of temperature (decreasing as temperature decreases) and the cleanest possible steels are highly alloyed or high carbon steels due to lower ladle processing temperatures.

3.1 *Trends in Deoxidation*

In order for oxygen contents to decrease lower than 3 ppm, either processing temperatures must be significantly reduced or a stronger deoxidizer must be developed. Minima in oxygen contents, as seen in Fig. 2, are not unusual and high oxygen contents at high deoxidizer concentrations are seen with other deoxidizers. For example in Fig. 2, note the high level of oxygen solubility in Ti–Al alloys.

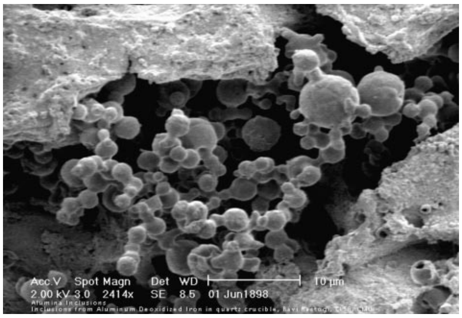

Figure 3
Alumina morphology from a steel deoxidation experiment.

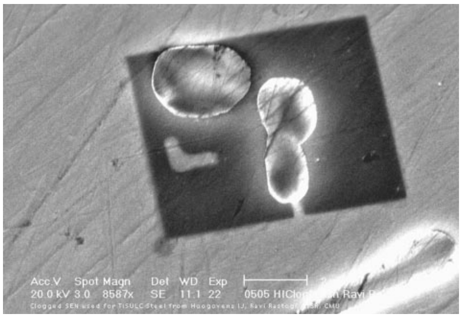

Figure 4
Titanium nitride heterogeneous precipitation on alumina.

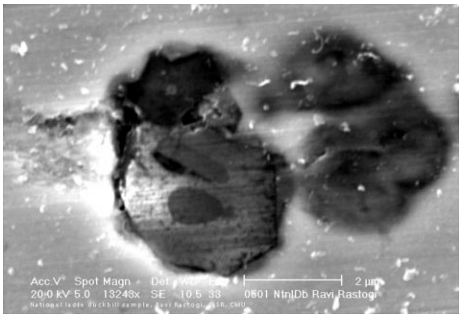

Figure 5
Manganese sulfide precipitation on alumina.

The formation mechanisms of inclusions are also poorly understood from a fundamental view—it is clear that alumina forms in an aluminum killed steel but it is not yet possible to predict the distribution and growth or agglomeration morphology of the alumina that is formed in a given environment. An example is shown in Fig. 3. Thus refining of steel to remove alumina is an inexact science where the large three-dimensional alumina rafts that are found in steel castings are not predictable. To better understand alumina distribution in killed steels, fundamental knowledge of the nucleation and growth of alumina is necessary and models to predict the nucleation rate and growth morphology of alumina are necessary. This is of course the area of solidification science.

Inclusion formation in steels is becoming a very interesting topic as it is now understood that the primary inclusion from deoxidation can be the nucleation site for further precipitation. An example from a titanium stabilized aluminum killed steel is given in Fig. 4 where TiN is seen to precipitate on alumina.

Sufides also precipitate on oxides as seen in Fig. 5 and this topic has been explored in detail by Mizoguchi (1996) as control of oxide chemistry and the subsequent precipitation of other second phase materials can be used to control the grain structure of solidified steels and ultimately to control steel properties. This area of ‘‘oxide metallurgy’’ will become increasingly important in the future as it is possible to grain refine the solidification structure, control the distribution, size and number of MnS, carbide or nitride precipitates, and to control the δ to γ phase transformation in the solid state using the proper combination of deoxidizers.

Oxide metallurgy also leads to the use of deoxidizers other than aluminum and work on the use of titanium and zirconium as complex deoxidizers is underway. A very interesting study of complex deoxidation was carried out by Mizoguchi (1996) where manganese silicates were first formed and then stronger deoxidisers such as zirconium and titanium were added. In Fig. 6 MnS is seen to precipitate at the surface of this complex oxide, indicating that it was an oxysulfide before solidification. By this technique it is possible to control the distribution of MnS particles and control the nucleation of the δ to γ phase transformation in the solid state.

