Steelmaking Technology for the Last 100 Years: Toward Highly Efficient Mass Production Systems for High Quality Steels

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Progress of steelmaking technology in Japan over the last 100 years is overviewed covering hot metal pretreatment, primary steelmaking with open hearth furnaces, converters and electric arc furnaces, secondary refining of steel with degassers and ladle furnaces, and ingot- and continuous-casting. Key issues that contributed considerably to the progress of the unit processes are highlighted with scientific, technological and engineering breakthroughs involved. Also, systematization of the unit processes is depicted for optimizing full cost, productivity and quality of steel products to meet the constraints on the resources and socioeconomic demands of the steel market at times. Possible future development of steel technology is briefly commented on the basis of the above observation.

KEY WORDS: Historical overview; hot metal pretreatment; primary- and secondary-steelmaking; ingot- and continuous-casting; steelmaking system.

1. Introduction

Celebrating the centennial anniversary of the Iron and Steel Institute of Japan, an attempt is made to give an overview of the development of steelmaking technologies in Japan in the last 100 years with own limited experiences in the field of 55 years and available literatures. The technologies cover hot metal pretreatment, primary- and secondary-steelmaking and ingot- and continuous-casting, which were improved and optimized for materials and market available at times by the lasting efforts of our predecessors. The overview is intended to give a concise but panoramic understanding of the past developments and stimulate the coming generation to further revolutionary technological advance for the future development of the steel industry.

2. Open Hearth Steelmaking1–9,12)

2.1. From Crucible Furnace and Bessemer Converter to the Golden Days of Open Hearth

Steelmaking furnaces so far industrialized in the world were: Converter with acidic refractory lining and air blowing bottom tuyeres in 1856, Siemens open hearth in 1857, and Martin furnace for scrap melting, and Siemens-Martin open hearth which combined the last two in 1864. It took, however, about 20 years more, when the converter and open hearth, both lined with basic refractory, successfully dephosphorized hot metal for mass production of steel with acceptable quality. Hot metal in Europe was high in phosphorus (P) since iron ore available there was high in P.

Mass production of steel in those days was dominated by Britain, Germany, Belgium and USA. Japan imported necessary pieces of equipment, materials, operational skill, and raw materials from these countries to start industrial steelmaking with crucible furnace in 1890. Acidic open hearth and acidic Siemens-Martin open hearth were installed in 1890 and 1896 at navy- and army-steelmaking factory. Annual production of the factories was a small sum of 2.4 k tons, only about 1.1% of annual steel imports of 220 k tons.

Integrated iron and steel plant ever started in Japan was in 1901 at state-owned Yawata Works. A 160 ton blast furnace (BF) was put into operation in Feb., and steel melt from a 25 ton open hearth was cast into 3 ingots in total of 10 tons in May. In November, steel melt from a 15.6 m³ Bessemer converter was cast into 5 ingots, totaling 8.5 tons. Japanese naming for open hearth, Heiro, and converter, Tenro, was given by Imaizumi.5)

After the end of the Russo-Japanese War in 1905 until the outbreak of World War I in 1914, Japanese steel industry suffered from a recession, facing plant shutdowns and mergers. Inadequacy of equipment for operation and lack of decent quality coal and iron ore were considerable. Despite the unfavorable circumstances, efforts paid by Yawata Works made it possible in 1914, 100 years ago, to convert steel ingot production from remelting and casting iron made with traditional charcoal based Tatara process (17 ktons/year) to casting steel made with Basic Open Hearth (BOH) (275 ktons/year) and acidic Bessemer converter (106 ktons/year).

Productivity of the acidic Bessemer converter was much greater than the BOH (Fig. 1),6) but the slopping loss of met-


al out of the converter mouth and erosion wear of the bottom tuyeres resulted in 8% lower metal yield on ingot basis and 3.4% higher cost of production. In addition, the Bessemer converter could not make P content lower than about 0.1% with the acidic lining, and hence the application of steel products was limited to commodity wire, rod and medium gauge rail. The high P content was a consequence of unavoidable use of P-bearing iron ore (0.2–0.3%) for blast furnace due to the war time shortage of low P ore imports. To improve dephosphorization (deP), refining the converter melt with BOH was attempted by the name of Converter-BOH Combination process (double refining). However, the process was found 6% lower in metal yield and 14% higher in ingot cost, could not compete with advanced operation of BOH, and hence terminated in 1927.

The recession period was followed by the Japanese participation in World War I which took place from July, 1914 to Nov. 1918. In the early period of the war, 4 BFs and 12 BOHs were made operational, added with 6 BOHs of 50 ton capacity by 1918. To supplement the insufficient supply of scrap, use of iron ore instead was practiced in BOH. With these measures, ingot production reached 440 ktons/year to suffice the demand. In the above period, private steel companies also started steel supply with new plants which include: (1) Sumitomo Cast Steel Works (later Sumitomo Metal, now Nippon Steel Sumitomo Metal, NSSM) at Osaka in 1902, (2) Kawasaki Shipyard Plate Plant (later Kawasaki Steel, now JFE Steel) at Hyogo in 1907, (3) Kobe Steel at Kobe in 1911, (4) Nippon Kokan (later NKK, now JFE Steel) at Kawasaki in 1914, all with BOHs of 3.5 ton to 15 ton capacity.

2.2. The Rise and Fall of the BOH Steelmaking

New installations and modifications of BOHs to larger capacity continued after 1915 to meet the increasing steel demands with the progress of domestic industry after World War I and the outbreak of the Manchurian Incident in 1933. Total number of BOHs reached 113 (91 above 25 ton capacity) in 1933 to produce 3.06 million tons, excluding those in Manchuria and Korea in Japanese occupation. Among them, BOHs operated by the private steel companies with pig iron and scrap increased to 77 (59 above 25 tons). Pig iron of 0.455 million tons and 0.172 million tons was imported from Manchuria and India, while scrap of over 1 million tons was imported from USA. In 1934, the imperial congress passed a bill for the merger of the state-ownedYawata Works to form Nippon Steel Company (abbreviated as Nittetsu, now NSSM) with private plants including Wanishi, Kamaishi, Fuji, Kyusyu and Ken-Ninpo. Suspected short supply of scrap and pig iron with the developing Incident promoted the approval, construction and operation of 200–1000 ton/day class BFs of each company.

The Manchuria Incident developed into the Sino-Japanese war during 1937 and 1945. In 1939, 2.17 million tons and 0.11 million tons of scrap were imported from USA and India to increase all Japan production of BOH steel to 5.65 million tons. This level of production was somehow maintained until 1943. However, World War II broke out in 1939, import of scrap was prohibited, and hence BOH was forced to operate with high ratio of hot metal instead of scrap. As a countermeasure, NKK introduced 3 basic refractory lined bottom air blown 20 ton Thomas converters from Germany, and started operation with high P hot metal in 1938. Two more Thomas converters were installed by 1941 to produce 0.35 million tons of steel in 1942. However, bombed out circumstances compelled all the converters to shut down in 1945.

Progress of steelmaking technology in Japan until 1945, when Japan was defeated in World War II, was the period of conversion from traditional Tatara process into modern processes with Bessemer converter and BOH. Our predecessors implemented the modern processes, optimized them to fit Japanese conditions, making them competitive in productivity and quality with those of advanced countries. In the era when the disturbances dominated over the society and economy of Japan, unique technology was not invented. Depicted below are, however, noteworthy progresses made under the very difficult conditions:

(1) Decrease of the refining time and energy consumption in BOH steelmaking with shift of fuel from generator gas to heavy oil or mixture of coal gas and BF gas,
(2) Industrialization of the use of pig iron with ore, or hot metal with scrap to replace 100% scrap operation in BOH,
(3) Implementation of hot metal mixer for hot metal pretreatment for homogenization,
(4) Enlargement of BOH for greater productivity, and
(5) Domestic production of furnace refractory of acceptable quality.

As a consequence, all Japan BOH steel total of 5.63 million tons was produced even in 1943, among which 3.38 million tons, 60%, was due to Nittetsu. At the end of 1945, the number of BOHs amounted to 197 among which 67 were 50–80 tons, 10 were 100 tons and 11 were 150 tons capacity. As the impact of the war got worse, supply of good quality iron ore and scrap became scarce, and the equipment and personnel for steel production were damaged and decreased by bombing, resulting in a sharp decrease of steel production to 1.23 million tons in 1945 when World War II ended. Situation deteriorated further in 1947 when post-war disturbances still remained. We saw only 20 BOHs in operation, producing a very limited amount of 0.4 million tons/year of carbon steel.

The General Head Quarters (GHQ) of the United Nation forces (UNf) demanded to dismantle 91 BOH to indemnify
in kind UNf for war damage. Fortunately, it was soon withdrawn to promote economic self-reliance of Japan and meet the need of GHQ to supply materials to support UNf for the Korean war which lasted during 1950 and 1953. Thus, steel industry in Japan was made exempt from crashing down. Increase of steel production started, followed by the removal in 1948 of embargo on the import of iron ore and coal.

2.3. Enlargement of BOH after World War II and Development of Oxygen Steelmaking\(^{10-12}\)

German type BOHs were dominantly utilized in Japan in the war time. During 1948 and 1949 after World War II, equipment and operation of USA type BOHs, which were superior to German type, were introduced to Japan by USA specialists. Delegation to implement the BOH technology was also sent to USA for training. Consequent improvements transferred were:

1. Enlargement of stationary hearth BOH with hung down refractory ceiling structure,
2. Movable down-spout for tapping, and jet tapper,
3. Venturi combustion system with enlarged gas port, gas uptake, and checker brickwork in recuperator chambers,
4. Blaw-knox type valve to change gas flow,
5. Quick charging of scrap box,
6. Positive pressure operation of BOH to prevent the intake of ambient air,
7. Conversion of generator gas or mixed gas combustion to heavy oil combustion due to the removal of oil embargo,
8. Utilization of sensor controlled operation with pressure gauge, gas flow meter and thermometer,
9. Use of basic refractory bricks for the front- and rear-wall and the ceiling of BOH, and
10. Magnesia stamping and dolomite running on the hearth.

During 1949 and 1957, average capacity per heat of BOHs increased from 62 tons to 92 tons, maximum nominal capacity being 150 tons. In 1957, the number of BOHs with heavy oil combustion or heavy oil mixed combustion reached 115 out of 124. In the following 5 years, BOH capacity kept increasing. Within the major 4 companies, Yawata, Fuji, NKK and Kawasaki, for example, 4 × 150 ton Märzt/Märzt Böhrens\(^*\) type stationary- and tilting-BOHs with Venturi combustion system and 3 × 200 ton BOHs were installed together with revamped 9 × 150 ton BOHs and 11 × 200 ton BOHs (*Note: All basic refractory brick structure with checker brickwork type No.1 chamber and ordinary type No.2 chamber. First put into operation at Sumitomo Metal Wakayama Works in 1959).

Also, oxygen injection steelmaking process, which was popular in USA, was introduced after joint industrial tests carried out by 8 domestic companies. This was in collaboration with the installation of Linde-Frenkel type mass production system for pure oxygen. The oxygen steelmaking process\(^{12}\) utilized oxygen for:

1. Enhancing the combustion of fuel from burner,
2. Cutting the scrap debris before melting down, and
3. Bessemerizing of steel melt after the melt down.

These measures considerably improved the productivity and fuel consumption of BOH.

In fact, the peak production of steel with BOH oxygen steelmaking in Japan recorded a high 16.17 million tons in 1961. At Fuji iron and Steel (now Nippon Steel Sumitomo Metal, NSSM) Hirohata Works, scrap 210 tons were overcharged in a 150 ton BOH, converted into steel in 6 h (productivity 33 tons/h) with 25 Nm\(^3\)O\(_2\)/ton at a fuel consumption of 1 420 Nm\(^3\)/h, much better than 12 h (16 tons/h) and 4 180 kJ/ton for normal operation. Similarly, at Kawasaki Steel (now JFE Steel) Chiba Works, scrap 185 tons were overcharged in a 150 ton BOH, and converted into steel with large supply of oxygen in 2 h 40 min. With 6 of the BOH and oxygen supplied from Linde-Frenkel oxygen generators in total of 13 400 Nm\(^3\)/h, average productivity of steel achieved 65 tons/h/BOH. Maximum productivity surged to 100 tons/h/BOH when maximum oxygen supply of 50 Nm\(^3\)O\(_2\)/ton was executed. Chiba with the 6 BOHs counted the highest production record of 180 ktons/mo. as a single BOH plant in Japan.

Bessemerizing (oxygen injection) was made via calorized steel tube inserted in steel bath in BOH through a view port at the charging doors of BOH. It was quite an experience of the author to watch the surface of the bath while pushing the consumable pipe into the bath on shoulder as it melted away during the Bessemerizing. As bath temperature rose with time, decarburization and refining proceeded with carbon boil. Top slag on the bath was mixed up with metal on vigorous break up of CO bubbles. When compared with chemical analysis report of samples taken from time to time, the author realized how decarburization and refining went on. It was a marvelous moment of on site and real time observation of metallurgy of steelmaking.

3. Steelmaking with Oxygen Top Blown Converter\(^{9-13}\)

3.1. Evolution of Oxygen Top Blown LD Converter Steelmaking

Oxygen top blown Linz Donawitz converter (LD) started its operation at Vöest Linz with 3 × 30 t vessels in 1952 and at ÖMAG (Alpine) Donawitz with 2 × 30 t vessels, all with BOH hot metal. In Europe, Thomas converter process was in operation with high P hot metal smelted from European iron ores with high P content. However, such P-bearing iron ores were not available in Austria where only low P hot metal was produced. Low P hot metal was insufficient to sustain heat balance in Thomas converter. In addition, demands for steels low in P and N were surpassing to guarantee better cold formability. Thomas converter steel was difficult to meet such demands. Attempts were made to decrease N in the converter steel with oxygen enriched air blow, but not successful due to heavy tuyere erosion. Scrap supply was insufficient in Austria to sustain BOH operation despite the fact that BOH steel lower in P and N is better in cold formability.

To solve the problems, Dürrer and colleagues carried out experiments with pure oxygen blown from water cooled top lance to the steel melt surface with success. Vöest and ÖMAG adopted the technology, went into joint development, and succeeded to operate 2 ton vessel, subsequently 12–15 ton vessels in 1949, making the contents of P, N and O reduced below BOH steel.

3.2. Transfer of LD Steelmaking Process to Japan\(^{10-12}\)

Regarding pneumatic converter operation in Japan, Yawata had operational experiences of Bessemer converter which
lasted until 1927 and of 5 ton top blown converter since 1954. NKK revitalized basic Thomas converter operation in 1954 with oxygen enriched air blow. The two companies had an exposure to the information on the LD operation in Austria via Ministry of International Trade and Industry (MITI) and a trading company of Japan. They were stimulated by the operational advantages over Thomas converter or BOH of LD that fits low P hot metal, lower scrap ratio, lower refractory consumption, and needed no heavy oil as fuel. Also, productivity, installation cost, labor cost, operating cost and steel quality of LD were speculated better than Thomas converter or BOH, although the process technology was still in its infancy of industrial mass production.

The two companies sent separately their representatives to confirm the speculation on sites, believed the future potential of LD process, and attempted to negotiate independently with Alpine to introduce LD technology. In view of national interest, however, they accepted, under the auspices of MITI, to let NKK as the sole representative licensee of the use and granting in Japan of the technology. Accordingly, the licensee contract was struck between NKK and Brassert Oxygen Technik AG (BOT; licensing company) via Alpine in 1956. Yawata struck with NKK sub-licensee contract which has been kept open for domestic third parties. Installation and operation of 50 ton LD at Yawata and 42 ton LD at NKK started soon in 1957 and 1958, as the milestone in the history of LD steelmaking in Japan.

The aforementioned advantages combined with financial support by MITI on the second rationalization program of Japanese steel industry prompted other steel companies to install LD converters (Fig. 2, upper left). The share of LD steel production started around 5% in 1958, surpassed BOH steel share in 1965 to reach 55%, and achieved in 1970 a high 79% with a production of 73.51 million tons, top in the world. New installations of LDs and conversion of BOHs to LDs, and revamping and merger of obsolete LDs to build new LDs continued until 1973, just before the oil shock crisis. It was the time when we saw a total of 92 LDs including 11 × 250 ton vessels and 6 × 300–340 ton vessels kept the leading position in both the amount and share of LD steel production in the world, exceeding West Germany, USA, Britain and USSR.

In contrast, BOH steel production declined sharply. In 1970, BOHs in major steel companies were all shut down, leaving only 1.99 million tons produced in 1971 in Japan. Last BOH was shut down at Tokyo Steel Okayama works in 1977, closing long glorious history.

3.3. Development of LD Steelmaking Process in Japan

The prosperity of LD process was brought about by such advantages as a few times greater productivity, lower production cost (~10% for carbon steel, ~30% for HSLA steel) and lower need of scrap than BOH process. The advantages were materialized due to the following improvements and developments in equipment and operation elaborated after the LD technology transfer:

1. Enlargement of the shell volume, supporting and tilting mechanism for the vessel with concentric tulip profile and taphole, eliminating detachable bottom. For a 300 ton vessel, inner steel shell volume and height/diameter ratio were set, for example, to be 553 m³ and 1.3. Top cone angle was optimized, and trunion ring support and stepless variable speed tilting system were selected,

2. Water cooled main lance with multiple hole nozzle tip was invented to prevent spitting and bottom refractory erosion during the blow (1962–1970),

3. Automatic exchange system of sub-lance, equipped with temperature sensor and carbon meter, was made fully operational (1966–),

4. Non combustive off-gas recovery system (OG) was developed by Nippon Steel (now Nippon Steel Sumitomo Metal, NSSM) to retain off-gas energy and minimize off-gas volume and particulate emission (1962–1969). The system has been upgraded and popularly accepted in the world,

5. Considerable reduction of vessel refractory consumption to ~7 kg/ton-steel with the development of tar bonded dolomite, stabilized dolomite bricks followed by magnesia carbon bricks,

6. Significant improvement of the hit rate of carbon content and temperature (C-T) window at the blow end was achieved with a static and dynamic computer control of the main lance height and oxygen flow rate, utilizing accumulated blow data calibrated with C-T values measured on time with the sub-lance,

7. Production of hot metal low in Si and P for LD by use of advanced operation of BF with low P iron ores imported from Brazil and Australia, accompanied by decreased return of P-bearing BOH slag to BF,

8. Development and implementation of hot metal pretreatment process and secondary refining process prior to and after the LD blowing,

9. Advance of single slag and catch carbon blowing technique for medium and high carbon steels, low alloy steels and stainless steels to the extent that the resulting steel quality was approved by the standards in JIS specifications,

10. Prolongation of vessel life beyond 5000 heats/campaign by developing zone lining of refractory, hot gunning...
refractory repair technology and enrichment of magnesia in LD slag during the blow, resulting in increased LD productivity.

