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Progress of Instrumentation and Control Technology in JFE Steel†

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Abstract:

Instrumentation and control technology plays a key role in stable manufacturing of high-quality steel products. This paper overviews the progress of instrumentation and control technology in JFE Steel in the most recent 10 years and reviews its background and technology trends. In order to respond to further increases in the importance of this technology, instrumentation technology has been improved by applying recent developments in its seed technology, and control technology has been extended to newly-emerging fields of application. The developed technologies are described with many specific examples.

1. Introduction

In the steel industry, high-mix small-lot production has become the mainstream, and as a result, it is increasingly important to deliver the required amount of high-quality products when needed in order to meet diverse customer requirements. Therefore, in the field of measurement and control technology, a variety of technology development has been conducted, prompted by the following needs: guarantee and management of product quality (internal quality, surface characteristics, size, and shape), quality control and stable operation in the manufacturing process, and advanced production planning and logistics technology to reduce production lead time and deliver products to customers reliably.

Regarding production planning and logistics, the special issue in this technical report No. 28 includes papers on related technology[1,2]. Therefore, in this paper, the advancement of measurement and process control technology will be described.

2. Technology Trends in Measurement and Control Technology and Their Background

More than 10 years have been passed since JFE Steel was established by the integration of Kawasaki Steel and NKK. This chapter outlines technology trends in measurement and control technology during this period and their background.

Kawasaki Steel Technical Report 1999, No. 41, which was published before the establishment of JFE Steel, carried a paper on progress in measurement and control research in the preceding 10 years[3]. At the time, increases in production of high-value-added products, mainly thin steel sheets, and construction of new large-scale facilities such as hot rolling, continuous annealing, and stainless steel production lines had increased the need for online continuous measurement of the internal quality and surface quality of products and for quality improvement and stable operation of equipment, which facilitated the development of new measurement and control technology and equipment.

In the field of measurement, laser equipment, imaging devices, advances in ultrasonic transmitting and receiving devices, and higher speed in signal and image processing apparatuses enabled the development for higher performance online measurement. In addition, robustness of measurements to cope with the harsh environment in iron and steel process measurement and the influence of changes in product characteristics on measurements were investigated, and hybrid-fusion measurement and intelligent technology were applied. In the field of control, state-of-the-art control theory, including robust control and so-called FAN (fuzzy control, artificial intelligence, neural networks) were applied to actual processes, facilitated by the development of software for

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analysis and design of control systems, and application of advanced control to actual processes became a major trend. Thus, the development of new technologies during this period was supported by advances in hardware and software technologies.

In contrast, in the most recent 10 years, emphasis has been placed on stable operation of existing equipment and quality control of high-quality products rather than on the construction of new facilities. Furthermore, development of control technologies for efficient development and stable production of new products that correspond to customers' needs and for reduction of environmental loads such as carbon dioxide and further energy saving in the manufacturing process came to be strongly demanded.

As for the field of measurement, along with the development of high-performance and high-density devices represented by high-definition CCD and phased-array technology, the speed of signal and image processing by PCs or dedicated processors has increased over the years, enabling high-speed, high-resolution multi-point, multi-dimensional measurement. In addition, accompanying the shift to high-functional materials, performance guarantees for products are becoming more common than specification guarantees, and the development of inspection technology for this purpose has become another trend.

