Abstract: The Japanese steel industry started to progress in the 1950s and reached maximum production in the 1970s. In the 1980s it changed its policy of pursuing quantity in production to pursuing quality. A slight decrease in production levels at the beginning of 2000 followed, but the industry has recently recovered production quantity while maintaining quality. In the process it has developed and accumulated a variety of innovative technologies, called “Japan original technologies” which were exported around the world. These are highly advanced control technologies, including sensors, controllers and control logics, and other electrical and automated equipment. This paper introduces some of the technologies developed by the Japanese steel industry that ushered in a new era in steel making worldwide.

Key Words: steel industry, control technologies, Japan original technologies, electronics, technology export.

1. Introduction

As shown in Fig.1, in the 1970s the Japanese steel industry marked the highest level of production in the world in terms of quantity and quality after its initial high-growth period. However, the Oil Shock and industry advances in other countries forced the Japanese industry to shift its priority from quantity to quality and to enter global price competition [1]. This meant that production had to become more efficient. Thanks to active demand from China and other emerging countries, recent rationalization efforts including large-scale mergers in the Japanese steel industry have led to the current favorable business climate.

Fig. 1 Chronological review of the world steel industry.

While most equipment and operational technologies in use at the beginning of the high-growth period were imported from Western countries, by the 1960s, many of these technologies were being developed and supplied domestically and came to be recognized for their high level of sophistication as “Japan original technologies”. By the 1970s Japan was exporting these ‘original’ technologies to the West, and to China and Korea whose steel industries were newly established by national policy. Japan’s shift of emphasis from quantity to quality had enabled the industry to achieve a high level of quality and efficiency in technological development as shown in Fig.2 (a). Advances in this period included a 20 percent reduction in energy consumption, a 10 percent rise in average yields, and a startling 50 percent rise labor productivity [1],[2], adding further competitive strength to technology exports. As shown in Fig.2 (b), during this era of qualitative change, instrumentation and control technologies were also significantly upgraded, helping the Japanese steel industry to accumulate highly advanced operational techniques and facilities. Examples of these innovations are shown in Fig. 3.

Process visualization in particular, and continuous automation of processes and facilities were targeted for technological development. As a major user of industrial plant and equip-
The steel industry has played a leading role in development of facilities in collaboration with heavy equipment manufacturers, and/or with EIC (Electric, Instrumentation and Computer) manufacturers.

Figure 4 shows trends in technology trade in the steel industry. Although the total amount of trade in technology has not been particularly large, exports have continuously exceeded imports in a range of 2 to 8 times ensuring optimum balance in income relative to expenditure [3].

2. The Iron-making process

This is the entry process at an integrated coastal steelworks in which coke plants convert coal to coke and blast furnaces reduce iron ore to molten pig iron.

2.1 Visualization of the blast furnace and the Go Stop System [4]

Figure 6 provides an outline of the blast furnace process. Blast furnaces were frequently the source of a serious operational problem called “hearth chilling,” which caused furnace production to decline to less than 10 percent, derailing the entire production plan of the steelworks. Visualization of the blast furnace operational process enabled the industry to evolve out of this situation. Prime examples of the introduction of visualization were in the areas of “thermal condition” and “top gas distribution.”

Thermal Condition is the amount of thermal leeway inside the blast furnace and is calculated as an index, usually based on the combination of a static physical model and the operator’s judgement based on experimentation. Top Gas Distribution measures the distribution of gas flow inside the furnace at the top and is controlled by the thickness in distribution of alternately inserted coke and iron ore in the radial direction of the furnace. When coke occupies more space in the furnace center and ore takes up more space on the furnace wall, gas distribution increases at the furnace centre due to the difference in permeability between the two substances. This result is called “excess central flow operation”. When it is the other way round, relatively more gas is distributed on the wall causing an “excess peripheral flow operation”.

Figure 5 is an outline of the manufacturing process at the main facilities of an integrated coastal steelworks. It is a large-scale operation producing 4 million to 10 million tonnes annually in a variety of process facilities on a site measuring 5 million or up to 10 million square meters. I will present three of the key processes based on “Japan original technologies” that advanced domestic production and were frequently exported overseas.