There are currently a family of stainless steels that are deoxidized by titanium instead of aluminum. In these steels the complex Ti–O–N inclusion that is formed is a nucleation site for solidification and has led to fully equiaxed solidification structures in continuously cast slabs. This is the first production example of the use of ‘‘oxide metallurgy.’’

One interesting problem that has occurred in recent years has been the problem of residual magnesium in steels. Advances in slag conditioning and control have lead to increasing levels of soluble magnesium in steels. According to the work of Hino(2000) residual levels of soluble magnesium that are lower than 1 ppm are able to cause alumina to transform into a MgO–Al_2O_3 spinel that causes significant processing problems due to nozzle blockage and increased frequencies of large inclusions.

The clogging problem associated with the formation of alumina in aluminum killed steels has been alleviated by the use of calcium in addition to aluminum as a deoxidiser. Thus many steel producers are forming a liquid calcium aluminate inclusion by this more complex deoxidation procedure.

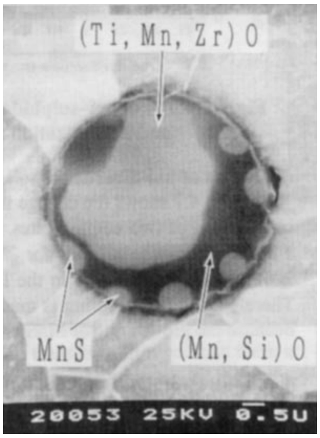

Figure 6
Precipitation of MnS within a Mn-Si-Ti-Zr deoxidised steel (after Mizoguchi 1996).

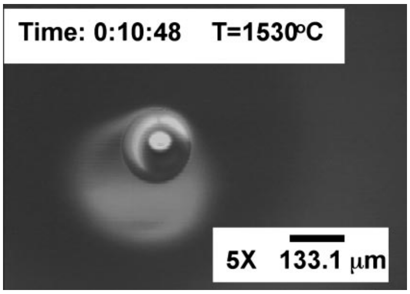

Figure 7
Confocal scanning image of a liquid inclusion at a slag metal interface (after Yin *et al.* 1997).

In the last five years of the twentieth century deoxidation technology has been under rapid change and where once there were only two basic deoxidation strategies, deoxidation by aluminum or the combination of manganese and silicon, now there are many routes to deoxidize steels, control oxygen content and inclusion chemistry.

3.2 Trends in Inclusion Removal

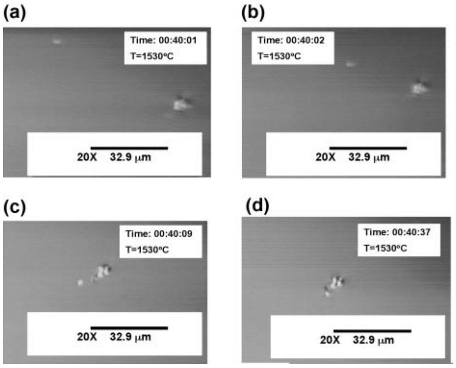

Figure 8
Alumina agglomeration at a slag metal interface as observed by laser confocal microscopy (after Yin *et al.* 1997).

Current bulk production of steel is focused upon aluminum killed steels where the product of deoxidation, alumina, must be removed before casting. A significant effort has been expended upon understanding the transport issues involved in moving an inclusion to an interface where separation is possible. However, the final two steps in clean steel production—separation to the interface and removal from the interface were largely ingnored until the application of confocal scanning laser microscopy, by Emi and his co-workers, to the problem of inclusion separation at interfaces (Chikama *et al.* 1996, Hino and Nagasaka 2000, Yin *et al.* 1997). Emi's work has allowed separation processes to be studied *in situ* and the discovery that solid alumina inclusions spontaneously agglomerate at gas metal interfaces—a previously unknown phenomenon.