(11) Progress in (a) Measurements at elevated temperatures of thermodynamic quantities and physical properties of the materials relevant to the process, (b) Equilibrium calculation for steelmaking reactions, (c) Modeling of heat, mass and energy transport phenomena for the process analysis, (d) Fluid dynamic simulation of the process, and (12) Development of the theory and system for the control and automation of the process.

Many of the above depended on the progress achieved in Europe and USA. Among them, however, original development and industrialization progressed in Japan were items (2) and (4), and considerable progresses achieved in Japan after they were originally introduced from abroad were items (5) through (12). Cooperation among the licensee companies to share relevant information on timely technological advances at the meetings and plant visits of LD committee (later Discussion Meetings for Japan LD Technology) promoted by NKK and Yawata for Japan BOT members (1958–1966), contributed greatly to the progresses. The meetings were succeeded by the Steelmaking division of Joint Study committee of the Iron and Steel Institute of Japan (ISIJ). Also, joint activities among academia and industry held by the Joint Study committee for the Fundamentals of Iron and Steel, by Melt Refining division and by bi-annual Meetings, all held under the auspices of ISIJ, and those held by 19th committee (1934–) of the Japan Society for Promoting the Science (JPS), all enhanced the progresses greatly. It must also be noted that these activities were supported by the Japan Iron and Steel Federation (JISF) and MITI either directly or indirectly.

3.4. Maturation of LD Process for High Productivity

LD operation continued to proceed toward higher productivity with extended flexibility for hot metal ratio under favorable economy which prevailed after 1967. Notable technologies that supported maturation of LD for higher productivity were:

(1) Charge time reduction with large capacity torpedo/ladle car to transport hot metal to steelmaking shop, and the same with scrap loading in charging shoot in separate building,
(2) Thinner refractory lining to enlarge the inner volume of the vessel with developed magnesia-carbon brick,
(3) Hot gunning of magnesia or dolomite with vessel profile monitoring, and slag coating, both to cutback the repair time and prolong service life of the vessel refractory,
(4) Computer control of the main lance height and oxygen flow rate, and optimization of the multiple hole lance tip design, both to minimize slopping and enhance deP under much increased oxygen flow rate,
(5) Three vessels operation out of 3 vessels installation,
(6) Development of “Direct tapping” which eliminated the time consuming end point sub-lance measurement of C and T, as the ultimate in dynamic blow control.

Consequently, average productivity of LDs reached 240 tons/h in 1974 with the improved equipment and operation. End point hit rate for C-T window in many LD plants achieved about 90% for low C steels, although scrap rate was limited. Vessel refractory life was very much prolonged, record being 10 110 heats/campaign established at Nippon Steel (now NSSM) Kimitsu Works.

Noteworthy progress of LD process since then has been further prolonged vessel refractory life with slag splashing practice developed in USA.16) After tapping, dolomite is added to remaining slag on the bottom of the vessel, main lance is lowered some 70 cm above the bottom, and the magnesia enriched molten slag at the bottom is splashed with nitrogen gas blown from the main lance to weld coat the inner surface of the vessel refractory. No particular equipment is necessary, operation is simple, lasting within a short period of time to proceed to the subsequent blow, and hence the splashing technique soon has become popular worldwide. Refractory life from fresh lining to the 1st relining exceeded some 20 000 heats. In the slag splash coating practice, however, clogging of tuyeres installed at the bottom of mixed blown converters (see later) was worried about in the beginning. It was resolved by controlling bottom gas flow rate at the nitrogen gas flushing. Recent presentation17) reportedly said that delivery of inert gas through concentric bottom tuyeres combined with proper gas flushing program made the refractory life extended up to 50 000 heats/campaign. Caution is, however, necessary to keep reasonable trade off, i.e., not to worsen proper blow characteristics in the vessel with off-design distorted inner profile which may result from too many times of the splashing.

Regarding the automatic blow operation, the C-T hit rate was made better for narrower target window. Trimming the blow pattern was refined for reduced spitting and slopping with amended material addition. These were made possible on the basis of integrated computer analysis of the data acquired with sensors for the volume and composition of off-gas, temperature and compositions of the steel melt, vibration of the vessel, and acoustic wave characteristics in the vessel.

4. Steelmaking with Bottom Blowing and Mixed Blowing Converter18–20)

4.1. Birth of Bottom Blowing Converter, OBM/Q-BOP

Except for its own advantages mentioned above, LD exhibited some drawbacks, i.e.,
(1) Insufficient mixing of metal bath, resulting in heterogeneity in temperature and chemistry of the bath,
(2) Sluggish molten slag formation of added lime,
(3) Loss of iron caused by excessively high temperature and over oxidation at the impinging points of oxygen jet on the metal bath, and
(4) Difficulty to prevent the slopping when abrupt CO bubble evolution occurred due to the over oxidation and heterogeneity of carbon distribution in the bath. The multiple hole lance tip was to some extent effective to reduce the slopping by decreasing the heterogeneity, but not fully. The slopping happens when the bubbles in the molten slag do not break up easily and retained in the slag under unfavorable combination of temperature and the bubble breakability of the slag when deC rate is high.

Thomas converter could avoid the heterogeneity and hence the slopping. As mentioned before, however, it could not take up more than 40% oxygen in the blowing gas due to the serious incidence of the tuyere erosion. Savard and
Lee\(^{20}\) of Canadian Liquid Air overcame the erosion problem with a new idea to employ concentric double tube tuyeres after many difficult trials. Hydrocarbon gases (propane, methane) were passed through outer slit of the concentric tuyere tube as a coolant which endothermically decomposed to cool the tip of the tube. Oxygen gas and lime powder were injected through the inner tube into the melt. A porous accretion called “mushroom” was formed on the tip which prevented direct contact of steel melt to the tip, and cool decomposed gas was allowed to pass through the pores.\(^{21}\)

Brotzmann of Maxhütte decided to replace the tuyeres with the concentric ones at 20 ton Thomas converter of Maxhütte, made trials in 1967, and succeeded in the industrialization in 1968 by the name of Oxygen Bottom Blown Maxhütte (OBM). Later, US Steel implemented the OBM in large scale at Gary works 200 ton basic oxygen furnace (BOF, same as LD, but claimed to be USA origin) in 1973 and at Fairfield works 160 ton BOFs in 1974, by the name of Q-BOP which stands for Quick refining, Quiet blowing, Quality Basic Oxygen Process.

Major problem encountered with Q-BOP was poor endurance of the bottom tuyeres. It was necessary to keep the mushroom accretion on all tuyeres in similar size for long life of the tuyere bottom. If imbalance in the cooling happened to let a mushroom melt away, the tip of the tuyere burned back excessively to damage the bottom. In an extreme case, the burn back proceeded to the outer side of the bottom, caused back fire to burn through the tuyere, and burned the connecting oxygen gas piping, resulting in steel melt leakage out of the vessel.

4.2. Blowing Characteristics of Q-BOP\(^{18}\)

In Japan, Kawasaki Steel introduced Q-BOPs in 1977 to build two 230 ton Q-BOPs with 18 and 22 tuyere bottoms at Chiba (Fig. 2, upper right).\(^{16}\) Parameters to control the blowing process were established through extensive investigation with a water model and a 5 ton Q-BOP for the melt flow in the vessel, mode of lime injection, characteristics of steelmaking reactions, and wear of refractory.

Q-BOP is distinctly different from LD as follows due to the full injection of oxygen gas and lime powder from the bottom tuyeres:

(1) Quick remelting of charged scrap,
(2) Very fast homogenization of steel melt is sustained to low C range. In terms of the time required for uniform mixing of the melt, Q-BOP takes only about 10% of that for LD (Fig. 3).\(^{23}\)
(3) The rate of decarburization (deC) is also very fast, proceeding in near equilibrium for C-O reaction.
(4) Loss of Fe and Mn in slag caused by over oxidation is smaller, and hence yield of Fe and Mn is higher. For example, total Fe content in slag (T.Fe) at 1630°C and 0.04%C is ~12% against ~23% for LD.
(5) Oxgen consumption for Q-BOP is lower, accordingly. Decarburization oxygen efficiency for LD decreases from unity at 0.8%C down to 0.6 at 0.2%C, whereas for Q-BOP, it keeps unity until 0.4%C and decreases to 0.9 at 0.2%C. Decarburization limit of Q-BOP is lower than LD, can be less than 0.02%C.
(6) Slag formation is quicker, over oxidation and slag amount are much smaller, and hence sample taken with sub-

lance represents C and T of the melt bulk better. Consequently, the hit rate at blow end reaches near 99% and reblow rate less than 1% for a target window of 0.05 ± 0.015%C and 1610 ± 10°C at 10% scrap operation,
(7) Slopping is much decreased and off-gas recovery with OG reaches 1.4 GJ/ton,
(8) Desulfurization (deS) ratio is better, and deP ratio is not much different from LD despite lower (T.Fe). Provided that split injection of lime in the initial period and later period of blowing is properly executed.

On the other hand, inherent disadvantages of Q-BOP are:

(1) Higher cost of investment,
(2) Refractory life of the tuyere bottom is still shorter than that of the vessel, calling for 2–3 times of the bottom exchanges during a campaign of the vessel refractory,
(3) Scrap charge ratio becomes less to the extent equivalent to the heat loss caused by the coolant gas usage,
(4) Blow end hydrogen content in Q-BOP melt, even after Ar flushing, is higher (4–7 ppm) than LD melt (2–3 ppm) due to the hydrogen input generated by the decomposition of the hydrocarbon coolant. In modern steelmaking system where vacuum degassing is commonly equipped, this may not be a serious issue, though.

As a similar process to Q-BOP, kerosene coolant was used instead of hydrocarbon gases in 240 ton LWS converter at Sollac in 1978.

The above mentioned blowing characteristics were semi-empirically well explained by Nakanishi et al.\(^{23}\) in terms of an Index for Selective Carbon Oxidation (ISCO) based on model study and on site operation data. The ISCO consists of the product of two terms;

(1) Thermodynamic term stands for the partial pressure of CO which defines C-O equilibrium on the melt bath surface, and
(2) Relative mass transfer term represents the ratio of mass flux of oxygen supplied from the bottom tuyeres (or main lance) to the gas/melt boundary to the mass flux of C supplied from the melt bath to the boundary. Here, the mass flux of C was approximated by the average melt flow rate, \(q\), in the bath, and \(q\) was defined proportional to the inverse of uniform mixing time, \(\tau\), of the melt (\(q = 1/\tau\)). \(\tau\) was determined proportional to about -0.4 power of the mixing energy, \(\varepsilon\), supplied to the bath (\(\tau \propto \varepsilon^{-0.4}\)). Term (2) shows the pre-
dominance of either the oxidation of Fe or the oxidation of C of the melt under a given CO pressure. The smaller the ISCO value, the better is the preferential deC to lower C range without much loss of Fe into top slag.

The ISCO value successfully described the first time in an integrated way the relation between the degree of melt stirring and the oxidation into slag of constituent elements in the metal bath for a variety of primary and secondary refining furnaces (Figs. 3 and 4, for example), and considered to be a great contribution to process metallurgy. Later, Kai et al. proposed an amended index, Balance of Oxygen and Carbon Feeding Rate (BOC), eliminating term (1) and replacing the metal flow rate in term (2) in ISCO with mass flux of C. BOC was reported to give a bit better correlation in describing the behavior of (T;Fe) than ISCO within a range of 0.02–0.22% C for LD.

4.3. Development of Q-BOP Toward Mixed Blowing Converters

A mixed blowing form between LD and Q-BOP, with 70% oxygen blown from top lance and 30% oxygen injected from bottom tuyeres, has been put into operation at Mizushima (3 × 250 tons) and Chiba (2 × 85 tons) during 1980–1981. The top and bottom blowing converter was named K-BOP (Kawataetsu-BOP where the prefix means Kawasaki Steel in Japanese, Fig. 2 bottom center). The ISCO value for the K-BOP is determined to be 64, close to 58 for the Q-BOP, and much smaller than about 230 for 160 ton LD, despite the limited fraction of oxygen bottom injection. K-BOP exclusively blows oxygen from top and bottom until critical C of 0.10–0.15% is reached, followed by inert gas bottom injection to promote deC in the range below the critical C (called Inert gas Decarburization, ID). It is capable of changing the main lance coolant, but decreased with increased q (= shorter τ). They considered that the anomaly is caused by the following: At the impinging points of oxygen jet on the steel melt, the activity of (FeO) formed by the oxidation of the melt is inversely proportional to q (ton/s) of the melt being the mass of steel melt.

For an inert gas bottom stirring 250 ton LD (LD-KGC) at Mizushima, τ is calculated to be 37 s at a small 10% bottom injection of Ar, much shorter than about 75 s for LD without the bottom injection, and not too much longer than 14 s for Q-BOP at Chiba. Concentration product of C and O in the melt did not change with the species of hydrocarbon coolant. Kishimoto et al. showed, however, that O content in the melt did not change with the species of hydrocarbon coolant, becoming little more with increased q (= shorter τ). They showed that the anomaly is caused by the following: The impinging points of oxygen jet on the steel melt, the activity of (FeO) formed by the oxidation of the melt is unity and O in the melt may come close to the equilibrium value corresponding to C and T around there. When melt stirring or melt flow rate is large enough, however, O in the melt should be dominated with (FeO) which is generated at the impinging points but diluted in slag which covers much wider surface area of the melt than the area of fire spots. The stronger the stirring or the greater the flow rate, the lower the (FeO) which dominates the O in the melt, and hence O decreases with q.

4.4. Wide Spreading Development of LD with Bottom Injection of Inert Gases

In view of the considerable improvement of blowing characteristics of LD with a small amount of inert gas injection from the bottom, the inert gas injection soon replaced oxygen and lime injection from the concentric tuyeres to eliminate the exchangeable bottom with the tuyeres and reduce the necessary investment and running cost.

The following type LDs with gas stirring have been...
industrialized by developing different types of Ar or N₂ bottom injection, resolving the erosion of gas inlet plug and increasing the gas flow rate: LBE by IRSID-ARBED, LD-BC by CRM and UBDT by Krupp employ either slit brick or permeable brick for the plug, while metal tube (mostly single one) is used by LD-AB by Nippon Steel, LD-KGC by Kawasaki Steel, LD-OTB by Kobe Steel and NK-CB by NKK. Injected gas flow rate ranged from 0.01–0.50 Nm³/min.ton (Fig. 5), mostly less than 0.2 Nm³/min.ton.

The inert gas bottom stirring LDs decrease critical C content where the rate controlling step for deC changes from mass transfer of O to mass transfer of C, and hence the decarburization oxygen efficiency in the lower C range is improved to make (T(Fe)) lower than 20% with increased iron yield. Thus, conventional LDs were rapidly converted into the gas stirring variants.

To avoid the confusion of the naming, LD in Europe and BOF in USA are collectively denoted here as BOF, gas stirred BOFs with bottom injection of inert gas are collectively designated as “Inert Gas Stirred BOFs”, BOFs with bottom oxygen blowing as “Top and Bottom Blowing BOFs”, and the two types of BOFs are collectively named as “Mixed Blowing BOFs or Combination Blowing BOFs”.

In 2000s, even better productivity was demanded for the mixed blowing BOFs. However, when greater oxygen gas flow was supplied into the BOFs for increasing the productivity, the top gas jet and melt flow interfered between the fire spots where the jet impinged onto the melt surface, generating spitting of melt drops out of the BOFs. The spitting became considerably when slag lean operation (see later section) with decarburization oxygen efficiency in the lower C range is improved to make (T(Fe)) lower than 20% with increased iron yield. Thus, conventional LDs were rapidly converted into the gas stirring variants.

4.5. Application of Mixed Blowing BOF to Scrap Melting and Smelting Reduction

In an integrated steel plant where OG system is installed, top and bottom blowing BOFs are capable of melting scrap, which keeps accumulating in market, with less energy consumption (~3.9 GJ/t, recovered off gas credit deducted) than electric arc furnace (EAF) (~4.5 GJ/t). Hirohata converted a BOF into top and bottom blowing one, and industrialized it as a coal base scrap melting BOF in 1993. Existing off-gas recovery system was utilized. When the combustion rate of off-gas in the vessel was increased up to 30%, scrap ratio increased by only 10% vs. 0% combustion. Addition of carbon bearing fuel material from the BOF mouth did not work either, since the material was blown away from the mouth. These shortcomings were resolved by hot heel operation of high C melt into which oxygen and pulverized coal with low volatile materials were blown in with nitrogen as carrier gas through the bottom tuyeres. Scrap was charged from shoot on top of the vessel, oxygen was blown from the top lance to enhance scrap melting by secondary combustion of off-gas in the vessel. High speed and stable low temperature melting practice increased the utilization efficiency of the coal, prolonged refractory lining life, and sustained to keep both the heat for melting and calorie contained in recovered off-gas by controlling the degree of the secondary combustion. Also, evolution of dust and slopping caused by bubble burst, enhancement of deP by controlling (T(Fe)), maintaining optimum C content of the high C melt, and stabilizing heat compensation were all optimized by controlling S and ash content in the coal, ratio of oxygen blown from the top lance and amount of addition of iron oxide pellets. Resulting hot metal was decarburized in another BOF to produce high quality steel which is said better than EAF steel.