Figure 7 (a) and (b) illustrate how these two occurrences can
be expressed through a linear equation of multiple measurements [4]. Both are a grouping of three representative operational conditions respectively, using discriminate function logics.

The Go Stop System (developed by Kawasaki Steel Corporation: illustrated in Fig. 7 (c)) provided a simple, comprehensive index derived from a linear equation of multiple measurements with a hierarchical structure. It was a kind of standardization based on the operator’s daily observation methods.

Initially, this system was aimed at being a tentative operational guide because the blast furnace process had been too complex to establish practical and reliable control models. Other major Japanese steel manufacturers also developed a similar system [4]. In overseas steel industries where workers from foreign countries predominated, this system was much appreciated for its quality in standardizing operations and was exported to five countries including Germany and France. Figure 7 (d) illustrates the operational guidance display in both the original and overseas versions. In Japan, this system was developed to even higher levels of sophistication as the Expert System, the Fussy System, and others [5].

2.2 Development of the $\mu$-wave level meter [6],[7]

Figure 8 shows the profile meter measuring burden profiles (ore/coke distribution in the radial direction), which control the gas flow distribution in the blast furnace [6]. The structure, illustrated in Fig. 8 (a), is composed of a hydraulically-operated probe, equipped with a built-in antenna with a $\mu$-wave circuit at the tip, and a signal processor. Although initially, mechanical, laser and $\mu$-wave types were developed almost simultaneously [6], only the $\mu$-wave type survived and remains in regular use thanks to its high reliability against high temperatures and dust and its ease of maintenance.

As an example, Fig. 8 (b) shows a very important operational situation where raw material measuring 1.5 m (approximately 600 t) abruptly dropped down inside the furnace (Kawasaki Steel Corporation, Chiba Works No. 6BF). Not only is this a very valuable operational record, it shows the superior capability of the $\mu$-wave over the others to observe this type of incident.

Initially, the $\mu$-wave type level meter was developed in Germany as a BF burden sounding meter, but its insufficient handling of interference phenomena on the raw material surface negatively affected its market dissemination. In the 1970’s in Japan, the meter was substantially improved as a result of cooperation between the steel maker and the electronic manufacturer [7]. And, this type came to be widely used for measuring under severe conditions, its versatility extended even to the measurement of the hot coke level in a CDQ (Coke Dry Quench) and the hot metal level in a torpedo car. Figure 9 shows an example of a hot metal level meter, which not only enabled automation of a bad labor situation, but also improved transport efficiency, preventing cooling during material transport and increasing reaction efficiency in pig iron pre-treatment processes [2].

Figure 10 shows users of these systems, which include not only Japanese steelworks but also companies in other countries that were frequent recipients of Japanese technology exports. Recently the $\mu$-wave level meter has been improved in terms
of noise suppression and resolution by introducing M-sequence (pseudo-random signal) modulation [8]. This has been applied recently to a steel-making process, and to detection and control of the steel sheet edge position in a CAL (Continuous Annealing Line) furnace, and the use of \( \mu \text{-wave} \) is still expanding.

3. The Steel-making process

3.1 Development of sub-lance [9] and end point control at BOF (Basic Oxygen Furnace) [10]

The BOF operates on a process where pure oxygen is injected into pig iron from the blast furnace to convert the pig iron into molten steel with a designated amount of carbon.

(1) Measurement of the molten steel temperature

The temperature of the molten steel is more than 1600°C at the smelting end period and measuring this temperature precisely had been a major problem of quality control in the steel-making process. An expandable thermocouple was one invention aimed at solving this problem. Despite its initial development in the United States, a joint study of industry and academia in Japan provided standardization of the technique including a calibration method of the thermocouple. In about 1950, the system established measurement accuracy of approximately \( \pm 3°C \) and thereafter became the standard method of measuring high temperature molten material.

