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Technology

Digital Twin of Steel-making Process Control in Nippon Steel Corporation

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Abstract

Overlooking of the changes in process control technology and the recent developments in Nippon Steel Corporation, we reconfirm that the digital twin is not a concept that has suddenly emerged today, but it is positioned as an extension of the technologies developed by our predecessors, and its universal perspective, or its essential position is digital sharing of operation technology, facility technology, and process control technology including human dynamics and man-machine communication. The digital twin in our process control is built on the universal perspective and the essential position.

1. Introduction

The digital twin concept was proposed as a framework in the industrial sector that replaces traditional time-based maintenance (TBM) based on statistical analysis with the construction of a system based on monitoring and analyzing the individual operating data of real plants. This new maintenance scheme is known as condition-based maintenance (CBM). This idea involves treating the behavior of real-world facilities as a collective of algorithms and models, referred to as a twin.[1] Currently, there is not a precise academic definition for digital twins. Recently, digital twins have been proposed in various fields. With the advancement and widespread adoption of IoT, computers and virtualization technology, the digital twin concept is generally recognized as a method that involves the real-time and comprehensive collection of information from the real world. This information is combined with models expressed in mathematical equations to reproduce the movements of objects. Digital twins allow the reconstruction of real events and logistics in a virtual digital world and enable the high-resolution reproduction of the real world.

This virtual world is also referred to as the digital space or cyber space. In the context of manufacturing process control, this cyber space is defined as a system composed of technological elements such as real-time data (process data I/O), physical models, analytical and knowledge-based algorithms like machine learning, control systems, visualization interfaces, computers, and databases. It carries a similar meaning to the term “Cyber-Physical System” (CPS).

The ideal form of digital twins in the steelmaking process and its process control are not currently clearly defined. However, in this paper, we take a broad overview of the evolution of process control technology at Nippon Steel Corporation, along with recent development cases. We aim to reaffirm that digital twins are not a suddenly emerging concept but rather are positioned as an extension of preceding technological advancements. Simultaneously, we provide concise insights into their universal perspective and essential positioning.

2. Changes in Process Control Technology and Origin of Digital Twins at Nippon Steel

2.1 Evolution and overview of Nippon Steel’s system and measurement control technology

The process control technology at Nippon Steel is built upon the progress in our foundational system and measurement control technology. An overview of this progress is summarized in **Table 1**.

We established self-developed support environments for computer control software systems (NSCASE and NS SEMI SYSTEM™ [*1]) in the 1990s, by considering the expandability, integration, compatibility, and openness of industrial computers (hardware and software) in the late 1980s. This allowed for the use of common personal computers to achieve 24/7 operation and sub-second responsiveness, leading to the widespread utilization of open systems that could absorb differences in hardware and operating systems (OS) from various vendors.

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Table 1 Overview of progress in system and measurement control technology in Nippon Steel

Item	Before 1990s	After 1990s
1) System configuration (H/W, S/W)	Manufacturer-specific/Dedicated/Single-function system	Open/General-purpose/Multifunctional system
2) Measurement/Control target	• Individual measurement (Time series chart) • Single process • SISO control	• Individual/Distribution measurement (Image information) • Serialization of pre- and post-processes • MIMO control
3) Operator's point of view	• Single process (Single facility) • Individual monitoring (Batch monitoring, Time series chart monitoring)	• Multiple processes (Multiple facilities) • Individual/Distribution/Feature value monitoring (Integrated visualization monitoring, Image information monitoring)
4) Man-Machine interface	Control room (Single function dedicated screen)	• Control room (Integrated large screen) • Tablet terminal, Wearable device (2020s and beyond)
5) Data transmission	Wired	Wired + Wireless (2020s and beyond)
6) Data storage and analysis	Individual (Local)	• Company-wide sharing • Private cloud (2020s and beyond)

Since the 2000s, the following new technologies have been developed and applied successively:

1) Operation navigation: Electronically transforming detailed instructions, traditionally handled on paper, and presenting them as needed while accumulating them as know-how information
2) Device technology for automatically recognizing and recording measured values or voices
3) Individual recognition technology using 2D barcodes and Images
4) Display technology for presenting large amounts of numerical data in a three-dimensional format on a big screen
5) Data-driven control technology for analyzing trends and causal relationships from extensive data and providing real-time feedback
6) Measurement technology for real-time processing of super-high-resolution digital images

With the development of these technologies, measurement technology has transitioned into the multidimensional realm, progressing from point measurements to encompassing surfaces and three-dimensional spaces and achieving enhanced precision. Simultaneously, visualization technology has emerged, enabling the visualization of substantial volumes of measured data. In parallel, control technology has transformed from individual functional control to quality built-in control and extending further into comprehensive autonomous operation and optimization control. Additionally, real-time observation and operation control systems have been developed, utilizing general-purpose computers to achieve high-speed process control at the millisecond level, connecting to the real-time processing hierarchy (Level 1).[2)]

From the 2020s onwards, operation control with large integrated screens has been implemented in instrument rooms. Simultaneously, the adoption of wearable devices such as tablets and other wearables and the wireless transmission of sensor data, has been introduced. This has led to increased efficiency in equipment inspection and maintenance tasks. Furthermore, the storage and analysis of data are now achieved within an in-house cloud environment.[3–5)]

2.2 Origins of digital twins in process control of Nippon Steel

In the evolution of Nippon Steel's system and measurement control technology, in the 2000s, the capabilities of programmable logic controllers (PLC) and general-purpose sequencers for industrial applications became comparable in terms of computational speed and data capacity. The substantial difference shifted towards software productivity and maintainability. Nippon Steel addressed this issue by developing the electric PLC software design and production technology (E-CASE) based on the IEC61131-3 language. This solution not only enhanced model components, but also introduced a virtual commissioning feature built within a general-purpose personal computer (PC). As a result, electrical control systems using general-purpose sequencers found widespread application in steel plants. Simultaneously, instrumentation computer-aided software engineering (CASE) was applied to general-purpose electric sequencers with integrated control capabilities and expanded the application of general control devices to the instrumentation controller domain.[2)]

The origin of digital twins in steel process control may be traced back to the virtual commissioning system[6, 7)] with general-purpose sequencers and computers used as electrical and instrumentation controllers for steel plants.