Top and bottom blowing BOFs were also developed for the smelting reduction of Cr ore to produce stainless steel. Okuyama et al. charged into the first stage K-BOP at Chiba 50% of deP hot metal, Cr ore pellet sintered in a rotary kiln, cokes and stainless steel scrap to reduce the Cr ore pellet, and obtained Cr and Ni bearing hot metal. The hot metal was separated from slags, poured into a large size mixer equipped with a channel heater which takes up addition of stainless scrap to trim Ni and Cr content. The hot metal was subjected to deC and deP blowing in the second stage K-BOP to produce SUS 304 and 430 since the latter half of 1980. The smelting reduction process provided Chiba with freedom to choose Cr sources depending on the market situation.

Recently, additional lance has been installed to add Cr ore fines with burner heating into the hot metal in the first stage K-BOP. Here, hydrogen bearing fuel is combusted with oxygen, and granular Cr ore is preheated in the combusting flame to compensate for the 20%(unit mass Cr ore) of the endothermic heat of reduction. Emission of CO₂ is naturally decreased, together with the erosion of refractory lining. Furthermore, top addition of coal to the hot metal combined with oxygen top blown through auxiliary lance has been in operation since the latter half of 2000s. The coal disintegrates and disperses as fine particles in the top slag, favorably reducing the Cr ore granules preheated and suspending in the slag. The auxiliary lance is with multiple hole tip, designed to combust the CO gas evolving in the vessel space from the Cr ore reduction to fully compensate for the heat loss of the reduction.

To obtain high Cr ferritic stainless steels extra low in C and N, the melt from the second K-BOP is further refined.
under vacuum with Vacuum Oxygen Decarburization (VOD) process or SS-VOD process. Total amount of stainless steels produced with the duplex K-BOP process has been about 0.7 million tons/yr.

Traditionally stainless steels have been produced from stainless steel scrap, Ni sources and Fe–Cr alloys with EAF and converter such as AOD (Argon Oxygen Decarburization) or CLU (Creusot Loire Uddeholmen). AOD and CLU control oxygen partial pressure in a wide range during the deC blowing to minimize the loss of Cr. The steels are then refined additionally with ladle refining furnaces (LRF) depending on the quality requirement. The smelting reduction type duplex K-BOP route is reported to consume about 35% less energy than EAF-AOD route.

Steelmaking and refining processes for stainless steels are quite diversified. In fact, Muroran installed RH-OB in 1972,Yawata put 150 ton LD-VAC (VOD) into operation in 1979 and hot metal pretreatment with soda ash combined with LD-OB in 1980, Wakayama started oxygen top blowing AOD and Nippon Metal AOD-VOD in 1983, Wakayama AOD-VOD/VOD-PB in 1990, Fukuyama top and bottom blowing BOF type Smelting Reduction Furnace (SRF) for Ni ore and Cr ore reduction in 1990, Daido Specialty Steel vacuum AOD (VCR) in 1991, Yawata REDA (see later) in 1995 and Hikari VOD in 1996. The choices are supposed to meet local conditions for each plant, but there are so many varieties.

5. A Wide Variety of Developments of Ladle Refining/Secondary Refining

5.1. Simple Processing of Steel in Ladle - Argon Bubbling and Flux injection -

Steel melt primarily refined in BOF, BOH and EAF is usually deoxidized (deO), desulfurized (deS) and removed of non-metallic inclusions (inclusion hereafter) in ladle. For the objectives, common practice was to cover the melt surface in ladle with non-oxidizing basic slag, inject Ar from the bottom of the ladle, and bring the melt flow caused by the gas injection stirring into contact with the top slag for refining.

Multi component top slag with Mannesmann Index (%CaO)/[(%SiO2)·(%Al2O3)] = 0.3–0.4 and alike were favorably used for deS. Optimization of the melt flow was made by controlling plume eye. For deS and inclusion control, Thyssen Niederrhein method (TN) and similar Scan Lancer method, both inject CaC2 or CaSi granules with inert gases through lance immersed into the melt, were popular since mid-1970s. For deO and deS, injection of cored wire, steel sheath with FeCa or CaSi core, into the gas stirred melt was practiced since 1980.

5.2. Development of a Variety of Ladle Refining Processes

Ladle refining and secondary refining furnaces (collectively LRFs) have been commercialized in Europe and USA since 1952 to decrease impurity elements, H, N, O, P and S and inclusions, trim alloying elements in primarily refined steel melt, and control the melt temperature suitable for casting. In Japan, introduction of LRFs started with vacuum degassing of melt stream with Bochmer Verein process (BV) in 1958, followed by Dortmund Hölder process (DH) and Rheinstahl Heraus process (RH), all increased rapidly after 1970. Simultaneously, TN process, Vacuum Oxygen Decarburization process (VOD) of Witten, Vacuum Arc Degassing process (VAD) of Finkl, Ladle Furnace (LF) of ASEA-SKF and AOD were also installed. The cited processes are classified according to the function, equipment and objective, and differ in application. Generally, steel melt is processed in vacuum, heated, added with alloys, and stirred for the removal of impurity elements and inclusions and for the uniformity of temperature and chemistry. (Fig. 6)

TN and ASEA-SKF refine the melt with slag under ambient pressure. TN injects slag particles with inert carrier gas through lance immersed into the melt, whereas ASEA-SKF utilizes electromagnetic rotation of the melt which is in contact with top slag and removed of the impurities and inclusions. In terms of equipment, TN and ASEA-SKF are the opposite extreme. AOD decarburizes the melt by blowing Ar and O2 at varied ratio, VOD by blowing O2 under vacuum, VAD by blowing O2 under vacuum, and AOD heats the melt with arc under reduced pressure, all
for refining stainless steel at a minimum loss of Cr. VAD and ASEA-SKF are equipped with arc heating function, and hence used to produce alloy steels and extra-heavy plates in batches. Later, ASEA-SKF has been furnished with vacuum degassing facilities. During 1965 and 1977, 8 AODs, 7 VODs, 3 ASEA-SKFs and 5 others were installed in Japan.

5.3. Development of DH and RH which Combine BOF with Continuous Caster\(^{35}\)

In an integrated iron and steel plant, more than several heats of steel are usually cast in a sequence into continuous casting machine (CCM) to secure better yield and quality of the cast strand. LRF is situated in between BOF and CCM, and plays important role to:

(1) Synchronize the sequence and keep productivity, and
(2) Control temperature and chemistry of steel melt to meet the quality demands of down stream processes, CC inclusive.

In the early stage of the introduction, upgrading of the function of LRF itself was carried out to maturity by the latter half of 1970. Since when CC was fully industrialized in 1970, efforts were paid to optimize the functions (1) and (2).

Important issues for such optimization were:

(1) High speed evacuation of large capacity degassing vessel,
(2) Enlargement of the interfacial areas between steel melt and vacuum or steel melt and slag ,
(3) Acceleration of the melt flow rate to promote the mass transfer of the impurity elements and inclusions,
(4) Chemistry control and removal of slag,
(5) Addition and homogenization of alloying elements,
(6) Heating to compensate for the temperature drop of the melt during processing, and
(7) Refractory which withstands the erosion and exfoliation and does not contaminate the melt.

Many of the above are more or less in common with the issues for BOF. However, the processing capability of LRF has been much advanced to meet the demands for increasing productivity of BOF and decreasing impurity concentrations of steel melt. The progress of highly productive secondary refining processes, RH and DH (Fig. 6, bottom), popular in integrated steel plants, are summarized as follows:\(^{14,15,19,21,23}\)

**DH:** Steel melt in ladle is spout out via. off-centered tube up into the vacuum vessel located above the ladle. Removal of H, N, O and inclusions are carried out from the free surface of the melt in the vessel. The melt in the vessel is subsequently returned through the tube and mixed in the remaining melt in the ladle. This cycle is repeated several times/min by up and down motion of the vessel. Yawata introduced DH in 1959, enlarged the vessel and tube, added electric heater in the vessel, made the cycle motion quicker (15 m/min for 180 ton ladle) in 1969 with a lever type mechanism, installed a device for Ar injection into the melt in vessel in 1974 to promote deC (DH-AD method), and adopted magnesia chromites brick to materialize in sequence the improvements listed in (1)–(7) in the above.

Nippon Steel converted DH in late 1990s into REDA (Revolutionary Degassing Activator) by removing the spout tube, extending the bottom end of large diameter cylindrical vessel to be immersed into the melt in ladle, and injecting Ar from the bottom plug of the ladle. The melt is sucked up into the vessel by evacuation, stirred with Ar injected from the ladle bottom, and circulated back into the melt in ladle. REDA reportedly exhibited similar degassing capability to RH, and has been used for refining steels low in C, N, O and stainless steels.

**RH:** RH was first introduced to Hirohata in 1963, put into operation as 100 ton facility. One each of upleg- and downleg-snorkel installed at the bottom of a cylindrical vacuum vessel are immersed into the melt in ladle to suck up the melt in the lower part of the vessel. Ar is injected in the lower part of the up-snorkel to give rise and spout the melt into the vessel with the air lift pump action. The difference in the height of the melt at the spout surface above the upleg-snorkel and the melt surface above the downleg-snorkel in the vessel drives the melt through the downleg-snorkel back into the ladle to be mixed with the bulk of the melt. Thus, the melt keeps circulating from ladle→upleg-snorkel→vacuum vessel→downleg-snorkel→ladle (Fig. 7). The melt is degassed at the interface of Ar bubbles and melt in the upleg- snorkel and the melt surface in the vessel including melt splash surface created by bubble break up. Agglomeration and removal of inclusions in the melt take place with turbulent stirring in the circulating melt.

Basic equipment and necessary operation for RH were largely ready by the middle of 1960. Further improvements including those by licensee companies by early 1990s were:

(1) Large capacity evacuation system for quicker achievement of high vacuum in the vessel to enhance degassing even in the very early stage of the processing,
(2) Increasing diameters of the snokels and the vessel, and enhanced Ar delivery rate through stainless steel tubing into upleg-snorkel, all for greater circulatory rate of the melt,
(3) Refractory brick changed to direct bond magnesia chromite for better durability, and
(4) Installation of electric resistance heater in the vessel to compensate for the temperature drop of the melt and to melt away the accretion of melt splash on the inner wall of the vessel.

In 1972, Muroran developed RH-OB, top blowing oxygen on the melt in the vessel with AOD type concentric tuyere (O\(_2\) from inner tube, Ar, N\(_2\), CO\(_2\) from outer slit) for stainless steel deC. In the latter half of 1970s, injection of
O$_2$ and refining flux with concentric tuyere from the side wall of the vessel into the melt was also developed as RH-OB-FD for deC, deS and heating up of carbon steels. Uniform mixing of the melt stream from downleg-snorkel and bulk melt in ladle was questioned in former times, but tracer measurement and CFD calculation confirmed the uniform mixing, provided that the circulatory rate is made sufficiently high.

During these periods, height and diameter of the vessel, the diameter of upleg- and downleg-snorkel and Ar injection rate were all made greater to further increase the circulatory rate, and RH has matured as a highly productive LRF. Today, the melt circulatory rate for 250–300 ton ladle is set about 150 ton/min, and the time for a circulation of 300 ton melt is about 2 min.

Once upon a time, RH and DH were employed for mass production of partially deoxidized steel melt to be continuously cast as a rimmed steel alternative (cf. Riband steel in later section).

RH is particularly useful for high productivity refining of extra low C steel. Other than RH-OB, Kawasaki Steel installed top lance to blow O$_2$ onto the surface of the melt in the vessel as RH-KTB (Kawasaki Top Blowing) in the latter half of 1980s to enhance deC rate in RH vessel. Advantages of RH-KTB over RH are:

(1) End point C of BOF melt does not need to be made extra low, and hence productivity and yield of BOF melt have increased,

(2) Combustion of CO gas evolved in the vessel with the top blown O$_2$ prevents temperature loss of the melt, enables to decrease the temperature of BOF melt at tap,

(3) Eliminates the troublesome formation and removal of the splash accretion on the inner wall of the vessel, and hence

(4) C-reversal of the melt caused by the fall of high C accretion into the melt in the vessel is minimized.

RH-KTB (Fig. 7 right) has been widely in use abroad as well.

Another enhancement of deC and deN to extra low concentrations has been developed at NKK which injected H$_2$ into the steel melt through the upleg-snorkel to be absorbed as H in the melt. During ascending to the surface in the vacuum vessel, the dissolved hydrogen forms H$_2$ bubbles into which C as CO and N as N$_2$ are removed and evacuated into exhaust system when the bubbles break up.

In 1990s, Nippon Steel commercialized RH-MFB (Multiple Function Burner) to combust LNG blown from a top lance inserted in the vacuum vessel to remove splash accretion on the inner wall of the vessel while RH processing is at rest. The removal helps preventing the pick up of C (contained in the accretion) in the subsequent heats. The lance is made functional during the processing to blow O$_2$ through it to heat and deC the melt. RH-MFB has also found popular use abroad.

Refining steel melt with slag or flux during RH processing was introduced from late 1980s to early 1990s, including RH-Injection at Nagoya, RH-PB at Oita and RH-PB at Wakayama in sequence. At Nagoya, flux is injected into the melt below the upleg-snorkel in ladle through a lance tip which is immersed in ladle melt and directed upward to the bottom opening of the upleg-snorkel. At Oita, flux is injected into the melt in the RH vessel through a submerged concentric tuyere tube. At Wakayama, flux is blown from a top lance with Laval nozzle tip onto the surface of the melt in the bottom of the RH vessel (Fig. 7, left). S ≤ 3 ppm and N ≤ 20 ppm were obtained with the injection of 8 kg/ton CaO–CaF$_2$ and C ≤ 10 ppm was attained with the injection of 10 kg/ton iron ore powder for 160 ton melt. In 2012, the nozzle tip of the lance has been replaced with Spike tip for processing 250 ton melt, decreasing S from the initial 20–25 ppm to 10–12 ppm in 27 min.

SIVA (Simplified all-round VAcuum treatment) process was developed early in 2000, RH vessel is equipped with a top blowing lance, and vessel bottom is removed and connected to the top rim of ladle for evacuation with Ar blown from the ladle bottom, like REDA process for DH. The vessel has been capable of strong melt stirring and inclusion removal, alloy addition and Ca wire injection, while preventing melt reoxidation and contamination caused by ladle slag. Refining capability is said similar to the combination of LF and RH.

5.4. Diverse Application of LF and LRF

LF was first commercialized for 100 ton melt early in 1970 at Nippon Specialty Steel for alloy addition and removal of S, O and inclusions with highly basic fluxes. Steel melt in ladle with Ar injection from ladle bottom is Arc-heated with graphite electrodes inserted through top lid of the ladle to prevent temperature drop during the operation. To minimize refractory erosion, oxidation resistant magnesia carbon bricks are used at the slag line of the ladle. Some 10 years later, LF has been equipped with flux injection lance, and the ladle has been contained in vacuum chamber for degassing, making itself like ASE-ASKF.

Traditionally, EAF steelmaking consisted of melting and oxidizing (deC, deP) operation followed by finishing reducing operation with replaced white slag. LRF took over the latter operation, making EAF specialized for melting and oxidizing. The above separation has increased the productivity of EAF considerably, and improved the quality of EAF steel much better.

LRF has been further developed for large scale refining of BOF steel for demanding applications such as line pipe, heavy plate for large input energy welding, plate with low temperature toughness, all of them call for extra low concentration of impurity elements. LRFs thus developed in 1980–1990 and operating under ambient pressure with flux injection lance include NKK Arc refining Process (NK-AP) and Nippon Steel Kimitsu Injection Process (KIP). KIP later implemented vacuum processing, and was named V-KIP. All of the three feature strong stirring refining with reducing slag under arc heating, capable of attaining S < 10 ppm.

Secondary refining, both ladle refining and degassing, contributed greatly to:

(1) Share a part of the function of primary refining furnace and meet demands for increased productivity and upgrading the quality of refining system, and

(2) Bridge primary refining furnace, BOF or EAF, and continuous casting machine (CCM) to keep the consistency of their productivities, while stabilizing CCM operation and improving the quality of CC strand.

Thus, investment and utilization of secondary refining facilities have increased with time. In recent years, about 85% of steel melt are processed with secondary refining and about 75% with vacuum degassing.
5.5. Diverse Application of Simple Ladle Refining\cite{31}

For steels of less demanding, cost and quantity oriented application, simpler refining processes have been developed. Composition Adjustment by Sealed argon bubbling (CAS) commercialized by Yawata in 1974 employs Ar bottom injection into ladle melt. Contamination by air oxidation and slag entrainment at plume eye is suppressed with Ar sealed closed-top refractory cap immersed in the melt around the plume eye. Addition of deoxidizing alloys and fluxes for chemistry trimming is made simple and less costly without the contaminations. Injection of O\(_2\) through top lance has been made possible with CAS-OB. CAS and CAS-OB have also found popular use abroad.

6. Evolution, Growth and Maturation of Hot Metal Pretreatment\cite{14,15,19,33}

6.1. Development of New Processes of Hot Metal Pretreatment for Desulfurization

BOF slag contains harmful P as well as useful CaO, MgO and iron oxides. To recover the useful components, the slag is recycled as an additive to sintering and resulting sinter is fed into BF. The recycling makes P in hot metal increased beyond the tolerable value for BOF blowing to meet low P, S for quality steels. Also, the blowing of high P hot metal necessitates increased use of CaO which in turn brings forth a large amount of slag against the environmental requirement to minimize the slag. In BOF blowing of hot metal, thermodynamic requirements for deP are lower temperature and higher oxygen potential, contradictory to higher temperature and lower oxygen potential for deS. Therefore, it is difficult to achieve both deP and deS in single BOF vessel with single slag operation (exception is to use sodium carbonate instead of CaC\(_2\) for simultaneous deP and deS, but it causes reversal of P from slag to steel at tapping temperatures with single slag and single vessel operation).

