Avenues to Innovative Steelmaking Technologies in Japan*

—Report of Steelmaking Investigative Subcommittee,
Research Planning Committee, ISIJ—

By *Kiminari KAWAKAMI***

Of the total annual production of crude steel, which has kept a level of about 100 million t for the past decade, that from iron ore has decreased from 83 million to 69 million t and that from iron scrap from 36 million to 31 million t. While the ratio of the former to the latter has remained almost unchanged at 7:3, the percentage of BOF crude steel has decreased by 9 points from 81 to 72 % (see Figs. 1 and 2 in p. 758).

Various technical innovations have been made in the BOF sector; 1) achievement of a low thermal energy consumption for crude steel of under 5 Gcal/t, 2) a high rate of continuous casting of over 85 %, and 3) upgrading of products through mass production of clean steel. Hot metal pretreatment, direct rolling of continuously cast slabs and cold charge melting in BOF have been developing. Lower-rate operations resulting from decline in demand is, however, urging more effective and more efficient utilization of production facilities. In the electric arc furnace sector, growth is remarkable in the area of ordinary carbon steel production. This has been achieved by the power consumption reduced to 400 kWh/t (a thermal energy consumption under 65 Mcal/t), and the melting costs reduced through the decrease in electrode consumption and other developments. Another contributing factor is that the electric furnace steelmaking process can flexibly cope with a wide variety in production levels, including short period shutdowns, because of the capability of relatively freely changing the operating scheme. Use of good quality scraps and application of the ladle refining process permit quality improvement in the areas of alloy steel and high grade steel.

Changes in social background such as the rapid growth of communications, computer and electronic sectors of industry, the diversification of materials and the move toward highly information-oriented society in future have created diversified needs for industrial materials including steel. Increase in importation of rolled steel products and the trend to produce more high-quality steels in smaller quantities are urging the steel industry to break away from its traditional standardized mass production system. Under such circumstances, it would be necessary to review established outlook of development program for new steelmaking technologies on the basis of social and industrial needs and seeds as viewed in an enlarged horizon.

Under restrictions in time as well as in materials, the Steelmaking Investigative Subcommittee of Research Planning Committee, ISIJ, have discussed four major subjects selected from among those relating to refining and solidification: 1) the new smelting process, 2) the refining processes of ultraclean steel, 3) the electromagnetic metallurgy and 4) the new solidification technologies. The present report is a result of these discussions, though not covering such associated areas as ceramics, C₁ chemistry, non-ferrous and amorphous materials.

New Smelting Processes

Intensive research and development efforts made during the past few years have resulted in a new process comprising a combination “hot metal pretreatment/decarburization with less slag in a top and bottom blown converter”. It is becoming clearer from economics that the commercial feasibility of this process lies in a rather limited range. This inevitably requires another challenge to a new steel-making process, keeping in mind the motto “producing steel at lower costs”.

In this new round of research and development in search of a commercially feasible process, stress would be placed on:

- (1) minimization of production costs of molten steel throughout the entire process from ironmaking through steelmaking as a whole;
- (2) extensive use of inexpensive iron sources such as scrap in larger quantities; and
- (3) direct connection of the alloy smelting process with the refining process of high-alloy steel.

Necessary prerequisites for these objectives would be:

- (1) establishment of technologies for generating much heat with low-cost fuels and efficiently utilizing it for melting and reactions;
- (2) development of techniques for allout elimination of impurities coming from raw materials and fuels; and
- (3) utilization of thus removed impurities as resources and reuse of metallic components as alloying elements.

Whether the ore-to-scrap ratio in crude steel production in Japan will maintain its present figure of 7:3 or will shift to the European type pattern of 6:4 is one of the key points for predicting future trends in the development of smelting technology. Crea-

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** Chairman of Steelmaking Investigative Subcommittee, Research Planning Committee, ISIJ; Technical Research Center, Nippon Kokan K.K., Minamiwatarida-cho, Kawasaki-ku, Kawasaki 210.

tion of a process capable of taking the place of the present processes of blast furnace, BOF, UHP electric arc furnace and electric ferroalloy furnace surely requires novel and original ideas and seeds in addition to those already studied to date. Research themes conceivable from such a point of view are listed in Table 1. In the area of fundamental research, subjects capable of foresighted future topics in the industry would be preferable to ones falling under the conventional followup research. Information and findings accumulated regarding physical chemistry, phenomena of liquid metal refining and phenomena of mass transfer may form a firm foundation for future research in techniques as well as in basic knowledge.

Ultra-high Purity Refining

Success in allout elimination of impurities in steel as achieved in the course of exertion made during the period of the end 1970's through early 1980's now allows mass production of clean steel. This work is still in progress today, and some researchers forecast levels of impurities of steel mass produced around year 2000 to be 6 ppm for carbon, 1 ppm for sulfur, 8 ppm for phosphorus, 5 ppm for oxygen, 14 ppm for nitrogen and 0.2 ppm for hydrogen (refer to the papers presented at the 90th-91st Nishiyama Memorial Seminar).