In the past, simulators created in a low-level language (ladder logic) were used for debugging electrical PLC control software. However, these simulators had low productivity and reusability, and conducting operational checks was also challenging. As a solution, a virtual commissioning system was introduced. In this system, standardized components such as solenoid valves, motors, and various sensors were registered as model parts. They were then configured and reused with Nippon Steel's proprietary in-house electrical software development technology. This led to the creation of a virtual environment with a plant simulator and a virtual plant screen. Although the virtual commissioning system was developed with the aim of improving the productivity and quality of debugging software, the conceptual diagram from the development era illustrates the juxtaposition of real-world operation (the real world) and the virtual commissioning system ("virtual test run system") (the virtual world) (**Fig. 1**).

The specifications of control devices were subsequently opened up. In the phase where general-purpose personal computers (PCs) were employed for real-time processing (Level 1), a method was devised to seamlessly integrate the substantial numerical processing capabilities and adaptable software development environment of personal computers with the high reliability and precise timing of industrial PLCs. This approach resulted in the creation of a "real-time observation and operation control system". This system facilitates the real-time observation of processes through sophisticated

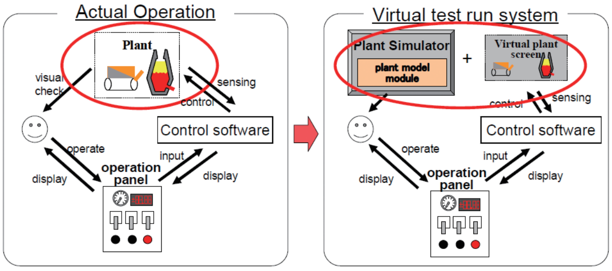


Fig. 1 Outline diagram of virtual test run system[6), *2]

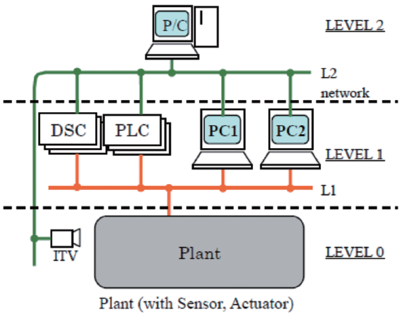


Fig. 2 Configuration of real-time observation and operation controlled system[8, 9)]

model calculations and enables the operation control function to be achieved in milliseconds through advanced computation based on the observed results (**Fig. 2**).

The real-time observation and operation control system plays a crucial role in processes like hot rolling, where high-speed millisecond-level process control is vital. It leads to substantial advancements in developing and implementing new control functions with high flexibility. Simultaneously, the system allows for a rapid response to previously unknown process phenomena once they are comprehended. Moreover, it offers valuable support and maintenance information for operators who may lack experience.[8, 9)] By enabling a more detailed reconstruction of the dynamics of real-world steelmaking processes in a virtual environment, this system promotes more precise information sharing among not only control engineers and system engineers, but also operators and maintenance personnel.

2.3 Technological challenges in steelmaking process control

In the preceding sections, we have taken a broad look at the evolution of Nippon Steel's process control technology. Within this context, we have explained that the systemization technology developed by our company should be recognized as the origins of the digital twin.

The steelmaking processes, represented by blast furnaces, is a essentially complex and nonlinear distributed parameter system. Additionally, the physical phenomena themselves, the systems that control them, and the production systems have a hierarchical structure with various time scales ranging from milliseconds to over one to two weeks. This hierarchical time structure contributes to the technical challenges in control engineering and production systems.

In the next section, we will focus on the measurement, control, and system technologies developed by Nippon Steel since the 2000s. We will provide concrete examples from the perspective of the digital twin. This will allow us to reaffirm our understanding and positioning of what the desirable form of the digital twin should be in the steelmaking process.

3. Examples of Measurement, Control, and System Technologies Developed by Nippon Steel

3.1 Blast furnaces

The ironmaking process produces molten iron from raw materials such as iron ore and coal. Stable production is of the utmost importance. In recent years, there have been demands to accommodate low-quality raw materials and to reduce greenhouse gas emissions while maintaining high productivity. The blast furnaces are operated with high productivity and a low reduction material ratio, aiming for a high pulverized coal ratio and a low coke ratio. Ensuring permeability and improving reaction efficiency in the blast furnace have become increasingly important challenges. We have developed measurement, control, and system technologies to support the stable operation of the blast furnaces through the early introduction of state-of-the-art device technology, image processing and analysis technology, computer technology, and image information technology.

The current state of blast furnace control is marked by precise monitoring of control inputs (such as burden charging and tuyere injection conditions) and corresponding measurements (like furnace temperature), as well as real-time tracking of control results (such as tapped iron flow temperature and slag inclusion ratio). The advancements in computer performance in recent years have facilitated the creation of simulators capable of accurately reproducing the reaction conditions within a real blast furnace. By successfully simulating real blast furnace conditions in a virtual environment and aligning them with actual control input and output results in real time, it becomes possible to uncover changes in the blast furnace dynamics. This is instrumental in enhancing the operational stability and efficiency of the blast furnace. This approach is rooted in physical principles and holds the potential to respond effectively to unexpected scenarios, unlike traditional approaches that rely on past operating data or require prior experience.