In Japan, integrated iron and steel plants need to run BOF at high hot metal ratio for economic reasons with sufficient supply of hot metal. Under such circumstances, BOF + LF process was not the best choice in many aspects, and hence developed were:

(1) Carrying out deS for high temperature hot metal at tapping from BF under low oxygen potential, and

(2) Subsequently executing deP for hot metal and scrap mixture at relatively low temperatures with high oxygen potential slag formed in the early period of oxygen blow in BOF.

Origin of elementary hot metal pretreatment (HMPT) dates back to an early era of BOH when hot metal mixer was employed to normalize fluctuating temperature and chemistry of hot metal from BF. HMPT deS was developed and quickly commercialized during 1965 and 1974 to refine high S (0.023–0.030%) hot metal for increasing production of quality steels such as ship plate (S < 0.02%) and plates with good low temperature toughness and resistant to hydrogen induced cracking (HIC) for line pipe for arctic areas (S < 0.01%, today < 10 ppm). In the middle of 1960s, soda ash was added to hot metal in the tapping trough of BF and transfer ladle, followed by the addition or injection of lime base flux to the ladle or torpedo car. However, deS rate was low and fluctuating (20 ± 10% for initial S of 0.05% with soda ash 2 kg/ton), and deS operation was not smooth. Accordingly, alternative deS method, shaking ladle, was worked out which showed much better rate but difficult for mass production. Many variants were put into operation since, and Kanbara Reactor (KR) has been developed among them, and industrialized successfully in 1965 at Hirohata.

KR has an impeller immersed and rotating in ladle to engulf and disperse deS flux in hot metal, providing hot metal with deS sites at the interfaces of engulfed/suspended flux particles and hot metal and top slag and meniscus of hot metal bulk. Large interfacial areas and long retention time of the particles in the melt make the utilization of deS flux better, and the speed of deS is much improved. KR has been installed at Tsurumi, Kamaishi, Muroran, Nagoya, Mizushima, Kashima, Kokura, Chiba, Fukuyama and Ohgishima in this order during 1967 and 1976. For deS flux, CaC\(_2\) was utilized in the beginning, but replaced later by CaO base flux for environmental concern. Optimization of KR processing has progressed greatly since. According to the author’s own experience, 180 ton hot metal containing 0.045% S at 1415\(^\circ\)C could be reduced to 3 ppm S in 12 min and 270 ton hot metal containing 0.03% S at 1240\(^\circ\)C to 10 ppm S in 10 min, both with 8 kg/ton of CaO–CaF\(_2\) mixture rather consistently, provided that the rotation rate and immersion depth of the impeller have been optimized. KR is even today an excellent reactor for deS, low in investment, running cost and waste flux to be disposed. Reuse of the disposed flux has been made in 2000s. Recently, Kikuchi et al.\cite{30} improved deS rate of KR with the addition of propane gas into and onto the hot metal bath around the impeller to decrease oxygen potential in the area where engulfment of deS flux occurs.

Until late 1960s when steels extra low in S were not demanded, deS was executed with CaC\(_2\) placed on top of hot metal in transfer ladle where N\(_2\) was blown from the ladle bottom in different ways. PDS employed at Yawata and Continuous Ladle Desulfurization (CLDS) utilized at Wakayama, Fukuyama, Kawasaki, Kashima and Hirohata fall in this category. For CLDS, hot metal containing 0.02–0.06%S was poured into intermediate ladle where 5 kg/ton of CaC\(_2\) was charged in advance. Turbulent hot metal flow during the pouring and subsequent 5 min stirring in transfer ladles where N\(_2\) injected from 3 bottom tuyeres decreased S to less than 50 ppm. Since early 1970s, lance injection of CaC\(_2\) into hot metal mixer was widely used for better productivity at Nagoya, Sakai, Yawata, Kashima, Wakayama, Kimitsu, Oita, Mizushima, Chiba and Kakogawa in this order. At Chiba, CaC\(_2\) powder was replaced for the environmental issue by CaO powder of improved fluidity with a surfactant addition. Kakogawa commercialized a facility to deS with a rotating bubble pump type reactor (GMR) in the ladle. Wakayama put into operation of Mg-coke method which immersed Mg-impregnated coke into hot metal for deS. As a result of these implementations, hot metal deS rate in Japan attained nearly 100% in 1977.

In recent years, injection of 20%Mg–CaO mixture into hot metal has been practiced for its convenience and less amount of slag formation. MgS, formed from S in hot metal and injected Mg, combines with CaO, ascends and is absorbed into top slag, preventing the reversal of S to attain lower S. Tools for hot metal deS for BOF steels of extra low
S grade (<10 ppm) and low S grade (<50 ppm) seem to have converged to be KR process and Mg–CaO injection process. In BOF, S originating from scrap is additional, and hence supplemental deS is required in RH, DH or LF for extra low S grades. Also, increasing demands for better strength and ductilities of steels have requested further reduction of the size and quantity of oxide-, sulfide- and oxysulfide-inclusions. Secondary refining has become mandatory means to meet the demands, accordingly, making the secondary refining ratio about 80% at BOF plants and over 50% at EAF plants in 1987.

6.2. Development of Hot Metal Dephosphorization in Transfer Vessels

Early stage in BOF blowing has been known suitable for deP since temperature is relatively low and slag gets high in oxygen potential. Under the constraint that single BOF only is available for primary blowing, double slag process with deslagging in the early stage of the blowing or LD-AC (ARBED-CNRM) process to inject powder CaO from main lance into BOF could have been a solution to blow steels low in P as it was the case in Europe (cf. NKK was a licensee of LD-AC process).30)

The double slag process promoted early formation of liquefied slag for deP in the early stage of BOF blowing when bath temperature is not high, removed the slag rich in P after deP blowing at the expense of BOF productivity, and prevented the reversal of P from slag in the following high temperature stage of deC blowing. However, large amount of slag required for deP increased heat loss and sloppy, decreased iron yield and productivity, and was contradictory to the waste slag reduction. LD-AC also had operational disadvantages including powder transfer and powder injection through the lance.

As a hedge against these drawbacks, each company in Japan commercialized, after about 1980, deSi of hot metal at the BF cast house runners combined with deP in either torpedo cars or transfer ladle with high basic oxidizing slag mix. The flux was injected into the desiliconized hot metal with O2 as carrier, or added on top of gas stirred hot metal onto which O2 was blown. Low Si operation of BF and pre-treatment of deSi of hot metal in transfer ladle with O2 injection, deslagged, subjected to deS with KR and then to deP with deP flux blown through immersed lance with O2; as career gas. The amount of slag in BOF after deC blowing reduced to 10 kg/t, and total sum of the slags for deSi, deP and deC decreased to 60 kg/t, only about one half of the sum for conventional BOF operation. Operational benefits obtained were better end point hit rate of C and T, improved iron yield and increased productivity by 20%. Also, smelting reduction of Mn ore during deC blowing became favorable due to decreased loss of Mn ore in the reduced amount of slag in BOF which in turn decrease Fe–Mn alloy addition.31) Consequently, annual crude steel production of 10 million tons at Fukuyma has been totally replaced by ZSP.

Advantages of above mentioned variants of hot metal deP processes in transfer vessels are that additional investment is small, processing period of time is made in match with the cycle time of BOF, not causing bottleneck for BOF operation. On the other hand, unit process steps involved are too many, and improvements are required in slag/metal mixing intensity and utilization rate of slags for deS and deP, exhaust gas treatment, deslagging and heat loss.

6.3. Development of Hot Metal Dephosphorization with BOF

In 1983, Chiba trialed production scale deP of hot metal by utilizing intensive bath stirring, bottom injection of CaO and O2, quick deP in the early stage of blowing, high free board and good separation of slag and steel at tap, of Q-BOP (Fig. 9)18) while benefited with existing off-gas processing system. 20 kg/ton CaO, 3 kg/ton CaF2, 28 kg/ton iron ore and 6 Nm3/ton O2 were used to blow 230 ton hot metal containing 4.5%C, 0.2%Si, 0.4%Mn, 0.14%P and 0.010%S, and virtually without temperature loss. As no extra Q-BOP was available at that time, commercialization was not attempted despite the operational success.

In 1988, Nagoya commercialized a HMPT process, named Optimizing Refining Process (LD-ORP)39) with mixed blowing BOF (Fig. 10, top).40) DeS hot metal was subject to deSi and deP together with scrap melting in the BOF. Slag rich in P was separated at tapping from steel which is subsequently decarburized in LD-OB. Inflow of NKK developed Zero Slag Process (ZSP) which was industrialized in 1998 (Fig. 8).38) Hot metal in transfer ladle is removed of Si at deSi station with O2 injection, deslagged, subjected to deS with KR and then to deP with deP flux blown through immersed lance with O2; as carrier gas. The amount of slag in BOF after deC blowing reduced to 10 kg/t, and total sum of the slags for deSi, deP and deC decreased to 60 kg/t, only about one half of the sum for conventional BOF operation. Operational benefits obtained were better end point hit rate of C and T, improved iron yield and increased productivity by 20%. Also, smelting reduction of Mn ore during deC blowing became favorable due to decreased loss of Mn ore in the reduced amount of slag in BOF which in turn decrease Fe–Mn alloy addition.31) Consequently, annual crude steel production of 10 million tons at Fukuyma has been totally replaced by ZSP.
slag containing P and S to LD-OB was minimized, and hence reversal of P at deC blowing was suppressed, amount of slag reduced, and smelting reduction of Mn in LD-OB was carried out favorably. Nippon Steel produced nearly 30% of total crude steel with LD-ORP in 2009.40) Similar process to the above with BOF was industrialized by Sumitomo Metal in 1990 as Smart Refining Process (SRP, Fig. 11).41) Hot metal preliminarily treated for deS and deSi, leaving 0.1%P and 0.1%Si at 1 300°C was blown with O2 in the 1st mixed blowing BOF with an addition of 16 kg/ton iron ore and 4 kg/ton CaF2 to get 0.032%P melt which was subjected to deC and deP in the 2nd mixed blowing BOF with 10 kg/ton CaO as flux to reach 0.012%P. Slag from the 2nd BOF (20 kg/ton with 2.2% P2O5) was reused as a source of CaO and FeO for the 1st BOF. The reuse considerably decreased the amount of waste slag containing 10.8% P2O5 from the 1st BOF to 25 kg/ton.

In 2000, Nippon Steel commercialized Multi-Refining Converter (MURC, Fig. 10 bottom)42) as a variant of BOF based HMPT. Hot metal was subject to deS with KR or Mg–CaO injection, and charged into a mixed blowing BOF with scrap for deP blow. After tilting the BOF for slag removal, deC blow was carried out in the same BOF. De-P is promoted with the mixed blowing BOF, and the slag left in the BOF after deC blow is employed as the slag for the next deP blow. When the composition of the slag after the deP blow was controlled to be (CaO/SiO2) = 1.5–2.0 and (T.Fe) = 15–20%, hot metal containing 0.15%P at 1 170°C is reduced to 0.02%P in 8 min with total consumption of CaO only 10 kg/t for both deP and deC blow at 60% of deslagging rate after deP. Not only the consumption of CaO and the amount of slag formation, but also accompanied heat loss decreased. About 55% of hot metal produced at Nippon Steel in 2009 was reported40) to have been processed with MURC. When the deslagging rate stayed below 70%, P ≤ 0.010% was difficult to reach for medium C steels of 0.5%C class. However, 100% deslagging has been made successful to industrially blow the low P grades by the name of F-MURC.

After 2010, Sumitomo Metal have improved SRP to industrialize SRP-Z43) at Kashima, Wakayama and Kokura. Hot metal is desulfurized with KR, deslagged, charged in the 1st stage mixed blown BOF with scrap, lump CaO, iron ore and recycled CaO–Al2O3 type LF slag, and blown with pulverized CaO and O2 through Spike type top main lance for deP. After deP, the hot metal is processed for deC in the 2nd stage mixed blown BOF. Major characteristics of SRP-Z include:

1. Quick molten slag formation of CaO powder blown at the high temperature impinging points makes CaO utilization efficiency high, CaO consumption and slag volume decreased, resulting in a high speed deP in less than 6 min,
2. Occurrence of fume and dust out of the BOF is reduced,
3. The recycled LF slag accelerates melting and assimilation of lumpy CaO, and resulting slag dissolves calcium ferrite quickly to promote deP,
4. Foaming of slag often observed at this stage is suppressed by the top blow of pulverized CaO,
5. Slag formed in the deC BOF is returned to the deP BOF for deP blow, and
6. Waste slag out of the deP BOF bears low amount of undissolved CaO, and hence usable for road pavement with a short period of cure.

It is of interest to note that double slag and LD-AC process formerly developed in Europe have been improved in many aspects and systematized to revive for blowing high quality steels with much lower P content.

6.4. Choice of HMPT Processes

Each steel plant in Japan has made choice of some of the above mentioned processes for their HMPT by optimizing the choice fits best to their intrinsic pieces of equipment, environment, technologies and products. Keywords for the choice were, availability of excess BOF, pros and cons of the investment to build new mixed blowing BOF for HMPT,
which are influenced by the productivity of the process, heat loss, iron yield, unit consumption of flux additives, amount of waste slag formed, P- and S-buckel caused by retained slag in BOF, carry over of BOF slag into ladle, refractory life, matching of the productivity with preceding- and succeeding-process, and cutting back the loss of processing time for each unit and all over the system. Today, HMPT process is fully utilized for virtually all the hot metal produced in integrated iron and steel plants in Japan.\textsuperscript{40}

7. Development of Electric Arc Furnace toward Larger Capacity and Greater Productivity\textsuperscript{12,14,19,33}

7.1. Era from Heroult Furnace to Oxygen Steel Making in 250 ton Lectromelt Furnace

History of electric arc furnace (EAF) steelmaking in Japan dates back to 1916 when 1.5 ton Heroult furnace was made domestically and put into operation at Denki Seikosyo, now Daido Steel.\textsuperscript{3,4,7} The number of the EAF increased to 7 in 1927, although their capacity was ≤10 ton each. Demands of armed forces for EAF steels increased to fulfill wartime need since then, and installation of larger Heroult furnaces continued to produce specialty steels and stainless steels with 104 EAFs of ≤20 ton capacity in 1934. In 1951, total EAF steel production reached 2.39 million tons with 406 EAFs of ≤40 ton capacity.

It was in 1952, after World War II, when Daido Steel struck technical agreement with Lectromelt Co. to install a swing top type, top charging high voltage long arc EAF with domestic components and started production. Process for oxidizing refining changed from the use of iron ore to \( \text{O}_2 \) blowing in the early half of 1950s. The latter half of 1950s saw increased number of installation and enlargement of Lectromelt-, American Bridge- and Demag-type EAFs. As a result, average capacity of EAFs increased to 26 tons and the number of EAF over 50 ton capacity counted 12 in 1962. As an extreme, Chubu Kohan put into operation of Lectromelt-type 250 ton EAF (40 MVA, hearth diameter 7.62 m), nominal productivity being 1000 tons/day of carbon steel ingots in 1952.

7.2. Progress from Ultra High Power and Oxygen Steelmaking to Scrap Preheating Operation

EAF then stepped into the era of Ultra High Power (UHP) operation where 2–3 times of electric power could be put into the same size of conventional EAF by implementing high voltage large capacity transformer. UHP-EAF found popular acceptance owing to:

(1) Stability of arc,
(2) Reduced time for melting down,
(3) Consistency to continuous casting operation for the sake of increased productivity,
(4) Reduction of uprising price of electricity, that was made possible by the use of automatic electrode position adjustment system with thyristor controlled electromagnetic coupling, vacuum switch, water cooled electricity feeding cable and tapered nipple connection of the electrodes.

42 MVA 70 t EAF at Kobe Steel Kobe started in 1969, followed by 45 MVA 70 t EAF, 56 MVA 120 t EAF and 60 MVA/60 t in sequence in Japan during 1970–1973. Cooling of top and wall of UHP-EAF with water cooled metal pan-els, castings and tubing was introduced to prevent furnace refractory erosion caused by large power input, reducing refractory repair time. Also, promotion of quick scrap melt down and electricity saving were practiced by use of \( \text{O}_2 \) injection and high flame temperature burner with excess \( \text{O}_2 \) addition. Sensible heat of high temperature off-gas was utilized in a simple way for preheating scrap and saving electricity. In the middle of 1970s, injection of \( \text{O}_2 \) through lance was practiced to cut down and enhance the melting of charged scrap. To reduce iron oxides enriched in the slag by the \( \text{O}_2 \) injection, coke breeze was injected to the slag/metal boundary. Resulting CO bubbles made the slag foaming and surrounding the long arc to form submerged arc for high voltage UHP operation. The submerged arc decreased radiation loss, power loss and refractory wear, while increasing iron yield by 1% when 20 m\(^3\)\text{O}_2/ton and 3 kg/ton coke were blown at the power input of 400 kWh/ton. Addition of aluminum dross during refining further improved the productivity by 14% and power consumption by 7% of UHF-EAF with \( \text{O}_2 \) blowing.

7.3. Dividing the Function of EAF to Melting and Decarburizing, and Implementation of Eccentric Bottom Tapping Device and Sophisticated Scrap Preheating Facilities

With the progress of secondary refining, refining function of EAF was transferred to LF, making EAF specialized in melting and decarburizing. Labor productivity increased considerably from 9.6 h/ton in 1955, 3.4 h/ton in 1965, 1.7 h/ton in 1975 to 0.88 h/ton in 1979, while tap-to-tap time and electric power consumption decreased from 166 min and 543 kWh/ton in 1973 to 111 min and 439 kWh/ton in 1983.

At some integrated iron and steel plants, EAF operation with hot metal charging in excess of 50% of total was practiced with \( \text{O}_2 \) injection, depending on the availability of hot metal and cost advantage of hot metal over scrap and electricity (cf. calculated power consumption becomes zero at hot metal ratio of 80%).