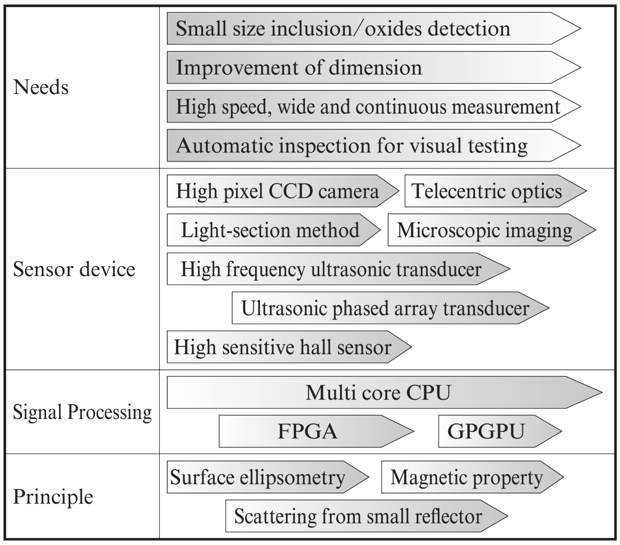
The evolution of control technology in the most recent 10 years can be viewed as an expansion of the covered area in all directions. This includes control for hard-to-measure control objects such as the material properties of products, expansion from control for individual processes to integrated through-process control, quality design of products and fault prognosis of processes for stable operation. These newly-emerging applications extend beyond the boundaries of conventional control technology. Statistical modeling technologies are also being actively applied to maintain high model accuracy, which has been made possible by improvement of operation database systems and high-performance PCs.

The trends in measurement technology and control technology are described in detail in Chapters 3 and 4, respectively.

3. Measurement Technology

3.1 Progress in Measurement Technology

Measurement technology consists of basic technologies such as sensors using optics, ultrasonics or electromagnetics, signal and image processing and data processing. Electronic devices have been applied to all types of elemental technology, and as a result, remarkable technical progress has been achieved in this field.



CCD: Charge coupled device
CPU: Central processing unit
FPGA: Field-programmable gate array
GPGPU: General-purpose computing on graphics processing units

Fig. 1 Trends in instrument technology

Measurement technology for new needs has been developed by quickly incorporating these latest sophisticated basic technologies.

Figure 1 shows the trends in measurement technology. Against the background of high-quality steel products, improved defect detection capabilities, improved dimensional accuracy, high-speed, wide-area and continuous measurement and automation of visual inspection are strongly demanded. In optical and image sensing, the high pixel density and speed of CCD imaging devices are remarkable, and peripheral devices such as lasers have become generalized and affordable. In ultrasonic sensing, higher frequency and arrayed transducers have been obtainable. In signal and data processing, PCs have become significantly faster and can now be applied where dedicated processors were necessary in the past. Flexible and customizable dedicated processors such as field-programmable gate array (FPGA) and general-purpose computing on graphics processing units (GPGPU) have been developed, which enabled special signal processing relatively easily. In addition to the progress of this hardware, approaches based on physical considerations such as the optical characteristics of the material surface, the propagation or scattering characteristics of ultrasound and magnetic properties have become a key to measurement technology development.

The following presents several examples of the development of measurement technology in JFE Steel from the viewpoint of product sectoral needs.

3.2 Examples of Development

3.2.1 Surface inspection for thin steel sheets

Quality assurance for surface defects of thin steel sheets is important because such defects can lead to cracking and poor appearance after the press process. JFE Steel has developed optical surface inspection systems in order to reliably detect surface defects of steel sheets in high-speed production. Initially, methods based on the diffraction of a laser beam in the defect were mainly used, but high definition cameras are now the mainstream.

In the trend of surface quality improvement, not only distinct irregular defects that can be detected by a laser method, but also defects with low contrast, which display a pattern-like appearance, can now be detected in the manufacture of automotive galvanized steel sheets. One challenge in detecting such defects is identification of harmless patterns due to oil adhesion and others. For this problem, attention is focused on the fact that harmless patterns correspond to dielectric reflection, which led to the development of "Delta-Eye™"[4], a surface inspection system using 3 channeled polarized light, as shown in **Fig. 2**. Practical applications of this technology enabled automatization of visual inspection and realized highly reliable full-length, full-width inspection.