A confocal scanning laser microscope (CSLM) equipped with a high temperature furnace makes it possible to image liquid steel surfaces. This technique was first applied to the study of slag–metal interfaces and to the dissolution of particles in slags during the 1990s. Both of these approaches have been successful. This technique of observation makes it possible to study the formation and elimination of both liquid and solid inclusions from liquid steels. For example, in Fig. 7, a large liquid inclusion of 100 μm in diameter can be seen sitting at a slag-metal interface. This was the first documentation of the fact that inclusion separation at a slag–metal interface is not instantaneous and that even 100 μm diameter inclusions can sit at slag-metal interfaces for significant time frames (Misra *et al.* 2000). In Fig. 8 alumina inclusions are seen to agglomerate at a slag–metal interface—a phenomena that was unknown at slag–metal interfaces before this work. Dissolution of an alumina particle in liquid slag can be seen in Fig. 9 (Sridhar and Cramb 2000). This is again a unique observation from the CSLM. This technique also allows inclusion dissolution rates to be determined.

It is clear that this new observational technique gives us the ability to clearly define and quantify phenomena in slags and at slag–gas and slag–metal interfaces. This technique is the key to developing an improved understanding of inclusion formation and elimination in steel production and, when combined with a detailed knowledge of transport phenomena, it will lead to an advance in our ability to remove solid particles from steel.

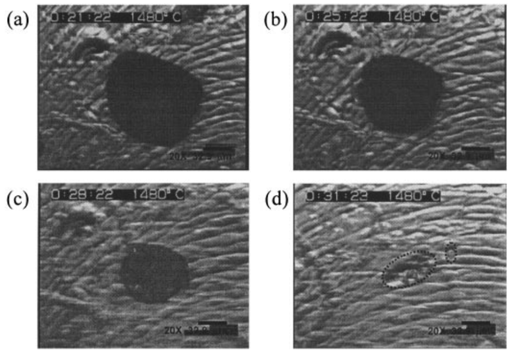

Figure 9
Dissolution of alumina in a liquid slagas observed by laser confocal microscopy (after Misra *et al.* 2000).

3.3 Trends in Process Modeling of Ladle Processes

The application of three-dimensional transient heat and mass transfer models to the steelmaking process is finally possible due to the advances in computer speed and reduction in computing cost. Current mathematical modeling is attempting to link the fluid flow driven by gas or electromagnetic force with the reactions that occur at the slag–metal interface (Jonsson 1998, Jonsson and Jonsson 1997, Jonsson *et al.* 1998). An example of the output of such a model is given in Fig. 10 where sulfur, oxygen, and aluminum contents in the steel and the sulfur content in the slag is predicted as a function of processing time. This is a very challenging area where there are two liquid phases and a gas phase with two free surfaces—the gas–metal interface and the metal–slag interface. Initial modeling attempts have coupled the fluid flow in the slag to the fluid flow in the liquid steel and account for the change in free surface between the slag and the steel during stirring; however, there are still significant issues to be overcome.

In desulfurization it is well known that the maximum desulfurization rate occurs under conditions where the slag is emulsified into the liquid steel. As yet this phenomenon is not fully modeled. In inclusion removal, the details of particle tracking is possible and has been demonstrated; however, new findings concerning inclusion separation at interfaces have not yet been included in modeling efforts. Thus although great strides have been made in mathematical modeling, further advances are necessary to completely predict the effects of refining reactions in the ladle.

3.4 Other Trends in Refining

Hot metal pretreatment before entry into oxygen steelmaking is employed in Japan as a method of the production of purer steels. Desulfurization, desiliconization and dephosphorization are all common. Levels as low as 5 ppm sulfur and 10 ppm phosphorus are possible with these processes (Sano and Ogawa 2000). Vacuum degassing is also well developed and extra-low carbon steels with carbon contents lower than 10 ppm are routinely produced using this technique (Kurokawa *et al.* 1993).

Reduction in slag volume during processing is also a major trend in Japanese steelmaking. This is driven by the wish to minimize landfilling. For example NKK's Fukuyama works has developed the zero-slag process (ZSP) (Sakurai *et al.* 2000). This effort to reduce waste will be a continual driver of developments in the future (Yamada 1999).