(2) Simultaneous measurement of the molten steel temperature and its components by means of Sub-lance [9]

The sub-lance facility, shown in Fig. 11, has been developed to measure the temperature and the amount of carbon for final quality control of the molten steel without stopping operation of the BOF. With a sensor (probe), shown in Fig. 11 (b), it uses expandable thermocouples to measure simultaneously the molten steel temperature and the solidification temperature of molten steel led into the solidification chamber. The solidification temperature is translated into carbon content using the Fe-C phase diagram. Sub-lance probes are kept in stock in the probe warehouse as shown in Fig. 11 (a), and they are automatically conveyed, attached to the lance, inserted into the molten steel, and removed from the lance. There was competition among many steel factories to put this technique to practical use, and it was finally established as a process facility in Japan in 1975 [9]. Moreover, by introducing these measurement results into smelting models for process control, the simultaneous end point hit rate of temperature and carbon content was raised from 45 to above 90%, bringing about radical change in BOF operation and product quality [10]. This technology was exported overseas as part of a scheme to assist the converter operation.

3.2 Molten metal level control at CC (Continuous Caster) [11]

Molten steel is continuously cast into slabs or blooms of the required form in the continuous casting machine. Figure 12 (a) shows the molding part of the caster equipment. The level of molten steel in the mold must always be as stable as possible in order to avoid inclusion generation and to keep the op-
eration stable. In earlier times, the molten steel level was observed manually, and then a γ-ray level meter was introduced. However, even with a γ-ray level meter, accurate measurements were often disturbed by mould powder feeding and the performance of the control system was limited by the filter for noise reduction.

Figure 12 (b) shows the eddy current level meter (developed by NKK) [11] which generates eddy current at the surface of molten steel and detects signals by the receiving coil to measure the distances between the coil end and the surface. By improving the circuit, the range of measurement was substantially widened, and improvements to the sensor structure and the sensor itself made it more compact and more robust against heat.

Figure 12 (c) compares control performance in two cases where the γ-ray level meter and the eddy current level meter were used respectively. The results showed that the improved response doubled the precision in level control from ±10 to ±5 mm. Moreover, adoption of the eddy current level control system improved the process tremendously including higher quality in cast pieces, automatic operation and reduction of operational troubles such as breakout.

Among sensor systems developed by steelworks, this system technology has been exported the most to other companies, both domestically and internationally, with actual export figures as high as 500 units domestically, and 450 overseas.

To address the system’s level control problem related to disturbances caused by clog and detachment of oxidized deposits at the nozzle area, control has been improved recently with the introduction of “H∞” control logics, for instance.[12],[13].

4. The Rolling process

During the period of transition from “quantity to quality”, the requirements for higher product quality from users such as automakers, shipbuilders and can manufacturers led steel makers to collaborate with equipment makers to develop advanced technologies. The following paragraph describes the respective rolling technologies and their applications.

4.1 Hydraulic AGC system

Slabs or blooms produced in the steel making process are rolled into various products in the rolling mill process. Up to the 1960’s, most of the rolling machines had been using electric motors for screw-down. However, due to inertia in the driving system of the electric screw-down machine, temperature deviations (skid mark) and/or other changes such as roll eccentricity could not be sufficiently controlled. To minimize the influences arising from these irregularities, one could only increase the mill modulus of the rolling machine.

In the 1960’s, an improvement in screw-down response was proposed by an engineer at a rolling machine manufacturer based on a hint he got from the operation at work [14]. Figure 13 shows a typical hydraulic AGC (Automatic Gage Control) system [15] developed by a Japanese manufacturer based on the improvement. Hydraulic equipment was installed in the rolling mill, which enabled fast and flexible screw-down manipulation, resulting in a response that is four to five times faster than the electric screw-down process.

Figure 13 (a) shows an example of the hydraulic Automatic Gauge Control (AGC) system. Here the roll position signal is used as a minor feedback signal, which substantially improved the stability and response of the system. One of the key tech-
ologies in the hydraulic AGC system is the roll position sensor with positional precision of 1/10μm and a high level response of approximately 1 m/sec. The position sensor is usually placed in the hydraulic equipment within the rolling machine in order to guarantee its highly accurate measurement performance. Therefore, durability and maintenance were major problems due to the harsh environment of rolling vibration, scale, and the vast amounts of water in the process. Figure 13 (b) shows a digital position sensor, called the “Magnescale,” produced by a Japanese maker [18]. Compared to the position detection results obtained by the former rolling screw, the “Magnescale” drastically improved measuring precision through direct measurement of the rolling position, which eliminated any backlash in the screw-down gear system.