The subsequent sections present the technologies developed by Nippon Steel to enhance the accuracy of controlling the burden distribution in the blast furnace. These also include technologies for analyzing images to measure the tuyere condition and tapped iron flow in the blast furnace, as well as technologies for visualizing the operating data of the blast furnace and for automating the operation of the blast furnace.

3.1.1 Measurement techniques to support stable operation of blast furnace[10)]

1) Techniques for tracking blast furnace burden materials using RFID

Control of the burden distribution in the blast furnace involves managing the deposition of burden materials in the radial direction of the blast furnace. As a means of achieving this objective, the layer thickness of charged coke and iron ore is controlled. Additionally, the particle size distribution of the burden materials in the radial direction of the blast furnace is controlled, and nut coke is charged mixed in the iron ore layers in the blast furnace.

To enhance the precision of controlling the particle size distribution of the burden in the radial direction of the blast furnace and of mixing coke with iron ore and charging the mixture into the blast furnace, it is necessary to understand the segregation of the burden materials as they pass from conveyors through hoppers into the blast furnace. To address this, technology was developed to track the burden materials by using radio frequency identification (RFID) tags as tracers.[11–13]

RFID is a widely used non-contact identification technique employing radio waves. It involves wireless communication between tags and readers. Tags are equipped with unique ID codes attached to various objects or individuals, allowing their positions and movements to be monitored in real time by the reader. The RFID technology can link the movements of real-world objects and individuals to the digital virtual world in real-time and has diverse societal implications. **Figure 3** provides an overview of the blast furnace raw material tracking technique using RFID.

Active RFID tags that imitate burden materials are mixed with the burden materials and read when they are conveyed to and charged into the blast furnace. The ID codes provide information on the segregation behavior of the burden materials on the conveyance route and help control the order in which the burden materials are dumped onto the conveyor. The RFID tags are contained in durable cases to protect them from the impact of being conveyed with the burden materials. The size and weight of the cases are adjusted to match the actual burden materials. A performance of the technique was evaluated in a real blast furnace with nut coke mixed in the ore layers where density segregation was likely to occur. It was confirmed that the timing of the RFID tags passing over the detection antennas of the reader could be accurately detected when the detection antennas were installed ahead of the place where the burden materials were to be charged into the blast furnace. It was also confirmed that the evaluation results correlated well with the raw material sampling results and with the furnace top bunker simulation results.[13]

2) Technique for measuring tuyere inside condition and tapped iron flow condition by using image analysis

To support the stable operation of blast furnaces, the outside periphery information measured with numerous thermocouples and pressure gauges installed in the furnace, the formation of the tuyere raceway and the condition of the pulverized coal reaction, and the temperature and weight of molten iron flowing from the tapholes in the lower part of the blast furnace have been carefully monitored as information to help understand the conditions of the high-temperature reaction zone and the hearth area inside the furnace.

In recent years, measurement techniques have been developed by utilizing image processing and analyzing techniques to obtain these pieces of information more accurately, rapidly, and continuously.

Each blast furnace has about 40 tuyeres and about four tapholes. The tapholes are switched over each time the molten iron is tapped. The tuyere and taphole inside conditions are monitored with cameras. Blast furnace operators are limited in their capacity to understand all the tuyere inside conditions and tapped iron flow conditions and operate the blast furnace accordingly while watching the camera images.

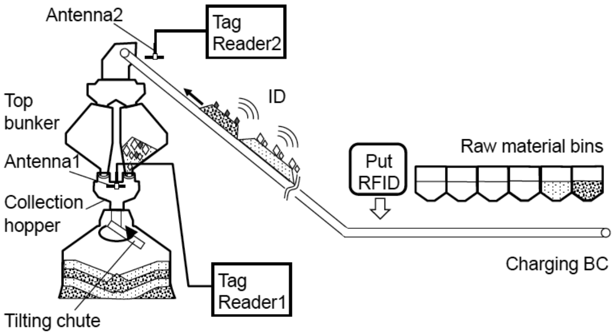


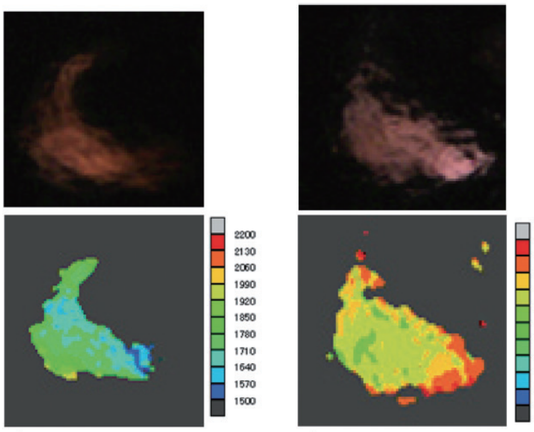
Fig. 3 Outline of burden material tracking using RFID for direct charge type[11), *2]

Therefore, to measure the tuyere conditions and monitor the inside of the blast furnace, a technique was developed for calculating the two-color temperature from CCD camera images and measuring the temperature distribution in the tuyere raceway.[14] Additionally, to monitor the condition of the molten iron stream discharged from the tapholes, techniques were developed for separating the molten iron and slag regions based on the analysis of brightness histograms by image processing and for measuring in real time the molten iron flow temperature, slag entrapment ratio, and flow velocity.[15, 16]