Recycling of steel dust and slag is another major effort towards minimizing the impact of the steel industry on society. There are many efforts around the world aimed at waste minimization, concentration and recycling (Fruehan *et al.* 2000).

Recycling of steel scrap is of course a major initiative in all countries around the world. The major issue in recycling is scrap quality. Copper and tin are the most common problems and unfortunately no economic solution to this problem has been developed even

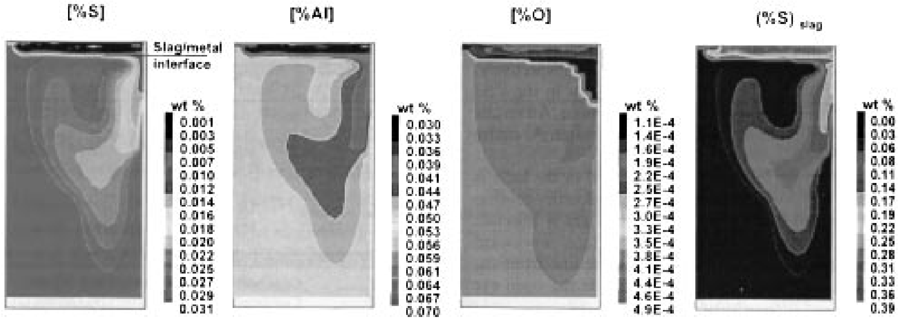

Figure 10
The sulfur, aluminum, and oxygen contents in steel and sulfur content in the slag after one minute of gas stirring (after Jonsson *et al.* 1998).

though significant investment in research in both Japan and Europe occurred in the 1990s. Dioxin generation during scrap melting is also a major problem.

4. *Sustainable Steel Production*

The last major issue in steel production is the trend towards the development of a sustainable industry (Fruehan *et al.* 2000). The Kyoto protocol indicates that the CO_2 production in the world must be reduced. By reducing iron ore with carbon, 1.26 tons of CO_2 are produced per ton of steel (Bizec 2000). Steel production accounts for 4% of the total emissions of CO_2 resulting from human activities. Energy conservation can help but it is not the solution to the CO_2 problem. The fact is that carbon is the cheapest reductant for iron oxide that is currently available. For that reason alone it makes it difficult to change the steelmaking process unless the world comes to a unilateral agreement to reduce the use of carbon as a reductant in steel processing. In electric based steel production the source of electricity must be considered and to reduce CO_2 emissions the electricity must be generated from a noncarbon energy source. At this time, without a unilateral agreement on control of CO_2 emissions, there is no driver for alternate noncarbon technologies of steel production such as hydrogen based reduction.

Sustainable steelmaking is not only CO_2 control but is also control of other pollutants such as solid residues, dust, environmentally harmful gases (dioxins, nitrous oxides, sulfur bearing vapors, etc.) noise, and vibration. One must also consider the development of an integrated life cycle of steel production, use, and recycling where all products, wastes, and emissions can be controlled and contained.

Energy recovery is one of the keys to energy efficiency and calorific and kinetic energies of the outputs of the steelmaking process must be harnessed and used in the process. Waste heat recovery, for example, has the potential to save $100\,\mathrm{kW\,ton^{-1}}$ of steel produced.

The ability to capture and render pollutants harmless is another great challenge. Water, smoke, and dust treatment are all necessary. Gas desulfurization to prevent "acid rain" is of course one of the most prominent issues that must be solved.

Of all the problems in steelmaking, sustainability is the largest challenge; however, significant progress is being made in Japan, Europe, and North America. Government policy will be a major driver in the development of sustainability as the economics of steel production are such that, if policies are not universal, significant advantage will be given to countries that do not adhere to the concept of sustainability.

5. *Conclusions*

Significant technological hurdles remain to be overcome before the steel production and refining developments are complete. This is an interesting time as the concept of sustainability of the industry brings with it a new set of challenges at a time when the product of steel production is a commodity.