The hydraulic AGC was applied to cold roll mills at the beginning. However, from the 1970’s it began to be applied to other processes as well, such as plate mills [16] and hot roll mills [17]. As a result of the quicker response system, the average yield in steel production markedly improved. At the moment, the system is applied at every rolling facility in the leading, domestic steel companies, and it frequently has been provided to foreign steel mills as well. The results are excellent, with a 900% increase in rolling speed, and an improvement exceeding 40% in accuracy of the thickness in the plate mill process [16].

4.2 Change of DC to AC motor of rolling mill through progress in power electronics

Rolling mill facilities were operated by DC motors for accurate speed regulation. However, it was urged that they be replaced with AC motors due to the following problems:

1. The DC motor needs an armature and brushes, and maintenance of these requires a great deal of time and skill.
2. The electric motor itself tends to be larger in size, requiring a large space for installation and more handling time.
3. The DC motor’s large inertia restricts the speed control response.
4. The DC motor tends to consume more electricity due to its inefficiency and the factor of deterioration of power.
5. The life of a DC motor is considered to be about 30 years, and therefore, the motor must be replaced in order to avoid difficulties in maintenance.

The replacement of DC motors with AC motors in the steel industry started first in Japan, where policy of the steel industry shifted from quantity to quality. Suppliers of electric devices for rolling mills were also developing power electronics for other purposes, such as the electric motors for bullet trains (Shinkansen), so, this initiative started very early in the world. It was a perfect case of needs matching seeds.

At the beginning of the change, there were some problems including the generation of harmonic noise and the increase in drop impact when rolls bit the strip. But most of these were resolved by close cooperation between engineers at the steelmakers and electronics manufacturers. The introduction of AC motors drastically improved thickness control, maintainability and power efficiency. It was reported that thickness control (AGC) accuracy was improved by 50 to 80% [20] and that power consumption dropped by 23% (Δ1,722 MWh/year) [22]. Across-the-board application of AC motors in the rolling mill is in process around the world, and in Japan, more than 50% of hot rolling facilities have already completed this transition.

4.3 Shape control technologies in rolling metal strip

Following the hydraulic AGC system, shape control emerged as a very important technology that brought about drastic change in rolling mill facilities. As shown in Fig. 15, the quality of the strip profile is an important factor in control in both hot and cold rolling mills [23]. The major cause of poor quality was roll deflection as a result of the roll barrel being much longer than the width of steel sheet, as shown in the figure.

This problem used to be dealt with by adjusting the shape of the work rolls (adding reverse crown at roll grinding), but this was not practical because the work rolls had to be replaced one after the other every time the strip width changed. It was proposed that the bending force of the work rolls be adjusted, but this offered only limited shape control. Therefore, the advanced shape control mills shown in Fig. 16 were proposed by rolling mill makers and developed in collaboration with steel manufacturers.

Figure 14 shows the main technical progress in the field of power electronics [19]–[21]. Recent developments, including the cycloconverter, GTO (Gate Turn Off Thyristor) or IGBT (Insulated Gate Bipolar Transistor), and development of vector drives and pulse-width modulation control using micro-processors, have made it possible to freely control the AC frequency. Around 1980, these technologies began to be applied to processing lines such as the Continuous Annealing Line, using AC motors with cycloconverters. With the arrival of GTO in the late 80’s, AC motors began to be used in cold rolling mills as well and in all types of rolling mills thereafter. Recently, due to the decline in DC motor manufacturing (no new production since 2000) and the falling number of maintenance technicians, most newly built or refurbished rolling mills are equipped with AC motors.

<table>
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<tr>
<th>Process line</th>
<th>Rolling mill</th>
<th>Re-marks</th>
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<tbody>
<tr>
<td>Full digitalize</td>
<td><em>1</em></td>
<td><em>1</em></td>
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<td>Logic insertion</td>
<td>Vector control</td>
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Fig. 14 Progress in power electronics fields [19]–[21].
as little as possible when they are used as sheet lamination. This was a 6-high roll mill system with an intermediate roll that could be shifted so that it was perpendicular to the rolling direction, and this reinforced the work roll bending function at the same time [24].