Some surface defects of thin steel sheets, which are caused by foreign matter adhering to the roll, are so faint that they are hard to recognize even visually. The unevenness of such defects is only on the order of a few micrometers, and becomes visually detectable only after surface polishing by an inspector. For this kind of defect, attention was focused on the fact these defects are caused by transfer of foreign matter from the roll surface to the steel sheet. Considering this, a method of detecting a distortion caused on the steel sheet by a magnetic method was conceived. A magnetic leakage flux detection method using a Hall device, which is suitable for the detection of minute magnetic field fluctuations, was combined with a signal processing algorithm to improve the *S*/*N* ratio by using the periodicity of the signal, which realized online inspection for these defects[5,6].

In the case of hot-rolled stainless steel sheets, detection of small scale particles on the order of 100 μm remaining on the steel surface is challenging, but this small scale is harmful to the appearance of the product. The conventional method was visual loupe inspection of sampled sheets. In order to realize full-length continuous inspection, a high-resolution surface inspection system using ring illumination and microscopic imaging was developed[7].

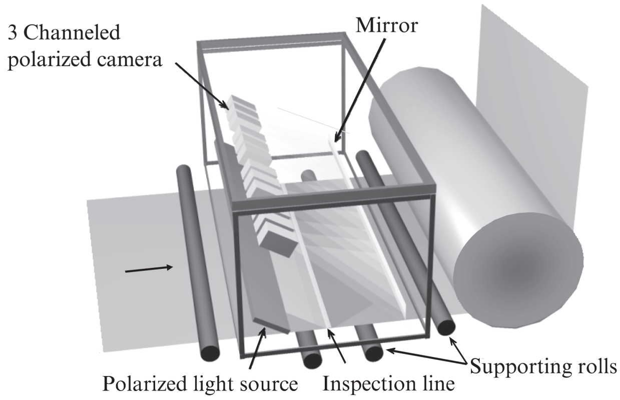


Fig. 2 Surface inspection system using 3 cannneled polarized light

3.2.2 Internal inclusion inspection for thin steel sheets

Strict quality assurance for small non-metallic inclusions in steel sheets is required, particularly in steel sheets for cans, these since inclusions cause cracking and penetration during the drawing process. In JFE Steel, an inclusion inspection system based on the magnetic leakage flux method was developed in the 1990s and introduced for inspection of cold-rolled steel sheets. JFE Steel also developed a micro-inclusion inspection technology for hot-rolled pickled steel sheets before cold rolling, which was realized by applying an ultrasonic flaw detection method using high-frequency line focus transducer arrays and has been put into practical use[8]. Micro inclusions with a volume 5×10^{-5} mm^3 are detectable. A trend management system for feeding back the inclusion information to the steelmaking process was also constructed to achieve quality improvement in the steelmaking stage[9].

3.2.3 Inspection and measurement of welded steel pipes

Because welds of welded steel pipes are a key point for product quality, weld inspection and process monitoring technologies have been developed. Here, the technologies for high-frequency electric resistance welding (HFW) pipes are introduced.

High-frequency electric resistance welding (HFW) pipes are produced continuously from hot-rolled strips by high-frequency resistance welding, which has excellent productivity and secures good low temperature toughness. To further enhance the reliability of welds, a bead shape meter, spark sensor, and array ultrasonic flaw detection technique which enables detection of fine oxides were developed to complete the overall weld quality assurance (QA) quality control (QC) system

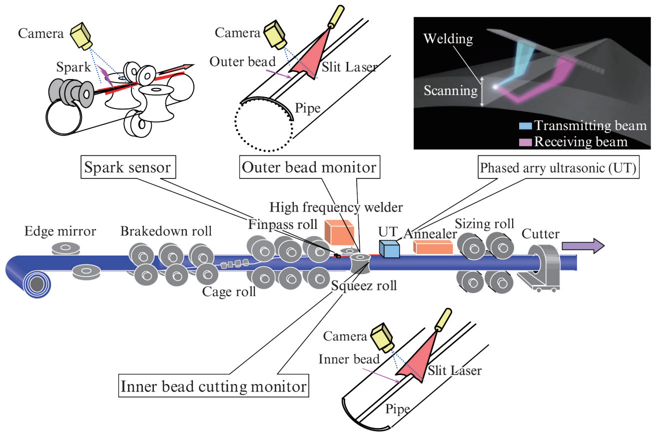


Fig. 3 Total quality assurance (QA)/quality control (QC) technology for high-frequency electric resistance welded pipe (HFW pipe)

shown in **Fig. 3**.