Significant plans exist to solve problems of steel production and quality, and new developments in our understanding of inclusion formation and removal are changing our methods of chemical treatment of bulk steels. Current trends are towards more controlled chemistries, lower solute and residual contents, and decreased energy consumption.

Future development will be towards increased recycling, waste minimization, decreased liquid waste, elimination of noxious gases, and decreased vapor and dust emissions. The problem of CO_2 production is not simply solved as no economic reductant, other than carbon, is available at this time.

Bibliography

Bizec R F 2000 Steel industry and climate change—constraints and opportunities. *ICSS 2000 Steel for a Sustainable Society*. The Iron and Steel Institute of Japan, Tokyo, pp. 3–6

Chikama H, Shibata H, Emi T, Suzuki M 1996 *JIM Mater. Trans.* **37**(4), 620–26

d'Entremont J C, Guernsey D L, Chipman J 1963 *Trans. IME* **227**, 14–17

Fruehan R J 1970 *Metall. Trans.* **1**, 3403–10

Fruehan R J, Jung S, Nogueira P, Molloseau C 2000 Critical aspects of recycling waste oxides in steel making. In: Irons G A, Cramb A W (eds.) *The Brimacombe Memorial Symposium*. CIM, Montreal, Canada, pp. 261–74

Hino M, Nagasaka T 2000 The limits of steel refining. In: Irons G A, Cramb A W (eds.) *The Brimacombe Memorial Symposium*. CIM, Montreal, Canada, pp. 243–59

Jonsson L 1998 Mathematical modelling of selected ladle operations—towards metallurgical process models based on fundamental equations. Ph.D. thesis, Royal Institute of Technology, Stockholm

Jonsson L, Grip C E, Johansson A, Jonsson P 1998 A new approach to model sulphur refining in a gas stirred ladle—a coupled CFD and thermodynamic model of sulphur refining in a gas stirred ladle. *ISIJ Int.* **38**(3), 260–67

Jonsson L, Jonsson P 1997 Modeling of the fluid conditions around the slag metal interface in a gas stirred ladle. *ISIJ Int.* **37**(5), 484–91

Kurokawa N, Tanigawa K, Nishida K, Shirota Y, Kikouri S 1993 Present and future technologies for producing ultra-low carbon steel. *CAMP-ISIJ* **6**, 134–37

Misra P, Chevrier V, Sridhar S, Cramb A W 2000 Observation of inclusions at a slag-metal interface. *Metall. Trans. B* **31**(5), 1135–39

Mizoguchi S 1996 A study on segregation and oxide inclusions for the control of steel properties. Ph.D. thesis, University of Tokyo

Novokhatskiy I A, Belov B F 1969 *Russian Metallurgy* no. 3, pp. 13–24

Rastogi R 2000 Nozzle clogging. Ph.D. thesis, Carnegie Mellon University

Sakurai E, Akai S, Watanabe A, Shirayama A, Isawa T, Matsuno H 2000 Reduction of slag volume generation by ZSP. *CAMP-ISIJ* **13**, 52

Sano N, Ogawa Y 2000 Outlook for the next generation of steel making research—Part 1. Recent development of refining process and target of research in Japan. In: Irons G A, Cramb A W (eds.) *The Brimacombe Memorial Symposium*. CIM, Montreal, Canada, 291–309

Sheppard C J R *Confocal Laser Scanning Microscopy*. Springer, Berlin

Shevtsov V E 1981 *Russ. Metall.* **1**, 52–7

Sridhar S, Cramb A W 2000 Kinetics of Al_2O_3 dissolution in CaO-MgO-SiO_2-Al_2O_3 slags: *in situ* observation and analysis. *Metall. Trans. B* **31**, 406–10

Yamada K 1999 Recent activities on reducing steelmaking slag quantity. *Proc. 10th Japan–Germany Seminar*. ISIJ, Tokyo, pp. 17–23

Yin H, Shibata H, Emi T, Suzuki M 1997 *In situ* observation of collision, agglomeration and cluster formation of alumina inclusion particles on steel melts. *ISIJ Int.* **37**(10), 936–55

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