In 1985, Topy Industries incorporated Eccentric Bottom Tapping (EBT) system, jointly developed by Mannesmann-Demag and Thysen Edelstahl Werke, to its 120 ton EAF at Toyohashi Works, resulting in the following success:

(1) Tap-to-tap time is made shorter,
(2) Slag is separated from metal on tapping, preventing the carry over of the oxidizing deC slag into ladle,
(3) Metal stream at tapping is separated from excessive exposure to ambient air, resulting in reduced N pick up and temperature loss,
(4) Reduced tilting angle of EAF at tapping made the distance from the bottom of water cooled panel to slag/metal boundary decreased from 300 mm to 90 mm, decreasing refractory erosion with the increased water cooled area of furnace wall, and
(5) Improved power efficiency with shorter length of water cooled power cable.

In view of the above advantages, number of EAF equipped with EBT sprang up to 22 in 1992.

For scrap preheating, various developments have been in place since late 1960s. In late 1990s onward, scrap heating systems have become sophisticated as exemplified by Con- tiarc by Demag, Danarc Plus M\textsuperscript{3} by Danieli, Korfarc by
Mann-Demag, Conarc by SMS-Demag and ARCON by Concast, some of them even incorporated with O2 injection, approaching closer to a combination process with BOF. The scrap preheating systems are designed to reduce effectively the emissions of dust, dioxins and NOx in EAF off-gas.

Industrialization in Japan of scrap preheating systems includes:

1. Twin vessel EAF was introduced to Hikari in 1985. One vessel is used for arc melting, while charged scrap in another waiting vessel is preheated with off-gas from the former vessel and oil mist side burner, improving thermal efficiency to decrease electricity cost.
2. Fuchs scrap shaft with two stage comb type gates was installed on top of EAF. High temperature off-gas out of EAF is delivered into the shaft to preheat the scrap during while melting and deC proceed in EAF, resulting in the saving of 90 kWh/ton. This was made into two shaft type later.
3. Intersteel Tech established Consteel system which delivers scrap from the side-opening of EAF after continuously preheating the scrap on a conveyer through the horizontal off-gas duct with heating burners. Scrap preheating to 600°C decreased power consumption to 300 kWh/ton. Consteel system was installed in 1992 at Kyoei Steel Nagoya Works.

Domestic preheating systems installed include IHI for Tokyo Steel, Daido for Daiwa Industries, and NKK for Kishiwada Steel. ECOARC system by NKK delivered in 2005 consists of direct connection of preheating shaft and EAF. Coal and O2 are injected in EAF to accelerate melting, CO in off-gas is combusted with delivered air to heat scrap in a shaft, improving the productivity by 50%. Also, 50% of dust in off-gas is trapped on scrap, and dioxins, white smoke and smell in the gas are removed in the waste gas treatment path.

In addition, melt stirring equipment such as inert gas injection through permeable refractory tuyeres (ex.100 Nm3/tuyere × 3 for 50 ton EAF) and electromagnetic stirring with electric current fed from multiple pin, both placed at the furnace bottom, have been commercialized to homogenize melt bath temperature and composition and promote steelmaking reactions and slag removal.

7.4. Birth and Maturation of DC-EAF and Giant High Power-EAF

UHP-EAF brought forth revolutionary advantages for EAF operation. It had, however, inherent disadvantages such as high consumption of the electrode and refractory together with the occurrence of flicker during power on time. To overcome the disadvantages, DC-EAF was industrialized in Europe and introduced to many steel plants in Japan. DC-EAF uses an upper electrode as negative electrode and steel melt as positive one which is electrically connected through the furnace bottom to current leads. Three types of enduring connection are popular:

1. Multiple steel bar contact pins by Mann-GHH,
2. Water cooled round steel billets of 200–300 mm diameter by CLESIRSM, and
3. Permeable and conductive MgO–C refractory backed up with Cu plate by IHI-ABB.

DC-EAF exhibited 50% reduced consumption of the upper electrode compared with AC-EAF which employs three electrodes. Hot spot formation and flickers decreased considerably. Melt bath stirring was also made better, equivalent to 100 Nm3Ar injection, owing to DC electric current which pinches the melt toward the furnace center. Topy Toyohashi put 30 ton DC-EAF into operation in 1988. Since 1990, introduction of DC-EAF increased to reach 22 in 2005. Tokyo Steel installed world largest class DC-EAFs, 130 ton furnace at Kyusu and 150 ton furnace at Okayama. Daiwa Steel Mizushima selected 100 ton furnace for hot metal charging operation.

For DC-EAF, hot heel operation is common, retaining 10–20% of melt after tap for the subsequent heat. Hot heel operation is favorable for early melt pool formation, which in turn makes early O2 injection possible. The largest DC-EAF ever built in Japan is one of the world largest Giant High Power (GHP) 420 ton Twin DC-EAF at Tokyo Steel Odawara. It has two top electrodes for 9.7 m diameter shell with 4 water cooled 70 kA bottom electrodes, equipped with Consteel scrap preheating system, followed by 300 ton VD/VD-OB. The DC-EAF operates with 120 tons of hot heel, taps about 360 tons/h at 45–50 min intervals with 33 Nm3O2/ton injection. The melting rate is 2.1 tons/h/kw at 387 kWh/ton fed by about 170 MVA (600 V × 280 kA) transformer, consuming 1.2 kg/ton of top electrodes.

On the other hand, AC-UHP EAF has also developed toward GHP (~1 MVA/ton) category in late 1990s, utilizing higher voltage (~1 MV), lower current and larger capacity transformers. GHP AC-EAFs operate with long arc and low short circuit current by decreasing the reactance and improving the balance among the phases, helped by optimized power control and operator guidance system. Coherent burners for highly efficient scrap melting have got popular too, to avoid the harm of hot spot formation. Recent developments in the technology for the equipment and operation of EAF in Japan followed the trajectory of the European predecessors (Fig. 12).55,46

Productivity of EAF is influenced by the choice of mixed raw materials (hot metal, scrap, DRI, HBI etc.), furnace capacity, scrap preheating, machine and practice for charging, efficiency of melting practice, and sequence matching with the preceding and succeeding processes (LF, CC). Efforts have continued to maximize the productivity of the EAF steelmaking system and minimize the cost of steel by enlarging the furnace capacity and advancing the automation and robotization of the operation.

Today, the productivity of EAF in Japan is around 100–180 tons/h, tap-to-tap time 1 h, excluding exceptional GHP
DC-EAFs such as that at Tokyo Steel for carbon steel which comes not far away from the productivity of BOF. As mentioned before, EAFs in Japan are largely combined with LRFs to produce wide ranges of specialty steels or stainless steels, the ratio of secondary refining for EAF steels in 1991 being 85.2%.

In Spain, Italy and Turkey, EAF steel production shares 75%, 66% and 75% in total steel output, respectively. A large amount of carbon steels is produced with modern GHP AC-EAFs of 250–300 ton capacity with 240–300 MV A transformers. On the other hand, EAF steel production in Japan during 2000 to 2012 has been slightly decreasing from about 28% to 23% (ca. 25 million tons/year) of annual total steel production of some 105 million tons which has not changed much during the period. The decrease is partly due to the increase in the scrap ratio of BOF steel production. Speculated chronological increase in EAF steel ratio in parallel to steel stock accumulation in Japan has not been observed yet within the short time span of 10–20 years. This indicates that the increase has been inhibited by many other factors such as scrap price, electricity cost, steel material price, steel grades mix and import/export balance of raw materials and steel products.

8. Progress of Ingot Casting and Improvement of Ingot Qualities

8.1. Ingot and Ingot Mold

Ingot casting in Japan in early times, when crucible steel-making dominated, was practiced in a small scale. No technically detailed documents are available. Ingots greater than 1 ton weight were cast probably first time in late 1901 with Bessemer converter steel at Yawata in 1.7 ton molds placed on a railway bogie.

With regard to the mold, factors influencing the durability were investigated from 1923 to 1927. Rather comprehensive technical reports on the ingot, mold and casting process were published in Tetsu-to-Hagane as the summary and discussion which were submitted by member companies to the 3rd and 4th Steelmaking committee of ISIJ in 1932–1933.

According to the reports, ingots were either top poured or bottom poured in 100–300 kg binocular molds, 10 ton class rectangular molds or 100 ton class polygonal molds for bar, wire rods, shapes, tubes, heavy plates or forgings, respectively. The ingots were then investigated for macrostructure and sulfur print. In the beginning, molds suffered from early period cracking, spalling, crazing and strain. To improve the mold durability, mold profile, weight ratio of ingot to mold, chemistry, pouring process, heat treatment, and microstructure of iron from cupola and BF were investigated. The investigation revealed the superiority of ductile cast iron mold which was then favorably used. Later, quality of less expensive, direct cast mold with BF iron for steelmaking improved, and got popular for rectangular carbon steel ingot molds.

Until early 1970s when continuous casting machine (CCM) was introduced in its infamy, steel melt was cast into ingots, soaked, subjected to roughing and supplied to downstream rolling for billets, blooms or slabs (collectively semis). The ingots were classified in the order of deoxidation degree into rimmed-, semi killed- or killed-steel ingot (Fig. 13).

8.2. Casting of Rimmed-, Capped- and Core Killed-Ingot

Rimmed steel ingot was produced by top pouring weakly Mn deoxidized carbon steel containing C < 0.3% into square mold for shapes and large flat mold for plates or strips. Immediately after pouring, thin surface layer with some skin holes of small diameter was formed, followed by the growth of columnar dendritic crystalline layer perpendicular to the bottom and peripheral walls of the mold. In front of the dendritic layer at the solid/liquid boundary, solutes C and O were concentrated with the progress of solidification, evolving CO gas bubbles. Some of the bubbles were entrapped by the growing dendrites to form tubular bubbles nearly horizontally located in the lower half of the ingot. The tubular bubbles started growing about 40–50 mm from the surface of

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![Fig. 13. Typical Solidification Structure of Rimmed, Semi-Killed and Killed Ingot.](image-url)
the ingot, the distance being controlled by the composition, cooling rate, pouring rate of the melt and the amount of minor addition of Al to the melt. The solidified shell layer from the ingot surface to the end of the tubular bubbles, called rim layer, was negatively segregated and clean, and the ingot was named rimmed ingot since it was surrounded by the rim layer (Fig 13, left).

CO bubbles other than entrapped ones left from the boundary, agglomerated, and ascended along the solidification front together with melt flow to reach the top surface in the mold where they broke up, forming sparks by air oxidation of splash droplets. In the upper half of the ingot, static pressure of the melt was lower, and hence CO bubbles formed at the boundary grew faster, left the boundary faster without forming tubular bubbles, and ascended with the melt along the boundary to the top to break up. Metal droplets formed at the break up burned up as sparks. The melt flow, partly oxidized at the top surface, descended through the central part of the ingot, forming strong circulating flow directed to the top again. The circulating flow was accompanied with many CO bubbles, looked from the mold top like boiling to form the rimmed layer, and hence it was called rimming action. It was quite a show to see great amount of the sparks arising from the top of large ingot molds which were lined up on the bogies.

Oxides occurred in the ingot in various ways as the air oxidation product of melt stream during pouring and on the top of melt in the mold, entrapped eroded refractory and ladle slag, and agglomerates of endogenous inclusions formed during solidification. They were engulfed in the circulating flow, and largely carried back to the top of the mold as scum.

Skin holes were scaled off due to the oxidation of the skin layer during the reheating of the ingot in a soaking pit for roughing. As long as reasonable thickness from the ingot surface to the starting point of the tubular bubbles was secured, the bubbles were not exposed to air and remain free from air oxidation, and hence clean and ductile surface was obtained on the rolled product. Further progress of solidification formed debris of sediment crystals with negative segregation of solutes but with entrapped large inclusions at the bottom of the ingot. The entrapping of large inclusions was due to the showering sedimentation of equiaxed crystals which formed the debris.

Above the debris, inner core was formed due to accelerated solidification. Solutes were enriched and globular bubbles were dispersed irregularly in and around the inner core. Top of the ingot solidified earlier than the whole of the ingot as a result of the termination of the rimming action and radiation heat loss from the top surface. From above the inner core around the vertical central axis to the top of the ingot, many sulfide precipitates appeared. As the inner core was subject to accelerated solidification, however, large shrinkage cavities and heavy segregation, often observed in a killed ingot, did not form, resulting in a better yield of sound part of the ingot. During 80% period of complete solidification, the ingots in mold on the bogie should be kept stand still without applying turbulent wavy motion by controlling the track time of bogie to avoid anomalous segregation formation.

For the rimmed ingot making, British Iron and Steel Association (BISRA) published comprehensive pioneering work done until 1928 (Jernkontoret) in 1939. The two works contributed greatly to the progress of relevant research in Japan. Many studies were carried out since 1934 in Japan on the distribution of surface bubbles, location, size and formation mechanism of the tubular bubbles and inner bubbles, and distribution and formation mechanism of inclusions and segregation of C, P and S.

In the period when high productivity ingot making was demanded, capped ingots were produced which intended to stop rimming action in the midway and suppress any further air oxidation with thick cast iron lid placed on the open surface of steel melt to quench and solidify the surface. Rimmed and capped ingots were favorably applied to the mass production of various cold rolled strip and surface treated strip owing to their superior surface quality and high yield on rolling. Also, utilizing rimming action in the early period after pouring rimming ingots, Al was added to deoxidize and stop rimming action after about 20 mm thick sound and clean rim layer was formed in the ingots. This type of ingot was named core killed ingots which were less expensive than Al killed ingots, better for surface quality with decent interior quality, and hence used in a mass for press forming strip for automobile.

8.3. Casting of Semi Killed Steel Ingot

Semi killed steel was developed in the USA. It became popular in Japan since 1955 for lower S segregation than rimmed ingots and better yield than killed flat ingot for plate due to decreased segregation and shrinkage in the top part of the ingot. Weakly Si deoxidized steel melt was poured with minor amount of Al addition to control the degree of deoxidation to form tubular bubbles in the upper half of the ingot. The deoxidation degree was monitored and controlled by the shape of the swelling of the ingot top which optimized globular bubble distribution and the shape and size of tubular bubbles in the upper part of the ingot. The swelling was also influenced by ingot size, width to thickness ratio of ingot, melt temperature at pouring and pouring time. S-segregation of semi killed ingot increased when the track time from the end of pouring and charging into soaking pit decreased. Accordingly, track time was kept longer than 80% of the time required for complete solidification of the ingot as it was the case for rimmed ingot. The use of semi killed steel plates for the outer hull of ship minimized the separation fracture of the plate on welding, greatly saving ship from wrecks.

8.4. Casting of Killed Steel

Killed steels were cast into ingot long since Si deoxidized acidic open hearth steel got popular. Melt refined in EAF for specialty steels was also cast as killed steel ingots for a long time. These ingots were cast with steels strongly deoxidized with Si, Si–Mn and/or Al. For particular applications, carbon steel deoxidized under vacuum was cast as killed ingot. Strongly deoxidized steel does not produce CO gas bubbles, keeping the melt in the mold quiet, and hence called killed steel. To compensate for the solidification shrinkage in ingot body with steel melt fed from the top of the ingot, lining with heat insulating refractory board or exothermic refractory board was placed around the inner walls of the mold top together with flux powder addition to cover the top to delay
Small size molds like binocular type ones were set on a heavy cast iron base/stool which has grooves leading from the center to where the molds were set. At the center, cast iron pipe with refractory brick inner lining was placed standing with melt pouring funnel on top and horizontal melt delivery openings at the bottom. Each opening was connected to a refractory delivery tube embedded in a groove. Another end of the tube led to the center of the mold bottom where the tube had upward opening. Steel melt from ladle was bottom poured into the mold through the funnel, pipe and delivery tube. Medium to large size ingots were similarly bottom poured, but with smaller number of molds per base. Bottom pouring offered less turbulent melt surface in mold, and less air oxidation since the surface was covered by mold flux. Larger size ingots were poured from the top opening of the mold which was usually placed big-end-up. For top pouring, graphite plate was placed on the base to reduce the erosion of the cast iron base by impinging melt stream from ladle, and short cylinder made of thin steel strip was set at the bottom and morasses was sometimes painted on the inner wall of the mold both to reduce the melt splash adhering to the wall and degrade the ingot surface.

Melt thus filled in the mold forms from the wall to the center of the mold:
1. Thin chill crystal layer,
2. Growing columnar dendrite crystal layer from the walls and bottom of the mold, and
3. Sediment of equiaxed crystals initially formed at the melt surface and in front of the growing columnar crystal layer. The sediment is negatively segregated for solute elements and includes ascending and suspending inclusions captured during the fall of the equiaxed crystals.
4. Further inside, coarse columnar crystal layer develops, and near the top of the crystal array where solid to liquid transition layer with solid fraction of about 0.3, interdendritic melt is enriched with the solutes to decrease its specific density,
5. The solute enriched melt ascends through coarse inter columnar dendrite crystal area while melting the dendrite arms and accompanying interdendritic melt around,
6. The trajectory of the ascending melt streak as it proceeds higher is somewhat pushed toward the center of the ingot due to the horizontal growth of the columnar crystal layer, forming inverse V shape segregates or A segregates in 2D. The 3D envelope of the A segregates looks like big-end-down irregular truncated cones.
7. In the area above the sediment debris around the central vertical axis of the ingot, coarse dendrites and coarse equiaxed dendrites exist with the melt in which the solutes are enriched. The volume fraction of the dendrites and the segregation of the solutes increase with the progress of solidification. Some fraction of the solute enriched melt in this area tends to ascend, but the ascending is largely inhibited since the dendrites formed dense clusters and heavy networks.
8. The networks or clusters sink discontinuously due to the increase of solidification shrinkage from the bottom of the ingot and the static pressure of the melt imposed onto the network or clusters.
9. The gaps, created as a result of the sinking, are filled with solute enriched melt from the above and around, forming heavily segregated V-shape lines which were called V segregates in 2D. 3D envelope of the V segregates forms irregular big-end-up truncated cones.
10. When the feeding of the gaps with the melt is inhibited, the gaps turn out to be voids and discontinuous cavities. In a flat shape ingot for slab, tips of horizontally grown columnar dendrite array/bundle sometimes reach near the center thickness of the ingot, get entangled with tips of the bundle grown from the other side, forming bridge which inhibits the melt to flow into the gaps. Large cavity and/or discontinuous train of cavities may occur in this case.
11. When the solidification proceeds further along the central vertical axis toward the top of the ingot, surface of the hot top solidifies as crust, and hence melt feeding from the hot top becomes insufficient, leaving there a large size pipe or funnel shape cavity.
12. The cavity is usually connected to ambient air through pores in the crust, oxidized on the inner surface, and hence does not weld on subsequent rough rolling, must be cropped off, causing loss of yield. On and around the cavity surface, segregation of S, P and C is heavy, sometimes precipitating MnS and FeS.