In HFW, the plate end surfaces, which have been melted by high frequency resistance heating, are butted together and the molten steel contained in the oxides is discharged by upsetting, resulting in a high quality weld. This means the bead shape is important in the management of the heat input condition. Therefore, JFE Steel developed a bead shape measurement system using a light-section method in which the measurement target is irradiated with a slit laser beam, and its three-dimensional shape is calculated by performing a coordinate transformation to the shape of the slit light obtained by a camera. An outer surface bead shape meter[10] and an inner surface bead cutting monitor[11] were applied practically by using this method.

Although rather rare, sparks can occur during welding. Sparks are believed to be due to the short circuit current path created by some foreign matter mixed in the butted portion. JFE Steel developed a technique for monitoring sparks over the entire length of welded pipes. An analysis of the image of the sparks by color separation revealed that the amount of the blue light component is dominant at the time of a spark, which led to the development of a highly reliable spark detection technique combining a short wavelength transmission filter and a CCD camera[12].

Oxides which are not discharged during welding and remain in a weld degrade the toughness of the weld. Studies on the relationship between the state of the oxides and the welding quality showed that the density of fine oxides of a few micrometers in size affects low temperature toughness, and their density can be evaluated by ultrasonic inspection using a focused beam. This led to development of the point focused beam tandem flaw detection technology with a phased array device[13]. Conventionally, welding quality had been evaluated only by mechanical testing such as the Charpy impact test, but the development of this technology enables evaluation of the state of the oxides that affect welding quality over the entire length.

This technology has been applied to "Mighty Seam™"[14], a line of new innovative HFW steel pipes with superior in low-temperature toughness, and dramatically increased the reliability of HFW steel pipe.

3.2.4 Inspection and measurement of steel plates and long products

Guarantee of internal defects in rails is conducted by ultrasonic flaw detection. A wide inspection coverage range and high detection capability are required, especially for the head of the rail. Therefore, JFE Steel developed a sector scan method using the phased array technology and thereby enhanced flaw detection coverage from 50% to 80%, realizing more reliable quality assurance[15].

A thickness gauge with a laser rangefinder was developed to guarantee the thickness of steel plates. Unlike conventional direct thickness measurement by the γ-ray method, this method calculates the thickness of the plate from the distance information from the laser rangefinder to the front and rear surfaces. The development of precise calibration is the key to commercialization[16]. In the field of steel bars, a roll placement guidance device using a parallel light emitting optical system and image processing was developed[17] and is utilized in improvement of dimensional accuracy by refinement of the roll arrangement.

3.2.5 Environmental measurement and equipment diagnostics

In steel works, dust in the atmosphere is periodically monitored in order to take proper measures against dust scattering. For more effective measures, it is necessary to determine the type of dust. Therefore, a dust type classification system[18] was developed and applied based on microscopic imaging using ring illumination and infrared transmitted light and color image analysis.

Ensuring the soundness of the steel plant gas piping system is very important not only for stable operation of the steel works, but also for accident prevention. To this end, an array type ultrasonic thickness gauge for easy and accurate diagnosis of pitting corrosion on the inner surface of the piping system and an ultrasonic inspection technique that enabled non-open non-destructive piping corrosion diagnosis of pipe bases were developed[19]. These technologies have been applied to diagnosis, maintenance and repair of the piping system in steel works.