Figure 4 shows the temperature distribution in the blast furnace tuyere raceway measured using a color CCD camera. The figure compares the measured raceway temperatures during oxygen enrichment, steam injection, and external air injection by a double-pipe lance in the East Nippon Works Kimitsu No. 4 blast furnace. Steam was injected at two levels of 100 kg/h and 183 kg/h, and oxygen was added at 10 Nm^3/min. The top of the figure shows the original image and the bottom shows the estimated temperature based on the two-color temperature calculation from the color CCD camera. The dark region from the lower right to the center of the image is a pulverized coal image. Though slightly understanding by the brightness of the original image, the temperature distribution image shows that the raceway temperature is higher during oxygen enrichment than during steam injection. This is confirmed quantitatively and also as image information.[14]

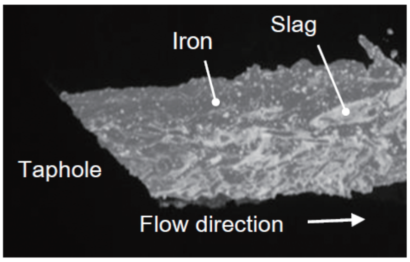
Figure 5 shows a thermal image of the tapped molten iron and slag stream and a brightness histogram of the thermal image. The molten iron and slag stream discharged from the taphole was photographed from the side with a monochrome camera. The exposure time was set short to prevent image blurring. The thermal image shown in Fig. 5 a) was obtained in this way. The slightly darker region on the tapped stream is the iron and the brighter region is the slag. The two high-temperature liquids are different in emissivity and so is their brightness.

Figure 5 b) shows a brightness histogram of the thermal image of the tapped stream. The iron region has a clear peak. The semitransparent slag changes its thermal radiation characteristics in thickness

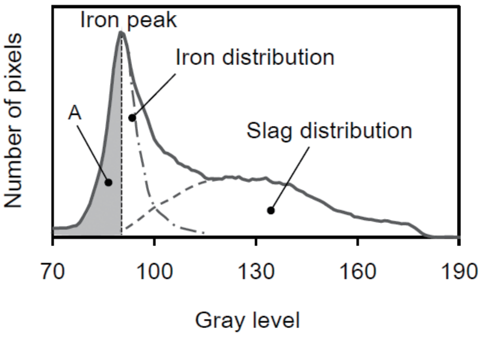


a) When steam injected b) When oxygen injected

Fig. 4 Example of measurement results and estimation results of temperature using CCD camera[14), *2]



a) Example of thermal image of molten iron and slag stream



b) Histogram of the thermal image

Fig. 5 Thermal image of tapped stream and analysis example of brightness histogram [16), *2]

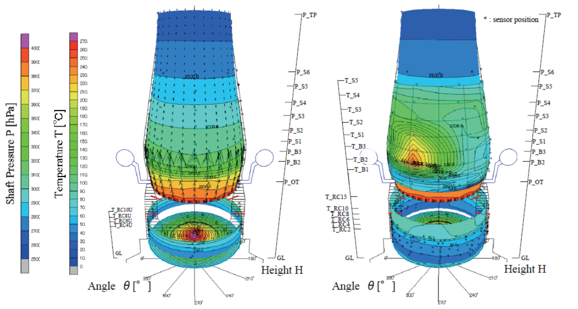
and hence the slag region has a broad brightness distribution. Assuming that the base of the slag distribution is up to the brightness peak of the iron region, that the area of the iron distribution is twice the area of region A in the figure, and that the area of the slag distribution is the entire area of the histogram minus the area of the iron region, the slag ratio can be calculated from the image information.

When continuous images are photographed at a high enough frame rate to track the slag pattern that deforms with turbulence, the tapped iron flow velocity can be calculated from the moving distance of the slag pattern. The tapped iron stream has surface waves due to deformation. When a composite image where the surface waves are extracted by differential processing of multiple images is obtained, the inner and outer diameters of the upper and lower waves are measured, and the flow rate is estimated from the flow velocity and the tapped flow diameter, it is possible to define an apparent tapped iron flow diameter between the inner and outer diameters.[16)]

3.1.2 Image information (visualization) technology for blast furnace operating data

Blast furnaces are equipped with many various sensors for temperature, pressure, gas composition, etc. These sensors can continuously measure these variables over a long period of time. Using the measured data, many technologies were investigated to analyze and predict abnormal blast furnace conditions, such as a sudden drop in hot metal temperature, fluctuations in top gas composition, abnormal burden descent such as slips, drops, and hanging, shaft pressure fluctuations, gas flow abnormalities such as gas leakage and channeling. Nevertheless, the experience and skill of the blast furnace operator play a large role in comprehensively judging the non-stationary behavior of a large number of measurement data's time-series charts spatially and temporally and in grasping and predicting them.

An image information system that supports blast furnace operators through on-line visualization of the spatial distributions and temporal changes of blast furnace operating data was developed and applied in the field.[17, 18)]



a) Shaft pressure, hearth wall (inside) and hearth temperature b) Shaft pressure, stave, hearth wall (outside) and hearth temperature

Fig. 6 3-Dimensional image of blast furnace process data (#2BF Oita Works, Nippon Steel) [18), *2]

This system is designed to reconsider the blast furnace as a process of the distributed parameter system with spatial distribution characteristics and to quantify and share its unsteady behavior by using objective image information.