With regard to the manufacture of ultra-high purity steel, the subjects left for future study will include:

(1) Properties of Ultra-high Purity Steel:

- 1) Properties of steel containing less than 1 ppm impurities; among others the effects of less than 1 ppm phosphorus, sulfur and oxygen on mechanical properties, corrosion resistance, surface treatment, and electric and electromagnetic properties;

Table 1. Some possible research subjects on new smelting processes.

Smelting reduction process	<ol style="list-style-type: none"> (1) BOF type iron smelting reduction process (2) Continuous steelmaking type iron smelting reduction process (3) Smelting reduction of ferroalloy or high-alloy melt with unused resources such as laterite, manganese nodule, <i>etc.</i>
Scrap melting process	<ol style="list-style-type: none"> (1) Scrap melting method without electric power: <ol style="list-style-type: none"> (a) Increased scrap charging ratio in BOF (b) Scrap melting method for continuous steelmaking process (2) High-efficiency scrap melting methods in innovative electric arc furnaces: <p>Direct current arc furnace, plasma arc furnace, <i>etc.</i></p>
Refining process	<ol style="list-style-type: none"> (1) Elimination of tramp elements in scrap: <ol style="list-style-type: none"> (a) Sn, Zn, <i>etc.</i> (b) Cu, Ni, Cr, <i>etc.</i> (2) Innovative technology for elimination of P, S, and N in carbon steel and alloy steel mother melts

- 2) Effects of interactions among trace impurities on material properties; and
 - 3) Development of analysis techniques capable of readily exhibiting the state of dispersion of impurities.
- (2) Refining Process:
- 1) Extension of the present limits of refining;
 - 2) Development of new refining processes for ultrahigh purity steel, such as:
 - a) Precipitation of solid phase through reaction of gaseous phases;
 - b) Utilization of ultra-high temperatures;
 - c) Application of solidification phenomena;
 - 3) Metallurgical physico-chemistry for the process leading to ultra-high purity steel: thermodynamics of phase transformation (to see if factors other than the mere extrapolation of the currently available data toward zero concentration are necessary), rate of reaction, *etc.*; and
 - 4) New refractories applicable in commercial production of ultra-high purity steel.

Research efforts on ultra-high purity steel with sub-ppm impurities will hereafter have to be done always in association with morphology of solidification and microstructure. It should also be noted that effective utilization of impurities thus removed as useful resources and reuse of metal constituents as alloying elements would be items inseparable from those on ultra-high purity steel, in view of the universal nature of steel as a fundamental material.

Electromagnetic Metallurgy

1. Application of Electromagnetic Force

The metallurgical processes utilizing the electromagnetic force are classified in Table 2 in terms of the method of applying magnetic flux and electric current. Referring to this table, one sees the subjects

Table 2. Classification of metallurgical processes using electromagnetic force.

Processes employing magnetic flux	AC travelling field	Electromagnetic stirring in continuous casting
		ASEA-SKF furnace
	AC field	Electromagnetic pump
		Electromagnetic atomizer
		Coreless induction furnace
		Electromagnetic mold for casting
DC field	Levitation	
	Handling of molten metal	
	Electromagnetic brake, single crystallization	
Processes employing electric current	AC	ESR, Arc furnace, Arc, Plasma
	DC	VAR, Arc furnace, Arc, Plasma
		Aluminum melting refining furnace
Processes employing magnetic flux and electric current	AC·DC	Electromagnetic stirring (Welding)
	DC·DC	Electromagnetic stirring by static magnetic field application method
	DC·DC	Magnetic stirring in ESR and VAR
	AC·AC	

Note *Shape control of molten metal

to be studied hereafter as follows:

(1) Functions of Electromagnetic Force in Molten Metal Handling

Electromagnetic force has two effects on molten metal:

- 1) Stirring and transportation of molten metal without contacting it; and
- 2) Shape control and stabilization of the free surface of molten metal.

Effect 1 has already been embodied in the form of the electromagnetic stirring process and electromagnetic pump, and has been fully discussed from theoretical point of view as well. On the other hand, materialization of Effect 2 is underway in the area of electromagnetic casting for aluminum, although the present level of theoretical and experimental studies seems to be still far from full clarification. Yet, the concept of Effect 2 will be widely applicable in such processes as flattening and stabilizing of a slit stream of steel in the twin-roll method strip casting, slag-metal separation, horizontal levitation and continuous casting without mold.