4. Control Technology

4.1 Changes in Direction of Technology Development

In process control development, first, a model describing the dynamic characteristics of the control object is created, and then the controller design is performed so as to obtain the desired control performance. In the aforementioned Special Issue, molten steel level control in continuous casting and tension and looper control in hot rolling were described as two examples of process control. In those two cases, a model can be created by considering the physical phenomena in each process. For control system design, it is necessary to obtain the parameters of the model accurately. In the case of iron and steel processes, however, a mismatch between the model and the actual process is inevitable because there are some model parameters that cannot be measured directly. Robust control theory considers this type of mismatch as an uncertainty of the process, and therefore has been applied to the design of controllers in such a way that the total control system with the controller maintains the desired control performance in the presence of the process uncertainty. The two above-mentioned control systems were both designed based on robust control theory.

Robust control theory also demonstrates the limits of control performance when a process uncertainty is present. It was found that a new control system which had been designed on the basis of control theory failed to perform as expected if the process uncertainty was large. This can be considered a reason why application of control theory to actual processes, which had been actively carried out from the 1980s to the 1990s, fell from favor in the 2000s.

In order to break through this situation, technology development was conducted from a wider perspective to expand the application fields of control technology, as shown in **Fig. 4**. This trend will be discussed in detail below.

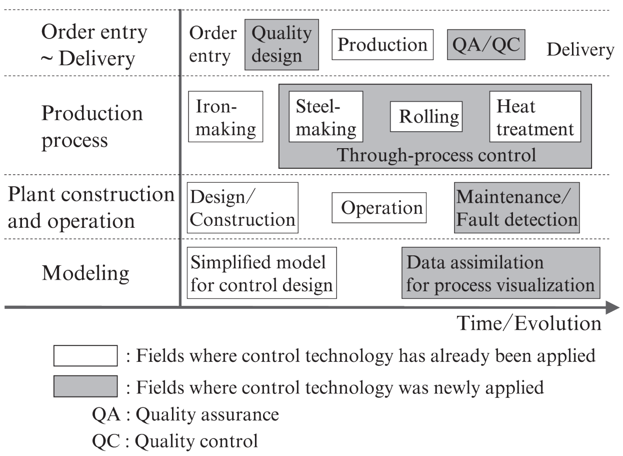


Fig. 4 Expansion of application fields of control technology

4.2 Expansion of Technology Development

4.2.1 Soft sensor technology

In the case of conventional control systems, it has been assumed that the controlled variables (physical quantity to be controlled), such as the dimensions of the rolled material, temperature, tension, and level, can be measured with sufficient accuracy. However, there are some variables that are important in quality control but are hard to measure continuously online. These include the mechanical properties (tensile strength, yield stress, elongation, etc.) of steel products. In addition, ironmaking and steelmaking processes also include some variables that are hard to measure directly but should be controlled. **Figure 5** shows the visibility of the control items for each process. Here, "visibility" means ease of measurement.

To cope with such controlled variables, control technology based on controlled variables estimated by soft sensors has been developed. The soft sensor combines a process model with some sensor information on the process in order to improve the model accuracy, thereby estimating variables that are hard to measure directly.

In soft sensor-based control of the mechanical properties of steel products, first, a model is created to estimate their mechanical properties based on the chemical composition and rolling and cooling conditions of the product. When the analysis values of the components of the steel are obtained, the rolling and cooling conditions are calculated using the model so as to achieve the desired mechanical properties, and feed-forward control is performed. This mechanical property control has been put into practical use in the manufacture of steel plates and sheets. **Figure 6** shows an example in the case of steel plates[20].

The mechanical property model[21] is also applied to quality design to determine the production conditions of each process for the products ordered by customers. Conventionally, quality design was performed by expert designers with a knowledge of the processes and products. Model-based design makes it possible to precisely determine the conditions of the production process. It also exemplifies the expansion of the application range of control technology.