The blast furnace is equipped with many various instruments, such as thermometers, pressure gauges, and top gas analyzers for the purpose of operation monitoring and facility management. The system accurately determines the position information of the instruments. Using the position information and measurement values of the instruments, the system estimates the temperature, pressure, and gas composition in the blast furnace regions without instruments by spatial interpolation calculation and sequential search of isolines. The spatial distribution characteristics of the measurement data are visualized as image information on a blast furnace body on a two-dimensional plane or in a three-dimensional space. General-purpose personal computers (PCs) decreased in price and improved in performance. Programming interfaces for 3D graphics processing such as OpenGL™[*1] and high-performance graphics units (GPUs) were popularized. As soon as possible, Nippon Steel applied this progress of computer technology to the construction of steelmaking process operation monitoring systems. A series of tasks from the collection of measurement data through update of virtual grid point values and search of isolines to preparation of 3D images and update of screens were stably completed within an instrumentation period of within 1 s, including real time calculation of secondarily processed values such as time rate of change and space rate of change vectors (**Fig. 6**).[18)]

3.1.3 Blast furnace operation automation technology

Blast furnace operation automation technology refers to a control system based on the latest and most advanced information and communication technology (ICT) and was developed by upgrading the measurement (visualization), control, and systemization technologies described in the previous section.

To operate its blast furnaces with high stability and efficiency, Nippon Steel has been pushing ahead with the development of blast furnace operation automation technology (BlastBrain™[*1]) to reduce operation variabilities arising from the personality of operators and the property change of burden materials and fuels. As one of the functions of blast furnace operation automation technology, the predictive control function optimizes the blast conditions (such as blast volume, oxygen enrichment rate, and pulverized coal injection rate)

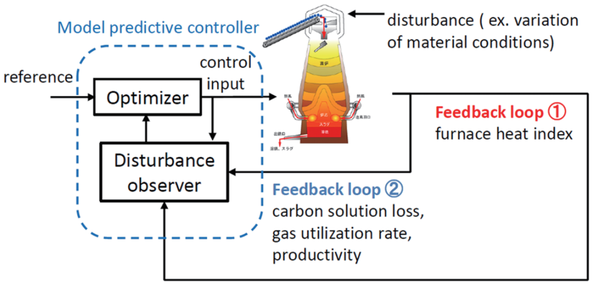


Fig. 7 Outline of the control system in automated blast furnace operation

and the top charging conditions (coke ratio, etc.) by model predictive control. The blast furnace automatic control technology based on model predictive control is described below.

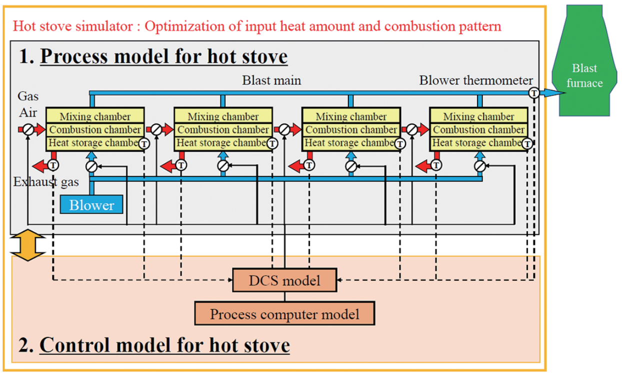
This control technology is based on a multi-input and multi-output state space model that expresses the dynamic characteristics of the blast furnace. A disturbance estimation observer is constructed by considering as input information the leading operation indexes (such as carbon solution loss and gas utilization rate) that change ahead of the furnace heat indexes (such as heat balance above the tuyere level and hot metal temperature) that are to be controlled. The control system is realized in combination with model predictive control to optimize the future prediction of furnace conditions up to 6 to 8 hours ahead (**Fig. 7**). When a disturbance occurs from the changes in the properties of the burden materials and fuels, this logic can quickly detect the disturbance through the change in the leading indexes. Control operation is thus enabled in anticipation of the change in the furnace heat index to be controlled. Model predictive control can be formulated by a mathematical programming method that includes equality or inequality constraints. It can consider various constraint conditions that must be met during blast furnace operation and is a suitable method for blast furnace control. This control system is currently being applied to various blast furnaces at our company, including the North Nippon Works Muroran No. 2 blast furnace.

3.2 Hot stoves and coke ovens

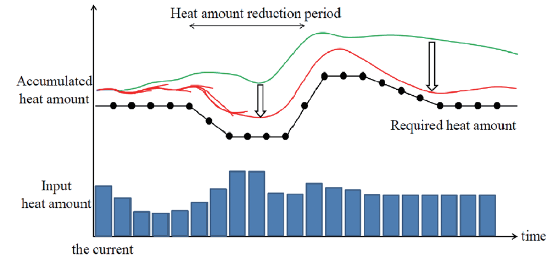
3.2.1 Optimal combustion control of hot stoves

A hot stove is a unit that supplies a large amount of high-temperature hot blast air to a blast furnace and is one of the processes that consume a large amount of energy at the steelworks. The energy-saving operation of hot stoves is required while satisfying the blast requirements (such as blast temperature and volume) of the blast furnace and the equipment requirements (such as minimum temperature control of silica bricks that store heat in the hot stoves). At this time, the hot stove should be viewed as an unsteady process in which heat storage (combustion period) and heat release (blast period) are periodically repeated during heat exchange in the checker chamber. Its time constant is as long as about 3 days. In addition, three or four hot stoves are operated in parallel and switched periodically. This makes it difficult to understand the dynamic behavior of the entire hot stove process. Operators tended to accumulate too much heat in the hot stoves because they could not predict how the state of the hot stoves would change.