To minimize the crop loss, the bottom tip of the cavity is designed to stay within the hot top, not extending into the body of the ingot. For that, combination of influencing parameters such as the ratios of width to thickness and height to thickness, taper, and the volume ratio of hot top to ingot, thermal insulation of hot top refractory lining, and exothermic and thermal insulation property of hot top flux (ex. ignition and burning time, rate of combustion, total heat generation, bulk density) are to be optimized. For exothermic combustion, reaction between CaSi powder and oxidizing reagent is favored for its high heat evolution and lasting combustion. Large inclusions carried over into the mold may cause “sand defects” detectable by ultrasonic inspection when they fail to be removed by early flotation.

To minimize such inclusions, enhancing flotation of the inclusions in the melt in mold is found effective by reducing the excessive showering of the equiaxed dendrite crystals falling from the top periphery and surface of the melt in ingot, since the showering accompanies ascending inclusions down to the debris in the ingot bottom. Preventing low temperature pouring and applying quick igniting and highly exothermic flux to the surface of the melt in hot top surrounded with insulating brick lining have been practiced countermeasures. Reduction of air oxidation of pouring stream is an obvious measure to prevent inclusion formation, but pouring the melt in inert gas atmosphere or under vacuum is not handy and unwelcome except for demanding steel grades.

Many proposals were offered to decrease A- and V-segregates. For example, decrease the contents of P and S, avoid low temperature pouring, choose proper mold thickness, and keep sufficient track time to avoid bridge formation due to abnormal fall of equiaxed crystal clusters of vibration origin. However, these measures were without notable success. On the other hand, decreasing Si to be ~0.1% has been found quite successful. Segregation of Si contributes greatly to decrease the density of interdendritic melt, enhancing the formation of A- and V-segregates. At ~0.1%Si, however, the Si segregation does not appreciably decrease the density, reducing the formation of the segre-
gates as proposed and confirmed by Yamada et al.\textsuperscript{29)}

In this way, valuable technological developments were made to improve the productivity and quality of rimmed-, semi killed- and killed ingot. Since 1970, however, ingot casting has been replaced with quickly developed continuous casting, producing only limited amount of ingots with declined number of R & D, except for special casting and extra heavy ingots for forgings which have shown the following continued progress.

8.5. Casting Ingots for Extra Large Forgings and Extra Heavy Plates and ESR Ingots

Japan Steel Works revealed its technology in 1989 to commercially cast 500 ton class ingot for forgings. Several heats of EAF steel melt were stream degassed and top poured into mold in sequence, under vacuum to remove hydrogen while preventing air oxidation. To counter the segregation of C in the ingot with the progress of solidification, C content of subsequent heats for pouring were decreased heat after heat.\textsuperscript{50}) A growth model for solidified fraction of the ingot with equilibrium partition coefficients of C made it possible to estimate the segregation ratio of C in the remaining melt in the ingot. To dilute the segregation to meet the aim C, necessary temperature and C content were calculated for the next heat, which were tapped from EAFs and poured into the ingot. This method was worked out due to the constraint of limited EAF capacity, but showed a peak of technology in 1992.\textsuperscript{49)}

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For special applications, Sumitomo metal commercialized horizontal ingot casting which employed low height rectangular mold for unidirectional solidification from bottom to top. After solidification completed, top of the flat ingot, where solute elements were segregated, was machined off for finish rolling. NKK industrialized 140 ton class hollow ingot casting for large hollow forgings. For greater size ingots, Japan Steel Works and Japan Cast Steel and Forging Steel have industrialized casting of 650–670 ton ingots and 650 ton ingot, respectively, in 2009–2011, successfully producing extra large low pressure turbine rotors for power generation.\textsuperscript{51)}

There have been progresses in large scale electro slag remelting and casting (ESR), too. Japan Steel Works revamped 100 ton ESR in 2011, and introduced world largest class 150 ton ESR facility with single electrode and 2200 mm diameter fixed mold. Precision of the melting and solidification operation has been upgraded to the extent that single electrodes are exchanged multiple times to make the large ingot with low frequency power source to reduce electricity consumption.\textsuperscript{52)}

9. Development toward High Quality and High Productivity Continuous Casting

9.1. Continuous Casting Technology in Early Stage of Introduction\textsuperscript{13,14,53,54)}

Development of continuous casting machine (CCM) with oscillating mold started in 1949 when Junghans in Germany and Rossi in USA trialed such CCM on the basis of the patent by Junghans. Industrial implementation of the CCM in Japan started in 1955 when Sumitomo Metal got license to sell and operate Rossi Continuous Casting Machine (RCCM), and commercially built and operated at Osaka Steel Works one strand vertical billet RCCM to produce rods for spring and wheel stopper for train. For stainless steel slab and bloom, Hikari put one strand vertical RCCM at the end of 1960.

RCCM at that time was technically not mature yet, and hence problems happened on the machines and operation. The problems were solved by 1964. The two RCCM operated successfully with accumulated technical understandings and operational skill, and the yield of the cast strands were confirmed to be better than ingot casting route by several percentages. However, the productivity in terms of metal-in-mold time of RCCM was less than 10%, casting rate was a low 15 tons/h, investment required was about 1.5 times of the ingot casting, accidental shut down occurred sometimes and quality of the cast semis was unsatisfactory. These drawbacks made the RCCMs not built until early 1960s in integrated iron and steel plants by the sea consisting of large BF and BOFs.

After that period, EAF mini-mills evaluated future potential for the development of CCM for their own circumstances, and constructed in sequence the followings:

Kitsunoh Tonkusuyokou (Northern Japan Specialty Steel), Mannesmann Demag vertical billet and slab CCM in 1964, the first one in Japan, Nippon Yakin, Concast vertical slab CCM and Kokkou Seikou, Concast curved (S-type) billet CCM both in 1965 as the 1st ones in Japan, Tohoku Satetsu, Olsson vertical and progressive bending billet CCM in 1965, the first in Japan. These CCMs were followed in 1967 by Osaka Seiko’s Concast curved billet CCM and Daiwa Seiko’s Concast curved slab CCM, and Nihon Kinzoku’s Olsson vertical slab CCM.

Integrated steel plants also put the following CCMs into operation during 1964 and 1967, i.e., Kobe Steel Kobe, USSR type vertical multi strand billet CCM and bloom and slab CCM both in 1964, NKK Tsurumi, DST type curved slab CCM first time, Yawata, Olsson vertical bending 6 strand billet CCM, Nissin Kure, USSR type slab CCM and Sumitomo Kokura Concast curved 6 strand billet CCM, all in 1967.

Acquired experiences of the construction and operation of these CCMs and relevant information on the CCMs abroad (mostly Germany and USSR) gained credit with integrated steel plants on the reliability and economy of the CCMs combined with BOFs, promoting further implementation of CCM to mass produce carbon steel semis. However, production of CC steel semis at that time with 10 billet CCMs, 2 bloom CCMs and 5 slab CCMs in total remained a small 5% or less of the annual crude steel production of 60 million tons.

In view of technologies, implemented in CCM and CC operation were;

(1) Application of warm forged Cu–Ag alloy for mold,
(2) Use of ZrO\textsubscript{2}–SiO\textsubscript{2} nozzle for tundish,
(3) Domestic manufacture of thermometer and spray nozzle, and
(4) Use of imported mold fluxes and silica base submerged entry nozzle (SEN).

Also, continuous-continuous casting technique was practiced to considerably improve the ratio of metal-in-mold time [%] to [% of cast semi] from [50/95.8] for single heat cast to [76/98.0] for 3 heats cast, [83/98.4] for 5 heats cast and [92/98.8] for 10 heats cast in sequence, but not quite.

To be consistent with the productivity of BOF at minimized construction cost while capable of sequence casting
slabs of the width for strips and plates, curved CCM, which fits in the height of existing casting bay building, was first commissioned at Tsurumi in 1967 for plates. The choice was taken since Concast S-type curved CCM operated successfully for plates at Dillinger, Germany in combination with large capacity BOFs. At Tsurumi, 100 ton LD was combined with Mannesmann curved CCM for plates, equipped with: (1) Ladle Ar bubbling, (2) Al wire injection into ladle for deoxidation, (3) Feeding steel melt from ladle to tundish via. Ar shrouded long nozzle to reduce both air reoxidation of the melt and carry over of ladle slag into tundish, (4) Melt transfer from tundish to mold via. SEN and (5) Casting with mold flux powder (powder casting).

Casting performance was so successful that 40 ktons/mo. of the melt were cast without break out for 6,900 heats in two years period. In the above, terms (1)–(5) are still important basics to sustain CC operation. Qualities of the cast slabs were better than the slabs of rimmed and semi killed ingot origin, meeting the demanding specification of line pipe steel plate API5LX52. In fact, 30% of the total amount of cast slabs was for the line pipe plate. For blooms, Concast 8 strand curved CCM was combined with 180 ton BOF to mass produce 43 ktons/mo. of carbon steel at Mizushima.

9.2. Enhancing the Productivity of Curved CCM at Integrated Steel Plants

Credibility of the curved CCM as a mass production facility compatible to BOF was confirmed as above in late 1960s to let integrated steel plants in Japan rush to adopt the combination of BOF and curved CCM since 1970. Oita combined three Hitachi Zosen-Demag curved CCMs with three 330 ton BOFs, starting a unique fully continuous casting plant first time in Japan in 1972. Metal-in-mold time was much improved with: (1) Large tandish, (2) Top insert of dummy bar, (3) Swing tower to exchange ladles, (4) Melt level sensing in mold with thermocouples, (5) System to quickly exchange the cassette stand module containing mold, mold oscillation mechanism and slab support rolls, (6) Long mold to cast slabs at a high speed of 2 m/min, (7) Slide nozzle for melt transfer from tandish to mold, (8) Casting in a constant width mold followed by width sizing up to 125 mm at roughing mill in hot rolling plant, and (9) Automatic casting operation.

Over 50% of crude steel at that time was cast as rimmed steel ingots for better yield, formability and surface quality, and hence open cast Riband Steel technology for CC developed by US Steel was introduced to replace the rimmed ingots. Compression casting technology developed also by US Steel was adopted to avoid internal cracks which form at one point bending during high speed slab casting. Oita started casting in April, 1972 and soon achieved a world record of over 320 ktons/mo. of cast strands with the three CCMs in Aug. 1973. Among the three, No. 1 CCM marked another world record of casting 161 ktons/mo.

It was in 1973 when all Japan production of CC semis reached 16.67 million tons, 20% of annual crude steel production. Throughout the early half of 1970s, Japanese steel companies made efforts to stably maximize the output of CCMs (in total 19) while minimizing the occurrence of defects of strand cast at a high speed. Technologies developed for the objectives include:

(1) Top insert dummy bar as mentioned before, (2) Erosion resistant refractory material for long nozzle and SEN (non-fused silica, alumina-graphite), (3) Tundish slide gate and Ar seal at the boundaries of tundish/slide gate and slide gate/ SEN, (4) Reduction of air oxidation during the melt transfer from tandish to tandish by use of Ar seal box or long nozzle, (5) Protection against the surface oxidation of tandish melt with Ar or tandish flux, (6) Use of large tandish and control the flow and stream line of the melt in tandish with furniture for inclusion removal, (7) Quick tandish exchange system, (8) Establishing the use of SEN in combination with powder casting as a routine, (9) Quick exchange of SEN during casting as exemplified by Kashima in 1978 (only in 1 min with 1 person), (10) Soft cooling and better lubrication at mold/cast strand boundary with improved mold flux, (11) Electromagnetic melt level sensor for mold as developed by NKK, which is superior in sensitivity to conventional sensors with radio isotope or thermocouple, (12) Rationalization of water cooling channels in mold, (13) System to acquire and process the data for temperature distribution in the mold plate measured with embedded array of thermocouples and friction force determined with Mold Tektor by CRM, Belgium at mold/cast strand boundary, both for preventing sticker break out. Incidentally, the breakout occurs when the shell of the cast strand welds or adheres to the mold wall and is torn as the strand is withdrawn out of the mold, (14) High cycle oscillation of mold which makes oscillation marks on the cast strand surface shallow and decreases both heat transfer resistance across the marks and solute segregation in the marks, contributing to reduce transverse surface cracks, (15) Improvement of cast strand support mechanism and water cooling below the bottom of the mold (cooling grid or plate), (16) Optimization of the cooling of wear resistant mold by the choice of material, plating, taper, and length of the mold. The length converged to about 900 mm from longer mold with corner slit for water cooling, (17) Previously mentioned quick exchange system of the cassette stand with manipulator, (18) Selection of wide angle water spray nozzle chips for the secondary cooling system. The chips prevented spray nozzle clogging and reduced surface defects and internal cracks, (19) Optimization of 2D water spray pattern to fit the steel grades and the width of cast strand, (20) Precise control of roll gap and roll alignment, (21) Adoption of smaller diameter split rolls to firmly support the strand to decrease the bulging, and (22) Automatic casting operation with comprehensive control of the tandish slide gate, melt level sensor in the mold, and pinch roll and dummy bar as materialized in 1973 at Wakayama.

For strand cleanliness, contradictory demand to increase
casting speed while decreasing inclusion engulfment was somewhat resolved by limiting circle radius (as used for the S-type curved CCM) of the strand to 30–50 times of the strand thickness, and making the metallurgical length* extended by straightening the strand to horizontal direction at 1/4 point of the circle (*The distance from the melt level in mold to the point where the strand solidifies completely = time required for through thickness solidification × casting speed). This helped the height of plant building reduced to save construction cost.

CC is in essence a near net shape casting process. Development to this direction was made in 1973 to cast H-shape with H-section beam blank CCM at Mizushima and in 1974 round section centrifugal bloom CCM at Keihin for seamless pipe. Maximum size of CC strands reached 300 mm thickness×400 mm width for bloom and (250–300) mm thickness×(2000–2400) mm width for slab. With the developments mentioned in 9.1–9.2, CC ratio for slab in Japan achieved 32.8%.

Productivity of CCM kept increasing since. Number of heats continuously cast in sequence per one dummy bar insert rose to 270 at Tsurumi in 1974, followed by over 200 at Yawata and Mizushima. To make such long sequence CC operation possible, employed were:

1. Technology for simultaneous exchange of ladle and tundish during casting,
2. Sequence casting technology of different grades developed in USA where the mixing of preceding and succeeding heat was prevented and the two heats were mechanically connected by chill metal device placed in between, and
3. Width change technology where narrow faces of the mold were either set back or push forward to get broader or narrower width strand without interrupting the casting as developed in 1975 at Mizushima. Rating up of the width change was developed further in 1983 at Sakai where variable taper and face shift type narrow face driven mold was commercialized, resulting in the width change speed up to 100 mm/min/side at casting speed of 1.8 m/min.

In those days, RH degassed and lightly Al killed CC steel developed at Oita from deoxidation controlled Riband steel was recognized better in productivity, cost and quality consistency than rimmed ingot steel. The former replaced, therefore, the latter which shared more than half of total ingot production in Japan. In 1976, NKK took the initiative to apply light inline roll reduction at the melt pool end in CC strand to reduce the segregation and porosity occurring in the center thickness of CC slabs. Also, Tsurumi started hot charge rolling (HCR) and direct hot charge rolling (DHC) of CC slabs for energy saving, decreasing about 360 MJ/ton versus conventional cold charge rolling. A step forward, Sakai industrialized hot direct rolling (HDR) in 1981.

Although circular CCM in this way exhibited the advantages and contributed to the proliferation of CCM, it has inevitable disadvantage to cause 1/4 thickness accumulation of large inclusions from the upper surface of the strand. The accumulation is due to the capture of large exogenous inclusions brought in and ascending out of the melt pool in the strand, and is detrimental to the mechanical properties of demanding products.

9.3. Evolution of Vertical Liquid Core Strand Bending Type Slab CCM

The upper quarter thickness accumulation of large inclusions increased with casting speed of CCM. Vertical solid core strand bending (VSB) type CCM was a solution but with drawbacks of increased building height and slower casting speed. As a better solution, Chiba introduced in 1974 a vertical liquid core strand bending (VLC) type CCM developed by Vöest-IHI. It has about 2.5 m long vertical entry (mold inclusive), followed by progressive bending at multiple points and multiple point unbending of strand with liquid core to reduce the accumulation at higher casting speeds. The VLC CCM was still in its infancy, and hence casting operation in early times suffered from insufficient rigidity of support roll segments and the fracture of rollers in the bearings for the support rolls. After solving the problems, however, the accumulation was drastically decreased to enable the casting of slabs for HIC resistant plate for line pipe.

Soon later, VLC CCMs were introduced successfully in 1976 at Keihin (SMI-Concast make), Kimitsu in 1980 (Hitachi Zosen-Demag make), and Fukuyama where circular CCM was converted by Hitachi Zosen-Demag to VLC in 1980. Since then, new installations of VLC CCMs (Fig. 14)84) were many in other steel plants in Japan. In Europe and USA, it took longer time for the implementation, but recently, the installation has been increasing, following the one at Dillinger. To deal with more demanding qualities,
VSB CCMs with longer vertical part of strands were put into operation in 1976 at Mizushima and Keihin. The CC ratio reached 89.1% of total crude steel production in Japan in 1984. Progress in operational skill, adoption of multiple taper narrow faces for mold, and mist spray for secondary cooling of the strands to reduce surface defects caused by the embrittlement at elevated temperatures, all contributed to increase the ratio of hot charge rolling (HCR) of cast slabs in many steel plants. On the other hand, hot direct rolling (HDR) and direct hot charge rolling (DHCR) of cast slabs have been limited to strands for hot rolled strip, not prevailed to strands for plate due to lot size limitation and quality issues.