(2) Utilization of Electric Current as Thermal Energy Source

In apparatuses like arc heating furnaces and ESR, high density electric current is applied to metal as thermal energy source. While molten metal flows at a moderate rate under the interactive effect of induction fields, it is possible to accelerate the motion effectively by applying external magnetic flux on metal, converting a part of the electric energy to kinetic energy.

(3) Control of Solidification Structure

Electromagnetic force is being utilized to control solidification structure in the form of, for instance, electromagnetic stirring based on travelling field to produce equiaxed structure and the use of direct magnetic field to obtain columnar structure or single crystals. These effects are attributed to electromagnetic force which controls the solidification structure through its function of inducing or suppressing the motion of the molten metal. Research on the direct effect of magnetic flux and electric current, without accompanying stirring, acting on solidification structures would therefore be an important subject to be studied hereafter.

2. Refining by Electric Arc, Plasma and Electron Beam

Development of new refining technologies is expected to meet the increasing demand for ever higher quality of steel. Of those, application and development of ultra-high temperature refining and high vacuum refining technologies are to be particularly stressed.

Refining at ultra-high temperatures, like 2 000 °C or higher, makes use of reactions of metal with slag and gas at those ultra-high temperatures using arc and plasma as the heat source. The purpose of this application would be to utilize those reactions that proceed only in the ultra-high temperature region with such features as a high reaction rate and the potentiality of eliminating impurities by evaporation. For

this purpose, it is necessary to study the full range of thermodynamic data on slag/metal and gas/metal reactions at ultra-high temperatures. Degassing at the hot spot by electric arc or plasma will proceed, not in molecular form but in atomic form, *i.e.*, not in the form of $2\text{N} \longrightarrow \text{N}_2(g)$ but in the form of $\text{N}(l) \longrightarrow \text{N}(g)$. Interfacial equilibrium concentration cannot be derived from the currently available thermodynamic data. Further, general attention seems to be given to the future development of refractories capable of holding molten steel at ultra-high temperatures and furnaces capable of freely controlling the atmosphere, and heat sources will be required to incorporate more sophisticated ideas to ensure more efficient and more rapid heating.

High vacuum refining is carried out under a vacuum atmosphere of 10^{-2} to 10^{-5} Torr. Melting is done in a water-cooled copper hearth or crucible, dispensing with refractories or slag, by means of such a heat source as arc, plasma, or electron beam.

The electron beam refining process is based on the energy of high-velocity thermal electrons. In this area, large-capacity electron guns of as much as 1 200 kW have been developed and are being actively utilized in the melting sector. Refining in this process is in principle by the fractional distillation, *i.e.*, selective evaporation, that takes place at the hot spot of beam bombardment. More specifically, the difference in vapor pressure between impurities, gaseous or otherwise, or suboxides such as SiO, and the bulk component enables this refining. This feature of the process is expected to act favorably on refining of pure metals and metals with a high melting point, whereas difficulties in composition adjustment may be encountered in refining of alloys. What are to be developed would therefore be effective heating and melting methods capable of ensuring appropriate adjustment of alloying compositions.

New Solidification Processes

1. Strip Casting

Efforts made to minimize the consumption of energies and resources since oil crisis have resulted, as one of the possible counter-measures, in positive encouragement of wider application of continuous casting processes. This has in turn led to direct connection of casting to rolling. The most recent achievement in this area is the industrialization of hot direct rolling, in which slabs are sent to the hot rolling mill as they leave the continuous caster, omitting the conventional step of reheating. In view of this general tendency toward elimination of the steps currently existent between casting and rolling, the major subjects to be studied would include alleviation of the burden on rolling and adaptation of the strip caster to steel following examples in aluminum and other industries.

Any of single-roll, twin-roll, twin-belt and caterpillar-type casters are conceivable for rapid solidification process of thin cast slabs. In this respect, the Hazellet casting process has once been studied for

steel. In anticipation of targets of future research and development getting diversified, emphasis should be placed on setting of strictly defined targets for development and preparation of research plans well meeting the objectives. A key to successful industrialization of strip casting is the productivity. Achievement of a higher productivity will require new ideas to bring about improvements in equipment, technology as well as such fundamental research subjects as phenomena of heat transfer and boundary film with a view to increasing the cooling rate, initial solidification phenomena at higher cooling rates and physical properties of cast immediately after solidification.

2. Rapid Cooling

Efforts are being made to upgrade steel properties through allout elimination of detrimental impurities and application of the refining technologies making full use of favorable characteristics of trace additives, controlled rolling and heat treatments. Studies will be made on the solidification phenomena and material properties at the cooling rates of 10^2 to 10^5 °C/sec accelerated from the current level of 0.1 to 0.5 °C/sec, so as to examine potentialities of new processes having features different from those of the conventional ones. Association of findings derived from these studies with new control techniques of material properties would also be an important subject of research.