Therefore, we developed a hot stove process simulator (cylindrical two-dimensional unsteady distributed parameter heat transfer model) that quantitatively and numerically calculates the dynamic behavior of the hot stoves. We built a hot stove control simulator equipped with a process computer and a distributed control system (DCS). The hot stove control simulator was configured with an optimization algorithm (genetic algorithm (GA)). We optimized the pattern setting of control target values related to combustion control such as combustion gas temperature and combustion gas flow rate. We minimized the energy consumption of the hot stoves or maximized the thermal efficiency of the hot stoves. We achieved optimization model predictive control to sequentially predict and evaluate with high accuracy how the hot stove condition would change when the optimum change pattern (target trajectory) of control target values derived by the optimization algorithm was adopted[19–21] (**Fig. 8**[22]).



a) Outline of process model and control model for hot stove



b) Example of optimization of input heat amount and combustion pattern

Fig. 8 Outline of optimal combustion control for hot stove[22]

3.2.2 Optimal combustion control of coke ovens

Coke ovens are units that produce coke as reductant and fuel to be charged into a blast furnace and is one of the processes that consumes a large amount of energy at the steelworks. Combustion chambers for burning fuel gas and carbonization chambers for charging coal are arranged alternately to form one battery. The combustion heat of the fuel gas in the combustion chambers is used to carbonize the coal in the adjacent carbonization chambers to produce coke. To prevent a sudden temperature drop after the completion of carbonization, coke is pushed out of a group of carbonization chambers at regular intervals. Due to the equipment structure and physical phenomena in the carbonization chambers, the time constant is long and the dynamics associated with changes in operation action standards represent a process that takes several days to reach a steady state. This presents operational and control engineering difficulties. In addition, in recent years, humidity-controlled coal has come to be used to meet the increase in the coke demand with the increase in iron production. Also, it has become difficult to obtain high-quality coal. The coke production has declined due to variations in coke carbonization, and the fuel consumption rate has wors-

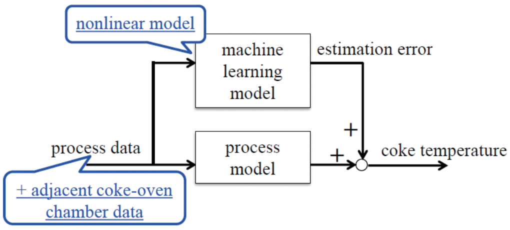


Fig. 9 Outline of gray box model for optimal combustion control for coke oven[23)]

ened.

The accuracy of end of carbonization judgement and oven temperature control in coke oven operation has been decreasing with the use of humidity-controlled coal and the deterioration of coal properties. Operators must estimate the carbonization condition in the coking chambers and adjust the heat input amount accordingly. At this time, to prioritize the prevention of uncarbonized coal that may cause coke sticking, operators tend to input an excessive amount of heat to increase the specific fuel consumption rate or to delay the pushing time to decrease productivity.

Therefore, an operator guidance system was developed based on combustion control. The coke temperature during pushing is taken as a controlled variable that directly indicates the carbonization condition in the coking chamber. This combustion control comprises a coke process model that accurately predicts the coke temperature during pushing from coke oven operation data and an algorithm that derives the optimal manipulated variable by real-time simulation using the coke process model.

The coke process model is a gray box model. The gray box model consists of 1) a linear process model that considers the influencing factors of heat transfer phenomena in the coking chamber and 2) a nonlinear prediction model that estimates and corrects nonlinearity resulting from thermomechanical properties or oven temperature operating point changes through machine learning and error elements considered as disturbances like the effect of heat from the adjacent ovens (**Fig. 9**). The gray box model allows the physical model to ensure macro trend prediction. While the gray model maintains the advantage of the process model that makes it easy to understand the dynamic behavior of coke carbonization, desired prediction accuracy can be achieved.

Optimum combustion control of the coke ovens makes it possible to accurately grasp the carbonization condition in the coking chambers. Even when manual intervention is required, it is possible to set an appropriate heat input amount. Variations in coal carbonization are suppressed. The coke production cost is reduced by stabilization of coke production and reduction in the specific fuel consumption rate. The CO_2 emissions are also reduced.[23)]

3.3 Hot rolling

In the hot rolling process, slabs produced in the steelmaking plant are rolled into the required dimensions. Recent years have seen the increasing use of thin-gauge and high-tensile strength steel sheets to meet the weight reduction and fuel improvement requirements of automobiles and to comply with the reduction of greenhouse gas emissions. When such thin-gauge and high-strength steel sheets are hot rolled, the deformation of rolling rolls increases with the increase in rolling load. The resultant walking and longitudinal bending increase strip threading problems. Improvement in threading stability has thus become a serious challenge. To build in the required mechanical properties, it is necessary to cool the steel strip according to the designed temperature history. Improvement in the temperature control accuracy during cooling has also become an issue.

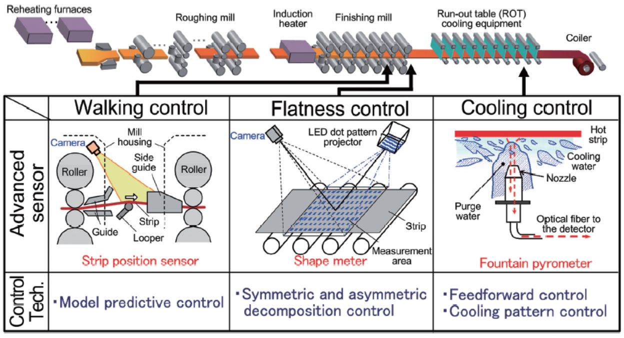


Fig. 10 Development of advanced sensors and control technologies[2)]

To address these challenges in the hot rolling process since 2000, Nippon Steel has actively developed instrumentation and control techniques together, sophisticated process control models, applied advanced control, optimized online operation, and conducted other development activities from the viewpoint of data modeling technology. As examples of integrated development of instrumentation and control, the development of control by use of advanced sensors and the control of cooling history by use of a cooling zone pyrometer is shown in **Fig. 10**.