1° is an advanced version, called a Universal Crown (UC) control mill, which has an added vending function to the intermediate roll as well as a shifting function and work rolls with one tapered end [24].

2° is a Pair Cross (PC) mill proposed by Mitsubishi Heavy Industry (MHI) and developed 8 years later [24]. It was conceived as a way to refurbish existing rolling mills more easily by crossing both work and backup rolls by 1 to 1.5 degrees, while the 4-high rolling mill system itself remained [25].

In addition to the above, many more rolling systems were developed [26]; such as a variable crown roll mill that could change the roll shape itself using hydraulic pressure. Most of these are more complicated versions of the 4-high rolling mill system and based on earlier development of the hydraulic system described above.

All of these technologies were first developed for practical use in Japan, where the strip shape quality requirements of steel users were extremely strict. The technologies were then exported to Western and Asian countries. For example, approximately 400 units of the HC mill shown in 1° have been produced for a variety of rolling mill machines (lately for cold rolling) and 100 units of the PC mill shown in 2° have been made for hot rolling [24],[25].

4.4 Enhanced accuracy of rolling gauge control via “In situ” sensor

Since the harsh environment of steel manufacturing prevented the installation of sensors in close proximity to the rolling mills, sensors would be remote to the specific location. Therefore, the large distance between the sensors and the actuators restricted the response of the control systems. The first solution to this problem was the proximate γ-ray thickness gauge, shown in Fig. 17, which could be installed in close proximity to the mill (approximately 2 m) instead of the usual 10 m distance or more, by reinforcing the sensor parts against shock, heat and water [27],[28]. Shortening of the system’s delay time achieved a 25% increase in thickness accuracy. The proximate γ-ray thickness gauge was the first attempt to introduce an “In situ” sensor into the mill gauge control system.

Figure 18 shows the No 3 hot strip mill at the Chiba works of Kawasaki Steel, which is currently the latest hot rolling mill in Japan [29],[30]. The space between the mill stands was so narrow (approximately 5.5 m) in such a severe environment that they had to avoid installing sensors there. However, in the case of the No 3 hot strip mill, inter-stand multi-purpose sensors for thickness, width, snaking and crown (the difference in thickness between the strip edge and the center) are laid between each stand for F4-F7, as shown in Fig. 18 (a) and (b). They monitor valuable information about each mill at the moments just before and after rolling, the results of which are used for operation control. Figure 18 (c) shows the excellent performance of the thickness control by means of the inter-stand thickness meter. Although the target thickness changed, the total deviation in thickness of the strip was kept within ±30μm in the case of endless rolling (to be explained later), the most distinctive aspect of this hot rolling equipment.

Figure 18 (b) shows the structure of multipurpose sensors, each of which has four sensor units that can be moved along the direction of the sheet width for positioning each sensor. This structure is much more complicated by comparison with the proximate γ-ray thickness gauge.

The two successful cases described above became the forerunners in establishing the use of sensors “In situ” in rolling processes thereafter. In any case, an advanced mechanism for keeping the sensors in good condition, and related maintenance techniques, are absolutely essential.

4.5 Fully continuous cold rolling process

The conventional cold rolling process once had six different batch processes, as shown in Fig. 19, starting from the pickling process and ending with the inspection and recoiling process, and it usually took approximately 10 days for total production. The longest process was the annealing and cooling process, which required almost one week. In 1972, a continuous annealing line (CAL) was developed with a total horizontal length of 200 m, as shown in Fig. 20. This shortened the processing time to less than 1/10, replacing conventional time change annealing
and cooling via a space change in the furnace [31].

In the batch cold rolling process, every coil sent from the pickling process was rolled one by one. This method, however, could not achieve the required accuracy in thickness due to the lack of tension at the top and tail ends of the coils. In order to avoid this problem, continuous cold rolling was introduced in 1971 in which the coils were welded together before rolling and cut into separate coils again after rolling.

Japanese steel-makers started gradually, partly refurbishing their conventional cold-rolling facilities based on this technology, and achieving fully continuous operation of total cold-rolling processes in 1986 [32].

This fully continuous system is truly an accomplishment in comprehensive facility technology, however, success was only made possible by developments in control technologies, including the introduction of various new sensors, coil tracking systems, the flying gauge change-technique [33] and the like.