Besides those methods that are intended for small or thin articles, several solidification methods are being studied to pursue the effects of applying ultimate conditions to massive objects. Some examples are described in the following paragraphs.

3. Unidirectional Solidification

Unidirectionally solidified slab ingots, having a height of 0.7 to 1.0 m with a square or rectangular bottom face having a side of up to 4 m, are produced on a stool by bottom pouring to a weight of 20 to 70 t. The ingot solidifies in a columnar crystalline structure proving unidirectional growth of grains from bottom toward top, and heavy ingots with sound inner quality free from segregation and shrinkage pipes are obtained. These ingots are rolled to large heavy section plates in a usual manner, that is, by rolling transverse to the direction of grain growth to break down the columnar crystals.

Comparison of mechanical and working properties, particularly at elevated temperatures, of the solidification structure between growth direction and the direction transverse thereto reveals that the properties in the growth direction are sometimes far superior to those in the transverse direction. This difference varies with the chemical composition and may be remarkable in some high-alloy grades, as is effectively used in manufacture of the single crystal heat-resistant superalloy casts. This technology would be more popularly utilized also in other areas.

A solidification process capable of minimizing grain boundaries or manufacturing of single crystal would be developed into continuous casting.

Continuous casting of such a material into rod or plate shape will lead to mass production of new materials excellent in formability and electromagnetic properties. For this, there is a motion of using hot mold to produce unidirectionally solidified casts through continuous casting, as is already applied to various materials with a low melting points.

4. Spray Casting

Techniques have been developed to produce ingots with a fine grain structure by causing incremental solidification of molten steel in the form of partially solidified droplets collected in a mold or on a chill plate. They are the spray casting such as the OSPREY process to realize an incremental solidification and the VADER process to produce a fine microstructure in a horizontal VAR. These techniques are reportedly suitable for the manufacture of composite materials. Ingots produced should be free from macro-segregation as well as from semi-macro-segregation in principle, although the actual progress of solidification in the interior of ingots is not as yet known. Incremental solidification of molten steel droplets will provide new research subjects such as control of fine grain size and phenomena around grain boundaries in microstructure.

5. Alloy Powder Solidification

Globular powdery particles with a fine microstructure free from segregation can be made by rapidly solidifying the atomized alloy melt. Since these fine particles will serve as new raw materials for powder metallurgy to develop new materials having novel properties, method of manufacturing those particles have to be furthermore developed.

Research will be needed in such areas as 1) manufacturing processes of powder having a uniform particle size distribution, 2) solidification behavior and resultant structure of powder, and 3) properties of parts manufactured by a powder forging process such as the DPC process.

Research regarding rapid solidification of thin film will be another matter. This will be a study on phase transformation taking place during recalescence from greatly undercooled solidification. As rapid solidification of a metal statically brings about an undercooled metastable equilibrium, clarification of the free-energy hierarchy of various phases and thermodynamic elucidation through experiments of phase transformation occurring during recalescence from undercooled solidification will assume considerable importance in this area of research.

Many topics intrinsic to the individual processes control of crystal orientation on solidification, solidification process of solid-liquid coexistence, interrelations of plastic working, recrystallization behavior, and resultant properties will serve as common subjects to many processes.

Afterword

Two major approaches in research and development will be increasingly more clearly defined in the steelmaking sector: one will be on the existing production technologies while the other on more creative subjects associated with quite new technologies, applications and procedures. Both are expected to play essential roles for the survival of the steelmaking industry in Japan.

To be successful in research activities in new areas, it would be necessary to carefully work out research plans as derived from the keenest sense of foresight and the most imperturbable insight prior to actual investment for development in terms of personnel,

time and costs. Then, objectives must be properly selected strictly in compliance with the research plans thus prepared.

The present paper has summarized the subjects in the four areas, and the members of Subcommittee hope that this will provide to the readers materials for more active discussion of future potentialities of the scientific features of refining and solidification.

The two possible orientations of future efforts, if made in close cooperation with each other, will surely bring about further advancement of steelmaking technologies as a whole and allow further innovations in techniques and applications as well as in functions.

Fig. 1. Breakdown of annual crude steel production according to raw material.
(Source: Research and Statistics Dept., Secretariat, Ministry of International Trade and Industry)

Fig. 2. Annual crude steel production according to the source.
(Source: Research and Statistics Dept., Secretariat, Ministry of International Trade and Industry)

**Members of Steelmaking Investigative Subcommittee,
Research Planning Committee, ISIJ**

(As of March 31, 1984)

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Kiminari KAWAKAMI
Head of Steelmaking Laboratory, Technical Research Center,
Nippon Kokan K.K.

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Laboratories-III, Nippon Steel Corporation
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Japan
Yutaka TAKEMURA
Staff Engineer, Technical Dept., The Iron and Steel Institute of
Japan

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