3.3.1 Control development by use of advanced sensors

To improve threading stability, it is effective to measure the behavior of the steel strip being rolled in real time and to control the rolling mill according to the measured results. We developed interstand strip walking sensors that measure in real time the walking amount, the strip position in the width direction, and between the rolling stands of a hot strip finishing mill. We developed model predictive control to predict the walking amount of the strip just at the rolling mill to be controlled from the measured interstand walking amount and to control the strip to reduce the walking amount. This technique suppressed the rapid walking of the strip at the tail end and reduced the threading problems.[24–26)]

To ensure the required mechanical properties, cooling temperature history control to control the steel strip temperature according to the specified temperature history and uniform cooling to suppress cooling temperature variations in the width direction and rolling direction are required when the hot-rolled strip is cooled on the run-out table.

To improve the accuracy of cooling temperature history control, we developed a fountain pyrometer of the water purge type that can measure the steel strip temperature in real time in the water environment in the cooling zones. Based on the strip temperature measured with the fountain pyrometers in the cooling zones, the cooling water flow rate in the cooling zones was controlled to improve the temperature history control accuracy.[27–29)]

Improving the flatness of the strip before cooling, which is one of the major factors, is effective in suppressing the uneven cooling temperature. We developed an LED dot pattern projection type shape meter. This shape meter does not deteriorate in accuracy and can stably measure the strip flatness when the strip forms a stationary wave. The strip flatness measured with the shape meter is used for the operation of benders and leveling of the rolling mill. This automatic flatness control has proved effective in suppressing the uneven cooling temperature resulting from poor flatness.[30, 31]

The 68th (fiscal 2021) Okochi Memorial Production Prize was awarded for these techniques developed and implemented in hot rolling as “Hot rolling technology of high tensile strength steel sheets using instrumentation and control adapted to harsh environments”.

3.3.2 Precise control of mechanical properties through cooling history control

Cooling history control with cooling zone pyrometers succeeded in accurately measuring the temperature of the steel strip being cooled over the entire length of the cooling zones. It is expected that the obtained information can be used to calculate the evolution of steel strip microstructure in a virtual space. These initiatives are considered effective in creating and manufacturing new and more functional steel sheets.

Conventional radiation pyrometers keep the measurement by removing the water that absorbs and scatters the thermal radiation from the optical path. The fountain pyrometer purges with fountain water and uses the water to transmit the thermal radiation. It can be used as a stable light guide. It is configured to detect wave lengths of thermal radiation with high spectral transmittance in water. While the steel strip is being cooled, a large amount of scattered cooling water droplets absorb and scatter the thermal radiation. The fountain water is sprayed from the nozzle to satisfy such an effective view angle whereby the necessary amount of light can be secured at a distance from the bottom surface of the strip. This made it possible to suppress the effects of thermal radiation absorption and scattering. Formerly, it was only possible to use the strip temperature information from pyrometers installed in one or two non-water cooling zones at the middle of the runout table. Now, it is possible to use the strip temperature information from multiple pyrometers installed in the cooling zones.

As shown in **Fig. 11**, cooling history control precisely controls the rapid cooling stop temperature, intermediate air cooling time, and coiling temperature that are important points for actively forming the microstructure of the steel strip. For rapid cooling stop temperature control, the feedback control was developed by selecting an appropriate cooling zone pyrometer from multiple pyrometers in the cooling zones to follow the rapid cooling stop position that moves according to the rolling speed. In addition, for coiling temperature control, the feedforward control was developed to correct the temperature history in multiple stages using the measured values of the cooling zone pyrometers to prevent the steel strip from being cooled too much to a temperature range where the heat flux becomes unstable.

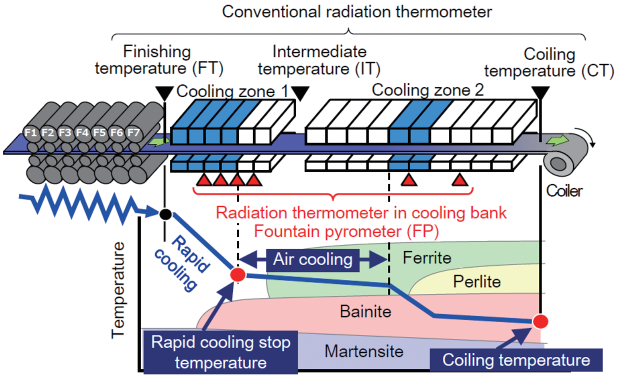


Fig. 11 Outline of cooling history control[26], [*2]

The practical application of cooling history control by using cooling zone pyrometers made it possible for the first time to accurately control the temperature history of steel strip. Also, the coiling temperature accuracy of high tensile strength steel strip improved to a level comparable to that of regular steel strip.[26–29, 32, 33]

3.4 Process control in 2020s and beyond

As its digital transformation (DX) strategy, Nippon Steel is committed to reforming its business and production processes to “strengthen its business competitiveness by making full use of data and digital technology”. With our “strength in connecting” and “strength in maneuvering” to change data into values, we also aim to increase our decision making speed and improve our problem solving capacity through the three values and effects named “location-free”, “data-driven”, and “empowerment”.