This system shortened the duration of the rolling process from 10 days to ca 15∼20 minutes (ca 1/1000), and also contributed to other drastic improvements such as reducing quality variation to 30∼40%, reducing production loss to 50%, a tripling of labor productivity, and reduction of energy consumption to 85%.

4.6 The endless hot strip rolling process

In the hot strip rolling process, continuous rolling had been also desired, but the solution of joining sequential sheet bars with welding at a high temperature of more than 1000°C was the major barrier.

Figure 20 shows an example of fully continuous finishing rolling or so-called ‘endless hot strip rolling’, the first in the world, in operation at the Chiba Works No. 3 hot strip mill of Kawasaki Steel [30],[34] in 1995. After a tremendous research effort, a method of induction heating and upsetting was used to join the head and tail ends of the sheet bars within the very short period of 5 seconds, ensuring that the strength of the welding
point was equal to that of the sheet bar. This process amounted to a comprehensive application of a variety of new technologies, including hydraulic thickness control, use of AC motors, shape control milling, and the introduction of “in situ” sensors.

Figure 20 shows the new technologies developed for endless rolling, with many applied in sheet bar joining and high-speed shear and coiler control. The whole process, from the slab yard to the coil winding and transport, is operated by only three people rather than the usual 10 to 15. This leap in labor productivity is an unparalleled achievement, world wide.

Endless rolling stabilized the quality of the top and tail ends of the strip, and stabilized threading enabled rolling of thin-wide and ultra thin strips, while conducting lubricated rolling along the full length of the strip. The resulting excellent products include an ultra-thin steel plate measuring less than 1.2 mm, and a wide steel sheet measuring 1700 mm in width.

5. Conclusions

In this paper, representative examples of breakthrough control technologies in the steel industry which brought about drastic change in respective processes and their operation are referred to as “Japan original technologies”.

The major features of the technologies and the reasons for their success are summarized as follows.

(a) Main features:
• Process visualization with sensors and physical and/or empirical models,
• Continuation of batch processes,
• Complete automation,
• Well balanced mechanical and EIC technology,
• Extremely high completion in every technology.

(b) Reasons for their success:
• High demand and extremely strict requirements of steel users,
• Good relation between operations and facilities technologies,
• Good collaboration between steel and facilities makers,
• Advances in facilities (especially electronics) timely with demands of the steel industry.

In short, process visualization and continuation processes were the targets, and the extremely strict requirements of users of steel and the close relationship between operations technologies and facility technologies were the key factors for success.

In addition to the original technologies described there are many others, including BF gas distribution control techniques [35], the BF recycling process [36], the ultra-short term BF revamping technology [37], top and bottom blowing converters [38], electromagnetic power applications at CC [39], the tundish non-oxide heating method [40], the new plan view patterns [38], electromagnetic power applications at CC [39], the revamping technology [37], top and bottom blowing converters [38], the BF recycling process [36], the ultra-short term BF revamping technology [37], top and bottom blowing converters [38], the new plan view pattern control in plate mills [16], accelerated cooling technology in plate mills [41], fixed outer dimension H-shapes production techniques [42], and more. Information and communication technologies (ICT) such as the total steel plant online computer control systems [43] established by the steel industry during the latter half of the “high-growth” period, are also typical “Japan original technologies”.

While it should be noted that many of the original ideas for developing these technologies originated overseas, Japan has played an important role in practical application and the expansion of practical application of the technologies. The next phase of development now depends on the next generation of engineers and their ability to break out of the current mature mold of the steel industry.

References

Tadaaki Iwamura (Member)

He received a Bachelor’s degree in mechanical engineering from the Yokohama National University in 1966, and a Master’s degree in control engineering from the Tokyo Institute of Technology in 1968. He joined Kawasaki Steel Corporation in 1968 and worked as a control engineer in various steel manufacturing processes.

He was manager of the Process Technology Department in the main office from 1994 to 1997. He moved to KAWASAKI STEEL Systems R&D Corporation in 1997, and also moved to Kawatetsu Electric Engineering Co., Ltd. in 1998. He left the company in 2002 and joined MOT Program Development at the Tokyo Institute of Technology in 2004. He is a 1982 recipient of the SICE technical award.