Accordingly, the productivity of CCM further increased, some of them up to 200–250 ktons/mo. To guarantee the qualities of strand, the roll gap, roll alignment, irregularity of roll rotation and clogging of spray nozzle for secondary cooling before casting are inspected with inline multiple function checker which passes through the roll gap with dummy bar, transmits the measured data wireless for correction. The checker data and corrective actions have been found effective to decrease the surface cracks and internal cracks arising from strand bulging. Substantial developments in the system design and the mechanism for CCM by this time are detailed in a good review after Harabuchi and Pehlke.53)

9.4. Highly Productive High Speed Slab Casting of High Quality Steels33,54–57)

During the latter half of 1980s, the productivity advantage obtainable by prolonging metal-in-mold time with the super long sequence of continuous continuous casting operation was largely offset by the downgrading of slab qualities. The downgrading loss occurred at the unsteady part of casting, i.e., joints of heats where melt contamination took place in association with many times of tundish exchange operation. The loss became profound with stricter demands for the allowance on the subsurface and internal inclusions, center segregation and porosity of the strand.

To prevent the loss, measures have been industrialized including:
1. Transfer of steel melt without contamination from ladle to tundish and tundish to mold,
2. Minimizing temperature drop of the melt during the transfer,
3. Rationalizing tundish structure,
4. Optimizing melt flow in mold, and
5. Inline reduction of the cast strand.

For preventing the air oxidation, seal box structure is one way where ladle and tundish are connected with a cylinder filled with Ar. Also, Ar is injected into the space between the melt surface and tundish lid set airtight on the top periphery of tundish to keep the tundish melt free from air oxidation. Another way is to pour the melt from ladle into tundish through Ar-sealed long refractory nozzle, while the melt surface in tundish is covered with non-oxidizing lime or lime aluminate slag to keep away from air oxidation. In addition:
1. Air tightness of the melt transfer route is made better,
2. Carry over of FeO bearing ladle slag is made minimal,
3. Starting tundish-open only after filling tundish to a certain depth (>minimum 600 mm),
4. Employ large volume tundish (> 65 ton for two strand slab caster),
5. Always keep the tundish melt level >1.2 m during steady state casting to minimize the carry over of tundish slag into mold by vortex flow which may occur in tundish otherwise, and
6. Inhibit the short circuit flow of melt from impinging point below ladle to exit nozzle of tundish.

A large 85 ton tundish58) successfully commercialized at Kobe is a typical example in line with the above concept in all aspects.

For super clean steel grades, a solution has been provided by Chiba in 1996 in the form of Centrifugal (CF) tundish (Fig. 15).59) It consists of a cylindrical front chamber where inclusions in the melt from ladle are separated to the central concave cavity of the melt generated with progressive circulating electromagnetic field set around the cylinder chamber. Cleaned steel flows out of a bottom opening of the cylinder chamber into rectangular rear chamber which has an opposite bottom opening to deliver the melt into mold. CF tundish has exhibited high ratio of inclusion separation, commercialized to cast high quality steels with excellent cleanliness.

Another development, H-shape tundish, has been made at Nagoya in 2000. It consists of two rectangular chambers connected side by side with bottom through hole to form H-shape tundish (Fig. 16).60) Two ladles for preceding heat and succeeding heat can be teemed into the 1st chamber simultaneously, without causing the harmful lowering of the melt.

![Fig. 15. Centrifugal Flow (CF)-Tundish for Clean Steel Casting at Kawasaki Steel.59)](image-url)
level in the chambers at the ladle change. 2nd chamber is equipped with DC arc heating guns to compensate for temperature drop of the melt within. At the bottom of the through hole, Ar injection plug is set to stir up all the passing melt with fine Ar bubbles to let even fine inclusions agglomerated and removed. Extended distance between the melt inlet point in the 1st chamber to melt exit point out of the 2nd chamber also favors inclusion flotation. The H-shape tundish has exhibited good capability to solve the problems inherent to the joints of heats, ensuring clean steel casting all over the heats.

Transferring the cleaned melt from tundish to mold through SEN requires special attention. Immersion depth of SEN in the melt in mold, number of exit ports and angle of inclination of the ports of SEN have been so designed as to minimize the penetration depth of the melt flow in the melt pool in strand, while not to cause the turbulence at the boundary of mold slag and steel melt by double roll type deflected melt flow toward the upper part of the mold. Also, various measures to reduce SEN clogging have been elaborated, including minimization of inclusions, making inclusions molten, SEN structure to modify melt flow and SEN materials to let inclusions coming in touch modified to be melted, although none of them are fully satisfactory yet.

In addition, electromagnetic devices to control the melt flow in mold have been industrialized (Fig. 17)[61,62] such as In-Mold Electro-Magnetic Stirrer (M-EMS) pioneered in 1980 at Hirohata, followed by Electro Magnetic Brake (EMBR) of ABB at Mizushima, later developed into Flow Controlled Mold (FC-Mold) of Kawasaki Steel, and LMF of Nippon Steel.

M-EMS accelerates and circulates upper part of the melt in mold horizontally with linear motor type parallel traveling magnetic field. The circulating melt flow washes away the solidification front of the strand shell, preventing the capture of inclusions and gas bubbles to the shell, makes the initial growth of the shell even to prevent the longitudinal cracks and break out of the shell. As a consequence, surface quality and yield of the strand have been much improved.

EMBR or FC-Mold reduces the speed of melt stream out of SEN ports at the two sides of the mold width near the port exits (EMBR) or over the whole width at upper half and lower half of the mold (FC-Mold) with static magnetic field applied through thickness direction of the mold. The penetration depth of the melt stream into the melt pool in the strand is reduced, enabling faster removal of inclusions by flotation. At the same time, wavy motion of the melt surface is damped and turbulence at the mold slag/melt boundary is decreased, both help decrease the mold slag engulfment into...
the pool. Some reheating of the strand shell periphery at the meniscus also occurs, reducing the hook formation there and consequent inclusion trapping below the hook.

Fukuyama commercialized Electro Magnetic Level Accelerator (EMLA) and Electro Magnetic Level Stabilizer (EMLS). The two employ traveling magnetic field, exchangeable by switching the cable connection. EMLA works like M-EMS, while EMLS like EMBR. Lasting elaboration was necessary for all the electromagnetic devices mentioned above until maturation, but after the optimization of the devices and operational parameters, all have become indispensable tool to achieve much improved cleanliness and surface quality of strands.

Another progress was in Cu-alloy for mold which should stand against higher operating temperature caused by high speed long sequence casting and high density magnetic flux imposed by the electromagnetic devices. The high temperature strength is materialized with precipitation hardening CrZr bearing Cu alloys. On top of the alloys, either spray coating with self-fluxing NiCr alloy or thick plating of FeNi alloy is made for wear durability. These measures are effective in preventing the deformation of wide face plate of mold, have guaranteed long campaign and eliminated the occurrence of star cracks which form when the surface coating/plating is lost and mold Cu penetrates into strand surface in contact.

Additional improvement of CCM productivity was necessary at this time to increase the HCR and combine CCM streamlined with hot strip mill. In 1980, No.1 CCM in No.3 Steelmaking Plant of Yawata successfully cast 268 ktons/mo. at max. 2.0 m/min. No.5 CCM at Fukuyama increased casting speed to an average of 2.1 m/min and max. 2.5 m/min in 1985 with a combination of high viscosity mold flux, non-sinusoidal high cycle mold oscillation, mold temperature control, high precision mold meniscus level control and secondary cooling control with mist spray. Optimizing mold melt flow, Fukuyama cast 302 ktons/mo. at max. 2.7 m/min in 1990. Kashima No.3 CCM maximized metal-in-mold time by developing a technique to ending the casting at a constant speed while start casting the next heat during the ending, and cast 309 ktons/mo. at max. 2.0 m/min in 1989. No.2 CC at Nagoya also cast 301 ktons/mo. at max. 2.2 m/min in 1993. Contrary to the high speed casting trend, Oita No.4 CCM directed toward a constant large section mold casting at a modest 1.48 m/min to reach 361 ktons/mo. productivity in 1985.

As mentioned, machine and operation for CC matured country wide during the latter half of 1980 and the early half of 1990 to attain over 80% for CCM availability, making the productivity of CCM compatible to BOF, and CC ratio reached 95%. In parallel, the installation of and conversion to VLB type CCM have increased up to 46% to meet the demand for high quality steels, and are still keeping increasing. To hedge the quality decline at the joints of heats in sequential casting, high speed CCMs have been moving toward single strand type when the productivity matches with BOF.

Single strand CCM is beneficial to save costs for machine, operation, maintenance and labor. Typical example is Fukuyama No.6 CCM built in 1993 to produce 180 ktons/mo. at 3 m/min. for which capacity and melt depth of tundish have been chosen to be 80 t and 1.2 m. Large tundish serves to enhance inclusion flotation and stabilize strand quality with constant speed casting at the joints of heats.

9.5. Temperature Control at Unsteady Part of Casting Including Joints of Heats

Even after secondary refining has become popular, melt temperature at the start, end and joints of heat tended to decrease below threshold value for quality certification. Lower temperatures are unfavorable for the inclusion separation and the hook formation. When the temperature is excessively low, hooks get thicker to form surface cracks. Extremely low temperature leads to the formation of crust at the melt meniscus. The crust sinks into the melt pool with adhered mold slag, sediment in strand to cause harmful large macro inclusions. When the temperature of the melt at the joints is set at the optimum value for CC, melt temperature keeps rising with the progress of casting, decreasing the volume fraction of sediment equiaxed crystal clusters at the pool bottom in strand, forming center segregation.

To prevent the temperature drop at the unsteady part, Hirohata industrialized first time in the world in 1987 a DC plasma arc heating of melt surface in large size tundish, followed by AC plasma arc heating by Kobe in 1990. For small size tundish, heating with channel type inductor was commercialized at Chiba and Muroran in 1986 and 1987. The heating systems for tundish melt got popular at many CCMs, contributing to normalize casting temperature and improve strand qualities.

Instead of heating the tundish melt during continuous continuous casting, hot recycling of tundish was considered better to retain heat and save tundish refractory. Here, at the end of casting, remained molten tundish slag is quickly dumped, tundish nozzle and SEN are exchanged on the fly, and renewed tundish is put into service as hot for a subsequent casting to considerably decrease the temperature drop and refractory consumption. Kobe Kakogawa developed this technology first in the world in 1989. After many improvements including automation of the exchange operation, it became possible to cast 500 heats in sequence at a short 25 min interval of the hot recycling. The success of hot recycling made it introduced to many 1–2 strand CCMs built in 1990s. Combined with the hot recycling, short period of preheating and non-oxidizing preheating have enabled starting the first heat casting with filled tundish after the tundish exchange, resulting in improved cleanliness and yield, reduction of refractory consumption by 90%, and considerable savings of labor and energy.

CC ratio in Japan kept increasing since to 99.5% for carbon steel slabs for plates and 98% for the same for strip in 1992. In 1998, the ratio for carbon steel slabs, blooms and billets reached 99.5%, and for specialty steel 91.2%. CC technology really attained maturity in 2010 when the ratios accomplished 99.9% for carbon steel, 96.4% for specialty steel, and 99.1% altogether.

9.6. Recent Progress in Casting High Quality Steels

9.6.1. Non Metallic Inclusions

To meet ever increasing demands for the qualities and cost of cast strand, improving cleanliness, center segregation, productivity, and premium yield of strand have been the central issues for CC in the last 20 years. For inclusions,
origin and measures to prevent and remove the macro inclusions arising from:
(1) Carried over slags from BOF, ladle, tundish, and mold,
(2) Alumina due to melt reoxidation by air and slag, and
(3) Agglomerates/clusters of fine deoxidation products, have been made largely clear across the melt path from BOF to cast strand.

Inclusion problems in specialty steel slabs and billets, often repeated ones like MgO·Al₂O₃ spinel inclusions in bearing steel and TiN–Al₂O₃ complex inclusions in tire cord steel, have also been diminished by similar measures, including the minimization of contamination with ladle glaze by means of proper ladle cycle management.

Inclusion problems are in some ways moving targets which vary as the quality requirements for final products made of cast semis become more stringent. For example, microstructure of TMCP-AcC steel and HSLA plate for large energy input welding is influenced by fine complex precipitates. Kinetics and thermodynamics for the formation of the complex precipitates made of micro alloying elements and S, O and N during the course of solidification and cooling may to some extent be estimated with Thermo Calc and FactSage in combination with melt flow and crystal growth simulation.

However, the database for the calculation in dilute concentration range is still insufficient and unreliable. To calculate the formation of fine CaMg (O, S) which serves as the nuclei for the crystallization of fine bainite to retain HAZ ductility in the large heat input welding, the database also lacks precision and reliability.

Separation behavior of fine inclusions associated with agglomeration and dispersion of composite inclusions in melt-bubble two phase flow field requires further investigation to unveil the detailed reality. In this regard, CFD tools and modeling have been made available. In fact, Miki et al. carried out an interesting simulation study on the engulfment of bubbles and inclusions in the early stage of growing strand shell as influenced by melt flow and applied magnetic field for FC-Mold operation in CC mold, showing good agreement with observation. Many body problem of the growth of multiple crystals/crystal bundles on solidification was dealt with by Steinbach in terms of multi phase field theory with strikingly good agreement with observations. Further progress in these issues is much expected.

BOF slag carried over from ladle into tundish has been traditionally a major source of harmful macro inclusions in tundish and mold. To prevent the carry over, attempts have been made for decades starting from a variety of throw-in type stoppers at BOF tap hole to a combination of AMEPA electromagnetic slag sensor and pneumatic gas jet blowing with butterfly stop valve or interstop CG120 at the tap hole. Some are shown effective, but not complete yet.

Clogging of SEN with alumina accretion has been another headache, since it triggers biased flow and turbulence at mold slag/melt meniscus boundary, deteriorating strand quality.

Countermeasures proposed were:
(1) Ar injection through inner bore of tundish nozzle and/or SEN to suppress aspiratory air permeation which forms alumina. The injection also reduces adhesion of alumina to the inner bore of SEN,
(2) Air tight coating of the outer surface of SEN to prevent the air permeation,
(3) Smoothing treatment of the inner bore surface of SEN to reduce alumina particle adhesion,
(4) Conversion of alumina to low melting point lime aluminates with Ca addition to steel melt,
(5) Apply lining of CaO base material to the inner surface of SEN to convert alumina to the lime aluminates,
(6) Control melt flow in SEN with various refractory structures to inhibit the adhesion of alumina particles.

Some of them were effective, but mixed view remained on the others regarding the effectiveness due to unfavorable side effect. For the time being, therefore, reducing alumina inclusions in the melt and exchanging SEN on the fly are the mainstay measures in addition to some of (1)–(6).

9.6.2. Center Segregation

Center segregation has been largely suppressed within acceptable margin by the combination of decently low temperature casting with electromagnetic stirring to increase equiaxed crystal fraction at the center thickness, followed by light to medium reduction in the vicinity of pool end in the strand shell. The above measures promote to disperse some of solute enriched melt into the boundaries of equiaxed crystals and others being pushed out into the pool. The reduction should be controlled to squeeze the aimed solid fraction area of the pool end uniformly all over the width. For that, secondary cooling should be controlled uniform widthwise to make the contour of the pool end flat without irregularity.

Degree and position of the reduction depend on the aimed solid fraction which is influenced by the chemistry, strand thickness, cast temperature, cast speed and secondary cooling, and the rigidities of roll pair and roll housing. Accordingly, the precision of the automatic control system should be upgraded to apply the reduction by dynamic calculation with these variables. Each CCM plant in Japan has operated long since with its own system, prior to Dynacs 3D/Dynamic Gap-Soft Reduction by Siemens-VAI.

In view of more stringent user demands to decrease the size and number of center segregation spots, however, the upgrading of the measures would be necessary soon. The above reduction in the roll gap at roll contact has its own limitation. Replacing the roll reduction by anvil reduction worked more effectively. In fact, area fraction of the segregation spots with Mn > 1.5% and P > 0.04% in CC slabs for plate containing 0.06–0.10%C, 1.0–1.1%Mn, 0.004–0.008%P decreased to 0.03% by use of an anvil type reduction. Like inclusion case, requirement for the critical size and number of center segregation spots is a moving target. As time goes by, more effective measures integrating the cooperation among EMS for mold and strand, strand bulging management with better control of secondary cooling and roll gaps, and advanced reduction system need to be developed.

9.6.3. Surface Defects

For most of strand surface defects, origin and preventive measures have been made clear and executed. In the high speed CC, appearance of surface defects have decreased considerably with:
(1) Relatively high basic mold slag which is immune to engulfment and gives modest cooling of strand in mold,
(2) Non sinusoidal short stroke high cycle mold oscillation which decreases the friction between mold and strand and makes oscillation grooves on the strand shallower, 
(3) Melt flow control in mold with SEN and EMS, and 
(4) Advanced secondary cooling pattern control with improved mist spray nozzles.

For some grades of steel, such as hypo-peritectic plate steel or HSLA plate steel for high input energy welding, high speed CC was inhibited due to improper primary cooling of strand in the mold or precipitation embrittlement of strand in the secondary cooling zone. For improving the primary cooling, crystallization of cuspidine or mellilite phase in the mold slag film is enhanced for modest cooling of the shell in the mold. For improving the secondary cooling, corresponding to the bending and unbending of the strand, rapid cooling followed by auto-reheating by sensible heat is imposed on the strand to promote \( \gamma \rightarrow \alpha \rightarrow \gamma \) transformation and reverse transformation for surface grain refining to promote the bridging of dendrites and associated solute enrichment near the central axis, causing heavy segregates and porosities there. For medium- to high-C steels, a combination of electromagnetic stirring in mold and mold EMS to decrease inclusions in the strands as mentioned in detail elsewhere. 