These three values and effects are combined to achieve the DX strategy. One of these values is “data-driven”, which means that new business and production processes will be created based on data. In the production processes, we will use digital technology to expand the formalization and standardization of our technology, including our implicit knowledge of expertise. We will also improve labor productivity through automation and predictive detection and achieve production stability and further quality improvement through the advancement of our production technology. Additionally, we will establish a foundation for remote operation management of our overseas facilities.[34]

Process control as a production process is also positioned in this strategy. Cyber-physical systems (CPS) are constructed as digital twins by making full use of the latest computer technology (hardware and software), simulation technology, analysis and knowledge technology such as machine learning, control technology, and systemization technology. The state and dynamic behavior of real equipment can be shared with high resolution in a digital space by not only control engineers and system engineers, but also equipment operators and equipment maintenance personnel.

In addition, we have implemented wireless transmission and monitoring technology (NS-IoT) for the values measured with sensors installed in actual equipment to further improve the efficiency of equipment inspection and maintenance. Also, data storage and analysis environments are implemented in in-house clouds (NS-DIG™[*1], NS-Lib, and AIRON-EDGE™[*1]).[3–5] In other words, environments are established where in-house engineers can grasp, monitor, and analyze the state of real equipment anytime and anywhere.

4. Conclusions

The ideal form of a digital twin in steel process control is not necessarily clearly defined or recognized at the current stage. Simply integrating real-time data (process data I/O), physical models, analysis and knowledge-based algorithms such as machine learning, control systems, visualization interfaces, computers, and databases in the digital space alone does not meet the practical and essential requirements for effective and useful technological configurations or production systems on the manufacturing floor as long as it remains limited to tool integration as a cyber-physical system (CPS).

In a steelworks operating continuously 24/7 and 365 days a year, equipment operators must operate the equipment accurately and maintenance personnel must maintain the equipment appropriately.

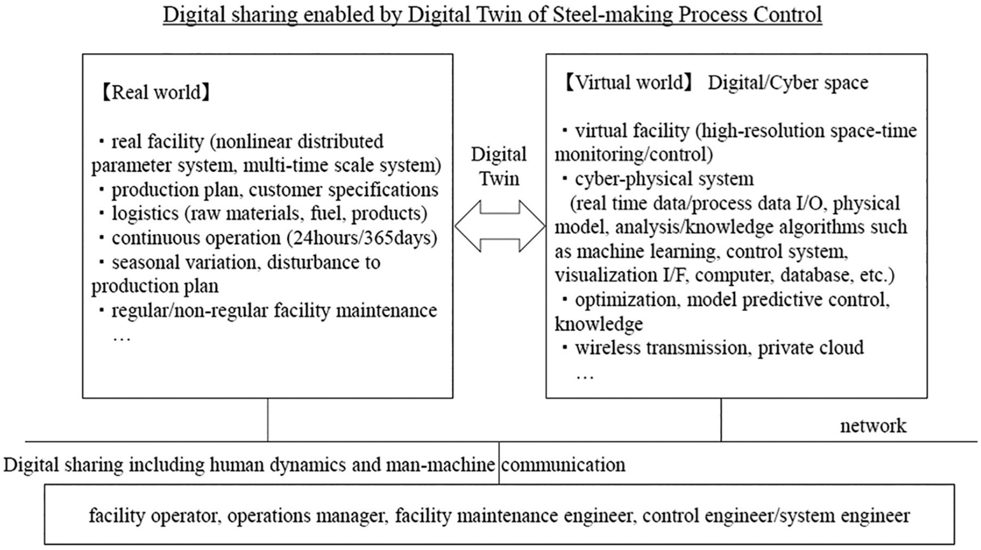


Fig. 12 Digital twin of steel-making process control in Nippon Steel

They must keep in mind the discontinuous processes such as seasonal variations, unexpected production plan disturbances, and regular and non-regular equipment maintenance in order to strictly adhere to production plans and customer specifications in various situations that change every moment.

In addition to the perspectives of automation, optimization, availability, and real-time performance, it is important for equipment operators and maintenance personnel (and all employees who support the steel plant), that is, humans and digital twins, to interactively work together to maintain and improve the production site.

The steelmaking processes such as blast furnaces, hot stoves, coke ovens, and hot rolling mills are essentially nonlinear distributed parameter systems. The dynamics of the underlying physical phenomena and their control system configurations vary over a multi-time scale from the ms order to over 1 to 2 weeks. The dynamics of the people who operate these facilities are that they take turns every eight hours. The state of the actual facilities must be accurately shared during continuous operation. With the implementation of digital twins, we can realize control that predicts actual (future) operation in steel process control. This prediction has been considered difficult to achieve due to long dynamics that exceed human dynamics. Digital twins can serve as advisors for human operators to enable the selection of optimal control outputs and sequences during parallel operation and actual operation.

One of the ideal forms of digital twins in the steel process is a digital space that includes human dynamics and man-machine communication, where the state of actual equipment is correctly and efficiently shared and accumulated (=knowledge) among operation technology, facility technology, and process control technology. A system that develops technology based on this sharing and accumulation is considered a necessary requirement.

In this paper, we have reviewed the evolution of process control technology and recent development examples at Nippon Steel. We have reaffirmed that the concept of digital twin is not a sudden emergence but rather an extension of our previous technological advancements. Its universal perspective and essential positioning lie in the digital sharing of operation, equipment, and process control technologies, including human dynamics and man-machine communication. It can be understood that our digital twins in process control are constructed within that framework (**Fig. 12**). The term "digital twin" may become obsolete over time or may be replaced by another term, but its fundamental essence remains unchanged.

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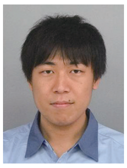

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