Another example of the soft sensor is standing wave estimation[22] in the continuous casting mold. In the molten steel level control technology in the Special Issue[3], a disturbance observer was applied to estimate fluctuations of the inlet/outlet molten steel flow rates of the

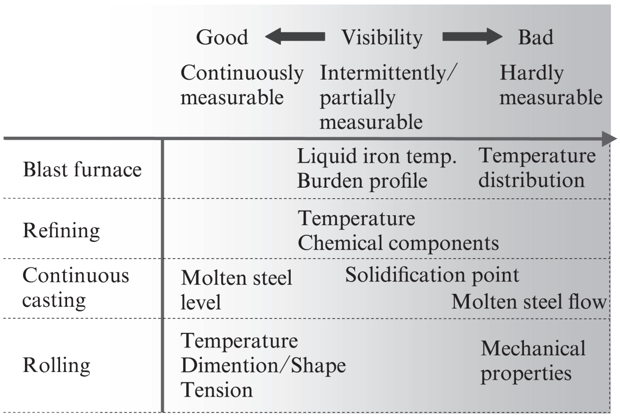


Fig. 5 Visibility of steel processes

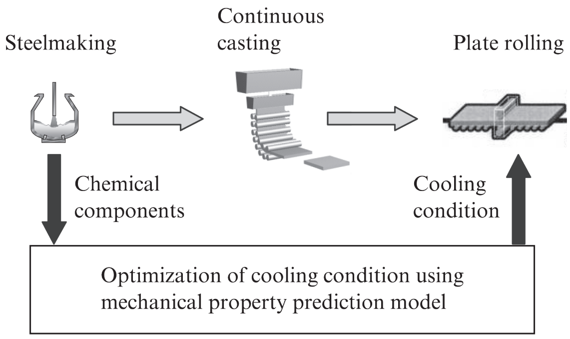


Fig. 6 Mechanical property control system for steel plates

mold, and the sliding nozzle of the submerged entry nozzle was manipulated based on estimated disturbances so as to prevent fluctuations of the molten steel level by cancelling out the effects of inlet/outlet changes. In that sense, it is a soft sensor-based control system. However, sloshing by self-excited vibration can cause molten steel level fluctuations, which are called standing waves. Since the variations in the molten steel level due to the standing wave phenomenon are not due to mass flow variations in the molten steel itself, the sliding nozzle operation should not be manipulated in response to those variations, as this may aggravate level fluctuations and can destabilize level control. However, such standing waves cannot be distinguished from fluctuations due to mass flow variations based only on molten steel level measurements, and for this reason, there was no appropriate control method for standing waves by conventional techniques.

The developed control system extracts the standing-wave component by an observer, and uses a signal obtained by removing the standing-wave component from molten steel level measurements for level control. Therefore, control action does not aggravate the standing wave. This means a higher control gain can be set in level control, and as a result, a more stable molten steel level and higher slab quality can be achieved.

In addition, soft sensor technology has been employed to visualize processes that are hard to observe internally. In the case of the shaft furnace[23)], a technique called data assimilation was applied by combining a model and partial sensor information, thereby enabling estimation of the state of the entire furnace.

4.2.2 Modeling techniques based on operating data

Not only dynamic control during operation, but also set-up control of the initial settings of the manipulated variables before operation is important for accurate process control. In the field of rolling, sophisticated rolling theory has been developed, and set-up models can be based on it. On the other hand, in steelmaking, there are some batch processes where the operating condition must be determined in advance for each batch operation, but sometimes sufficient accuracy cannot be obtained only by physical models. As for the mechanical property prediction method mentioned in section 4.2.1, it is difficult to construct a practical model to predict mechanical properties from operating conditions based only on metallurgical models.

Statistical models have been used if sufficient accuracy cannot be obtained only by physical models. The aforementioned Special Issue included a paper on the application of a neural network, which is a kind of statistical model. Since it is difficult to appropriately adjust the non-linear characteristics between the input and output, neural networks are no longer applied in control systems in the Japanese steel industry. Instead, JFE Steel has been working on another statistical model called the JIT (Just-in-Time) model.