10. Steelmaking System

10.1. System Conellation

In view of the preceding developments of unit processes and possible future raw materials supply, high productivity steelmaking system may be different from current one which retains cost competitiveness and meets demands for high quality steels like IF, HSLA, line pipe and AHSS. The system would consist of the followings:

Low Si hot metal production in BF\( \rightarrow \)deSi\( \rightarrow \)KR deS\( \rightarrow \)Hot metal deP in mixed blowing BOF\( \rightarrow \)deC in mixed blowing BOF\( \rightarrow \)deS, deO in LF (if necessary)\( \rightarrow \)deH, deN, deC, deS, deO in advanced RH\( \rightarrow \)CC in VLB high speed CCM.

A 4 million tons/year plant may consists of \([5,000 \text{ m}^3 \text{BF}] + [300 \text{ ton} \times 1 \text{ mixed blowing BOF} \text{ for deP}] + [1/2 \text{ in operation of } 300 \text{ ton} \times 2 \text{ mixed blowing BOFs for deC}] + [\text{RH-powder injection}] + [2 \text{ strand slab CCM} \times 1 \text{ for strip}]\). The productivity of the plant is consistent to 1 tandem hot strip mill. Also, 1 strand slab CCM is already compatible with 1 plate rolling mill in productivity. Accordingly, 8 million tons/year plant may consist of \([5,000 \text{ m}^3 \text{BF}] + [2 \text{ for deP}] + [300 \text{ ton} \times 2 \text{ mixed blowing BOF} \times 2 \text{ for deP}] + [2/3 \text{ in operation of } 300 \text{ ton} \times 3 \text{ mixed blowing BOF} \times 3 \text{ for deC}] + [\text{LF & RH-powder injection}] + [2 \text{ strand slab CCM} \times 2 \text{ for strip}] + [1 \text{ strand slab CCM} \times 1 \text{ for plate}]\) for flexible production, assuming accidental temporary shut down of a CCM. Here, the slab CCM for plate can be changed to multi-strand bloom CCM for rods depending on the product mix of the plant. The plant, compared with traditional plant with traditional CCMS, eliminates 2 CCMS for saving full cost. The productivity of mixed blowing BOF for deC is in harmony with preceding BOF for deP and succeeding secondary refining. For conventional grades, CAS or light processing in RH suffices instead of the above mentioned LF + RH. In this way, freedom is achieved in designing a combination of mixed blowing BOFs and CCMs to meet the product mix of a plant without constraints on the productivity of CCM.

Improvements and optimization have progressed on all part of the equipment and operation and on the total system, resulting in such a cumulatively high productivity.

Minimizing the materials flow paths among the unit processes, selecting simplest possible pieces of equipment to construct the above system to reduce the investment, decreasing labor by automation combined with robotics, aiming at minimized full cost of production seem to be the way to proceed. Such advanced mature system should have sufficient competitiveness in the world market in terms of productivity, cost and quality for some years to go.

10.2. Progresses of Interest in Unit Production Processes

Although not comprehensive, interesting examples (some touched on earlier) will be cited here of industrialized technologies related to high quality steel production:

(1) Injection of lime powder from top \( \text{O}_2 \) lance into \( \text{N}_2 \) bottom stirred BOF for deP with precharging in the BOF of
recollected lime aluminates waste slag from LF:43 Early formation of slag rich in CaO–FeO at hot metal temperature is made possible to promote deP, and dumped slag after deP has little free CaO, and hence does not require long curing time for road application,

(2) Injection of lime powder or iron oxide powder through top lance onto the melt bath surface in RH vessel to make steel ultra low in S or C:39 Steels with C, S < 5 ppm have been produced with 180 ton RH,

(3) Stainless steel production with the smelting reduction of preheated chromite ore powder injected into mixed blowing BOF:29 Loss of reductant carbon particles is reduced and dispersion in slag of the particles is enhanced on addition to the BOF. Also, heat loss due to smelting reduction of the chromite is compensated for by the addition of the ore carried into the BOF with combustion gas stream to industrially produce stainless steels,

(4) H-shape tundish with Ar injection.60 Fine Ar bubbles of ~1 mm diameter are injected into steel flow passing the through hole which connects ladle melt receptor compartment and melt exit compartment of the tundish to promote inclusion flotation. The long melt path from inlet to outlet of the tundish and full volume processing of the melt flow with the Ar bubbling are effective for inclusion removal,

(5) Reduction of SEN clogging with DC 50–100 A passed from the melt in tundish (+) to alumina graphite SEN (−):72 This method is confirmed effective in commercial operation at Kashima and Kokura CCM. Reduced wetting of SEN inner bore by the melt and reduced oxidation of AI in the melt by CO at SEN/melt boundary are considered effective against the accretion formation. Could the last several decades of headache be resolved?

(6) F-free mold flux is made available which stands against engulfment into the melt and provides the strand with decent lubrication and homogeneously decreased heat extraction for high speed slab casting:73 Also, relatively high viscous mold slag is developed with bascity around 1.2 and high slag/melt interfacial tension, chemical composition being in the range to have mellilite crystals precipitated on cooling. The mold flux is used to commercially cast 225–360 mm diameter round bloom for seamless pipe at 0.8–2.2 m/min.

(7) Decrease of porosity and center segregation by dynamic 2D reduction at near pool end of strands,

(8) Industrialization of medium thick slab CCM named QSP by Sumitomo and stainless steel strip casting with twin roll CCM at Hikari in 1997 (casting terminated in 2003):39 The two were sizeable achievements in new technologies. In Japan, investment in advanced CCMs has been done, with some surplus, to cast high quality steels with highly productive CCMs which have been continually upgraded. Under such circumstances, question is that would these new casters become competitive in quality and cost against the upgraded ones? or would innovative variants arise out of them (some comments follow later on this aspect)?

11. Ending Remark-Future of Technological Innovation in Japanese Steel Industry-

Steel industry in Japan started one century ago with materials, equipment, technology and operation all imported from abroad. Origin of core technologies for steelmaking was mostly from Europe and USA. Steelmaking related knowledge and science were of no exception. As traced back the history of steelmaking in the overview, however, the enthusiasm, endeavor and accomplishment of our predecessors in industry, academia and government are really praiseworthy once again who improved the core technologies, overcame the difficult times of messy crush after world wars, making the steel industry a world class system within about 60 years. We see the trajectory of capable people who competitively cooperated with each other with determination for the improvement and development.

Steel industry is a huge equipment based industry. After the commissioning, construction and start up of its operation in Japan, even though there seemed not many developments of innovative nature, there have been lasting progresses days after nights in the industry. We should be proud of the fact that the accumulation of such progresses has brought the current productivity and quality of steel industry up roughly about 100 times of the past. Also, the development in energy utilization and environment protection of the industry has been outstanding and leading the world. The development will be detailed in the following review papers in this journal and hence not touched on here. The accumulation of these comprehensive improvements and developments as the whole sum may be taken revolutionary.

As years go by, current steelmaking equipment, system and operation have come to maturity. On the other hand, some of the equipment and systems are not on the leading edge, calling for refurbishment with most modern ones at heavy investment. We remember clearly that whenever we had major refurbishments during the rise of the industry, many associated developments happened. Enthusiastic discussions held cooperatively between the engineers of steel industry and machine builder industry to determine the specifications, install and start up the equipment brought forth unexpected new ideas to further develop the equipment and systems. Major refurbishment becomes limited in recent years in steel industry. Domestic machine builder companies also decrease their potential either going out of the business or being dominated by European counterparts. Motivation to the developments and improvements in the mature period has come externally from the demands of the market on quality and cost and internally from the demands on productivity and cost. Despite such drawbacks, making dedicated team work with the motivation has traditionally been a talent of those of us involved in steel production. The concerted team work is still effective to bear steadfast results.

In steel industry, lead time from invention to industrialization usually takes long time. For that reason, it is now the time to develop new core production technologies to secure high ROE to overcome more expensive raw materials, labor and tax relative to our competitors, not only in high quality steel sector but also in commodity steel sector.

In this connection, representative technologies already emerged and industrialized quite a while in steelmaking and casting area include Thin Slab Caster (TSC), and Twin Roll Strip Caster (TRSC). The author communicated personally with the leaders of the development projects for TSC, Compact Strip Production (CSP), Inline Strip Production (ISP), and TRSC for nearly 30 years, and had pleasure to witness
They do not seem profitable yet to replace existing CCMs in Japan where investments have been heavily done to retain the capability of highly productive modern upgraded CCMs. However, in the world there are sites where scrap and electricity are sufficiently available to meet regional market but investment in traditional CCM is limited. Quality of strand cast with TSC and TRSC have also been reasonably improved due to recent developments.

TSC was industrialized at Nucor in 1984. Equipment and operation were improved considerably year after year to produce some 100 million tons/year with about 80TSCs in the world. TSCs have implemented advanced mechatronics and technologies improved in traditional CCM, strengthened its competitiveness, and are catching up with the productivity and quality of contemporary advanced CCMs. Among the TSCs, CSP and ISP have developed into their 4th generation. ISP was upgraded to be fully continuous Endless Strip Production (ESP) with the direct connection of casting and hot rolling. CSP by SMS-Siemag also turned out to be CSP-flex with modular design and has freedom to choose either VSB or VLB. The caster is directly connected to rougher, tunnel furnace and 5 stand hot rolling mill to roll low C and IF grade thin strip full continuously. For AHSS steels (APIX-70, Dual/complex phase, TRIP steel) that require TMCP, the thin slabs go through rougher and tunnel furnace and finished by 7 stand compact hot strip mill.

ESSAR steel built a 3 strand VLB TSC plant in 2011. Out of 5 million tons/year steel melted in 200 ton CONARC EAF × 2 and finished in LF × 2, 3.5 million tons/year have been cast into 55–80 mm thick, 950–1680 mm wide 3 slab strands. Central strand is connected to a roller hearth furnace and a 7 stand tandem hot strip mill inline. Other 2 strands are also transferred to the central roller hearth furnace for the inline rolling. The plant produces C steel, pipe steel, NGO Si steel and dual phase steel with full turn key, plug-in automatic control system.

Danielli-Davy and POSCO cooperated to build and operate TSC in 2009. The TSC casts VLB strand of 80 mm thickness × 1300 mm max. width at 6–8 m/min up to 1.8 million tons/year. Steel melt from two 130 ton ladles is poured into 60 ton T-shape tundish (simultaneous pouring possible). The caster is fully loaded with: dummy bar top charging, roll segment exchanged by manipulator, DC brake type EMS mounted on mold which oscillates at 500 cycle/min, funnel type SEN with 4 exit holes which deliver 7 t/min of the melt into mold, feed forward control of the melt supply which reduces meniscus level fluctuation caused by bulky bulging to be less than ±2 mm, and pool end light reduction. Products cover low C (0.02–0.04%), medium C (0.17–0.19%), high C (0.23–0.55%) and C-Nb type HSLA steel. Danielli-Davy also expects to start similar TSC mounted on mold which oscillates at 500 cycle/min, direct connected to hot strip mill to seamlessly/endlessly roll the strands. TSCs are also capable of performing TMCP and HCR of AHSS. In fact, a wide variety of AHSS has been in the product range of TSCs. Investment for TSC + hot strip mill appears lower than that for conventional counterpart.

Questions arise at this point if TSC + endless rolling hot strip mill would replace or remain supplementary to some of aged CCM + hot strip mill (HSM) in existing integrated steel plants. Or, if the former combination is limited to EAF plant, could hot strip produced in such plant strengthen the competitiveness in full production cost and quality against the upgraded conventional CCM + HSM combination in world market?

Regarding TRSC, IHI and Bluescope jointly developed and succeeded to cast 40 ton EAF carbon steel melt at Port Kembla in 1999. The process was transferred to Nucor for commercialization at Castrip in Crawfordsville, Indiana in 2002. At Castrip, steel melt is poured into the containment of 500 mm dia. twin rolls with side dams, pulled out of roll kiss as 1.5–1.8 mm thick strip under protective atmosphere in catenary profile. The strip is finish rolled with a 4 high hot rolling mill. Choice of the 500 mm diameter for the twin roll is said important. The casting-rolling operation has been made successful, producing 0.5 million tons/year of strip in the range of structural C steel, hot dip galvanized variant, HSLA 50–80 and 440 MPa high tensile strength steel. Another 0.6 million tons/year plant was built and is in successful operation at Blythevilles, Arkansas. Two advantages were reported:

(1) Hot rolling is not necessary in the temperature range where hot shortness appears due to Cu originated from scrap, and hence the strip does not suffer from cracks of Cu origin, and
(2) Si–Mn deoxidation is practiced to form fine manganese silicate inclusions. The inclusions provide the steel matrix with nuclei for bainitic transformation, resulting in high tensile strength steels.

For stainless steel, Nippon Steel rendered technical assistance to POSCO to build TRSC which seems operational to cast SUS somewhere in the order of 10 ktons/mo.

Investment to annually produce 1.5 million tons hot strip with 3 TRSCs or conventional CCM + hot strip mill is considered roughly 2 bil.JPY or 10 bil.JPY. 10 year flat depreciation per ton steel gives about 1 k JPY for TRSC and 6 k JPY for CCM + strip mill. Difference in the running cost between the two processes is uncertain particularly the twin roll cost for TRSC. However, the difference in the depreciation of 5 kJPY/ton is more or less overwhelming for carbon steel strip production. For 4 million tons/year plant, on the other hand, five TRSCs are required even when the productivity of a TRSC is increased by 20%. In this case, a crude estimate indicated that the depreciation cost is not much different between the TRSC process and renewal of the present CCM + hot strip mill process.

In the future, what about the increments of productivity of TRSC, how much could be the decrements of the running cost for TRSC, particularly roll cost, and how many grades could be produced with TRSC, all remain yet uncertain. In view of typical growth from those with conventional CCMs.

Thus, TSCs have been advanced, capable of casting 3–4 million tons/year for 2 strands at 7 m/min, directly connected to hot strip mill to seamlessly/endlessly roll the strands. TSCs are also capable of performing TMCP and HCR of AHSS. In fact, a wide variety of AHSS has been in the product range of TSCs. Investment for TSC + hot strip mill appears lower than that for conventional counterpart.
curve for innovative technologies, however, attention is necessary to the advance of TRSC.

Extra thick plate and pipe have been produced from extra thick CC slab cast with modularized CCM equipped with Dynas3D and DynaGap package at Vöest Alpine (355 mm thick mold) in 2007, and Dillinger (450 mm thick mold) Capital Steel (400 mm thick mold) both in 2010. An example at Capital Steel is VLB CCM with light reduction near the pool end, casting speed 1.1 m/min, casting 1.1 million tons/year of 400 mm $\times$ 2700 mm slabs.

A comment to be made on the future development of steel industry in Japan is the importance of personnel involved. Taking for an example the TSC and TRSC, the author is impressed by the lasting enthusiasm of those engineers who dedicated well over some 20 years of their professional life to the industrialization of the processes while keeping their eyes open on the possible market. Motivated capable people were the key to the success. Of course, people may not be well motivated and capable in the beginning. They should be motivated continually on occasions, in particular at hard times, and become more capable through challenges and lasting efforts.

In the steel technology area, the author noticed steep increase in the number of technical papers published by Chinese or Korean as the first author in representative international journals relevant to steel. During 2012 and 2013, the number was quite high about 30% in both ISIJ Int. and national journals relevant to steel. During 2012 and 2013, the number of technical papers published by Chinese or Korean authors as the first author in representative international journals relevant to steel was quite high, about 30% in both ISIJ Int. and national journals relevant to steel.

China and Korea kept increasing annual crude steel production to about 700 million tons and 70 million tons. During the expansion period, they imported numbers of modern pieces of equipment from Europe and USA. The equipment producers have updated technical information collected from customer steel industry all over the world for years to improve their hardware and operational software. The information has been made available from the producers to the customers with supplied equipment at a reasonable price, sometimes with detailed on site operational training upon request. The price for the information and training seems to have been far less costly than those acquired individually by own R & D efforts of Japanese steel industry.

For example, dynamic oxygen blow program for BOF end point control has long been sold commercially as a common software package with oxygen sublance system to monitor C and T. Soft reduction program for decreasing center segregation in CC strand has been sold to dynamically determine the amount and location of roll reduction and is built in a modular package equipment (ex. aforementioned Smart Segments with Dyna Gap Soft Reduction with Dynas 3D by Siemens-VAI etc.) Dyna Phase automatically controls the reduction and cooling at L2 level when chemical composition and expected mechanical properties of the strand are put in.

How steel industry in Japan should keep up its own advantages and deal with the challenge by competitors abroad in cost, quality and productivity? As mentioned already, steel industry in Japan is lower in the profitability, particularly ROE, and tax is higher with small room for reduction. Labor cost has been disadvantageous, cost of major materials and energy are not favorable either. Thus, we should stem not only on the improvement of technology but also on innovative technology as it has been the case for LD and CCM.

Technological standard of current system for iron making and steelmaking as well as product quality of Japanese steel industry are still at the leading edge in the world. On the occasion of continued investment for the refurbishment, everlasting technological improvements and new developments have been implemented, making the refurbishment as most modern challenge. For steel related technology in academia and industry, important R & D programs have been pushed forward in cooperation with the two parties along with long term perspectives. To make such endeavors not limited to the success only in reports, but let them traverse the “Sea of Darwin” in combination with advanced technological frontiers on equipment, instrumentation and automation, and industrialize them as innovative processes for actual steel production.

Wishing that the centennial celebration provides Japanese steel industry with a milestone to further enhance the technological superiority and cross major turning point for innovative developments.

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REFERENCES

7) Tetsu-to-Hagane, 50 (1964), No. 9.