The JIT model was first introduced by Prof. Hidenori Kimura in the working group for learning and update of rolling setup models of the “Modeling and control of the iron and steel process” forum (1998–2000) in the Technical Committee for Instrumentation, Control and Systems in the Iron and Steel Institute of Japan. In the JIT model, no model with fixed parameters is used, but model parameters are calculated whenever a query point is given. In the algorithm, first, the similarity between the setting condition at the query point and each data point in the stored operating data is evaluated, and a simple regression model is obtained considering their similarity. Therefore, if the database is properly updated, model accuracy is always maintained and it is possible to handle non-linearity. Applications of the JIT model include control systems in a wide range of areas, such as mechanical property control of steel products[20,21,24)], a desulfurization model[25)], a rolling force model in hot rolling[26)], a width model in plate rolling[27)], and modeling of operator actions[28)]. For more information, please see the paper[29)] in this special issue.

4.2.3 From control of single processes to integrated through-process control

Each process in the manufacture of steel products is equipped with control loops to control the controlled variables within an acceptable range around their target values. However, since steel products are produced through process chains, integrated control though the process chain can achieve further quality improvement. Integrated through-process control can be viewed as a supervising layer which gives each control loop its target values so as to coordinate and optimize the entire process chain.

The mechanical property control method described above is based on this idea. By changing the operating conditions of the subsequent rolling process based on the operation results from the steelmaking process, this technology suppresses variations of mechanical properties so as to maintain high product quality.

In conventional process monitoring for quality assurance and control, upper and lower bounds are set for each process variable so that large deviations of the variables can be detected. If the process data in several processes can be monitored simultaneously, this will enable early detection of the factors that lead to quality abnormalities. However, because the number of data item to be monitored is enormous, it is difficult to set an appropriate control range for each data item. Therefore, multivariate statistical process control (MSPC) was applied to a steel sheet quality management system[30]. MSPC enables efficient management of process data and enhances anomaly detection capabilities by applying principal component analysis to calculate some statistics. In the steel sheet quality management system, process data in steelmaking, rolling and annealing are aggregated and handled so that through-process control can be performed, and this has contributed to stabilization of the quality of products.

4.2.4 Anomaly prognosis of equipment and operation

Anomalies in facilities and operations lead to delays in deliveries to customers, and therefore should be detected at the earliest possible stage, or preferably, should be predicted in advance by prognosis. JFE Steel has developed sensors and systems for this purpose. In a steel sheet fracture prediction system[31] in the continuous annealing process, a statistical technique called canonical correlation analysis was applied. This technique can extract not only the relationship between the operating variables, but also the relationship in the longitudinal direction, which improves detection performance by monitoring changes in the relationship from the normal state.

In the coke oven, the force required to push out the coke from the oven after carbonization varies depending on the raw material composition, carbonization conditions and furnace wall properties. In extreme cases, the coke cannot be pushed out by the usual equipment, leading to operational problems. To prevent this situation, a model was developed to predict coke pushing performance[32]. The explanatory variables of the model were selected from an operational database by a statistical method, which made it possible to create a practical pushing prediction model.

5. Conclusions

Advances in measurement and control technology in JFE Steel during the last 10 years have been outlined. The aforementioned paper[3] stated that the requirements for the near future would include automation of equipment and inspection associated with a shrinking workforce, process monitoring and equipment diagnosis for environmental consideration and longer service life, mechanical property measurement for high value-added products and plant-wide control. The technology development described in this paper is consistent with those predicted needs.

In the future, the need for measurement and control technology is expected to increase inevitably in order to cope with higher quality, higher strength and higher functionality products. Because precise regulation of the controlled variables to their target values is necessary in the production of such products, further improvement in process measurement technology and control technology for this purpose is required. Moreover, a vast amount of process data must be handled in order to perform integrated through-process quality control by tracing the production history in the respective process chains, and this is another challenge for the future. To meet these needs, JFE Steel will continue to work to develop new instrumentation and control technology.

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