Measurement technology under special conditions

Advanced Measurement Technology Supporting KOBELCO's Manufacturing

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Abstract

Measurement technology is the cornerstone of science and manufacturing prowess. At Kobe Steel, a company that supplies a wide range of critical components supporting the world's infrastructure, measurement technology has evolved through continuous challenges in ensuring stable product supply and quality enhancement. It has become an essential foundational technology that supports the creation of safe and sustainable products, contributing to the company's unique development. In the future, the company will continue to provide stable supplies of essential components and products that underpin society, meeting the ever-increasing demands for quality, functionality, and performance. This paper also discusses the outlook for measurement technology as Kobe Steel strives to achieve a sustainable society through challenges such as carbon neutrality and manufacturing transformation.

Introduction

Measurement technology has played a fundamental role in the advancement of science, technology, and industry. Such advancements in turn create new needs in measurement technology.

At Kobe Steel, a company that supplies a wide range of critical components supporting the world's infrastructure, measurement technology has evolved through continuous challenges in ensuring a stable product supply and improved quality. It has become an essential foundational technology that supports the creation of safe, secure, sustainable products. In addition to nondestructive testing (NDT) and process measurement technologies, we have also developed unique measurement technologies for special applications and environmental conditions where all-purpose products do not exist or are not fit for purpose. Examples include distance measurement technology for use in dusty environments using microwaves and ultra-high frequency (UHF);[1] visualization/transmission technology using cosmic rays inside large structures; and remote real-time temperature monitoring sensors for processes over 1300℃.[2]

NDT ensures the quality of components such as valve springs for vehicle engines and crankshafts for marine engines, which require strict surface and internal quality to withstand long-term, cyclic loading. Productivity improvement and product creation require process measurement technologies suitable for use in adverse environments with high temperatures, dust, and vibration. These technologies are an essential aspect of Kobe Steel's unique solutions for reducing CO_2 emissions through high-volume charging of direct reduced iron (HBI, hot briquetted iron) into blast furnaces. Kobe Steel's precision measurement technologies ensure the safety and security of our products and our customers' products and manufacturing processes. For instance, our precision 3D measurement technology for complex machined parts and cast and forged parts achieves excellent finished product specifications. A further example is our surface profile measurement technology[3] for evaluating silicon wafer flatness, which requires accuracy at the atomic (sub-nanometer) level.

Additionally, as advancements in AI and the digital transformation (DX) of society advance at an accelerating pace, measurement technology will play an increasingly important role in using data to bridge the gap between the physical (real) and cyber (virtual) space. Automation and DX in manufacturing are essential considering the projected shrinkage of the labor force, and continuous improvement in measurement technology is in turn essential for advancing process automation.

For these reasons, Kobe Steel has long pursued R&D and continuous improvement in the field of measurement technology under special conditions. This paper describes our innovations in this area.

1. NDT technology

In the 1970s, Kobe Steel established the Technical Development Group to fortify and demonstrate the company's development and technological capabilities. The group that is now Instrumentation & Digitization Technology Research Section was established under this organization to develop high-performance sensors for the advancement of industrial science. **Fig. 1** shows an optical sensor for defect detection that was developed over 50 years ago, in 1972. Our company was ahead of its time in developing optical sensor-based inspection

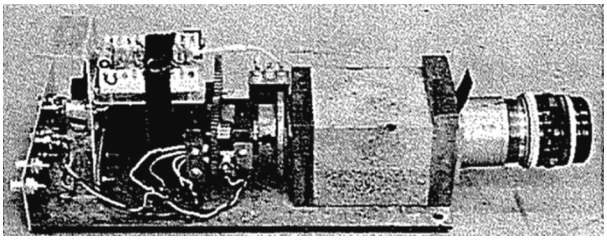


Fig. 1 Optical sensor for surface defect detection

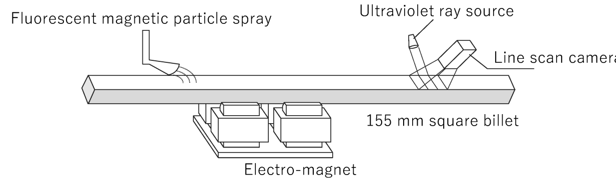


Fig. 2 Overview of automatic magnetic particle inspection equipment

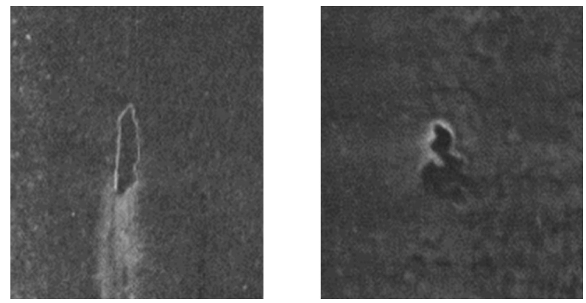


Fig. 3 Example of a hard-to-distinguish defect (left) and magnetic particle noise (right)

technology despite the scarcity and expense of imaging devices compared with today. We have developed a variety of technologies since then for areas including electromagnetic wave measurement, image processing, laser and ultrasonic wave measurement, and NDT methods such as magnetic particle inspection (MPI) and eddy current and ultrasonic testing.

This section details the application of our NDT technology to steel wire rod and bar products.

1.1 Inspection technology for quality assurance of steel wire rod and bar

Our steel wire rod and bar products, known as Kobe Wire Rod, are some of the most widely used products of their kind.

Kobe Steel produces cold heading quality wire rod and bearing steel wire rod, which are primarily used in vehicle parts that require high reliability. The quality level required of these products tends to grow more stringent year over year. Early detection of surface and internal defects and implementation of related countermeasures are particularly critical to the quality assurance of finished rolled steel products. However, inspection early in the process is challenging. Steel temperatures approach 1000℃ during hot rolling, and product travels at several dozen meters per second. Although we at Kobe Steel have developed solutions for inspecting the hot, high-speed wire rod rolling process, we guarantee excellent final specifications and quality through automatic MPI of steel billets, which are upstream semi-finished goods. This section presents our automatic MPI equipment.

Fig. 2 depicts an overview of our automatic MPI equipment, which operates as follows:

1. Fluorescent magnetic powder is applied to a ferromagnetic object to be inspected.
2. The object is magnetized by a magnetic field.
3. Surface defects on the object generate a flux leakage field and attract the fluorescent magnetic powder.
4. The surface is illuminated with ultraviolet (UV) light, causing the fluorescent magnetic powder at the defect to emit light.
5. An inspector or camera detects the defect via visual inspection of the area emitting light.

Kobe Steel has been developing automatic MPI equipment since the 1970s. As indicated in **Fig. 3**, our advanced image analysis technology is capable of discerning magnetic particle noise, which is not a defect. This advancement improves the detection of complex and irregular defects and minimizes erroneous readings and false positives.

Our system's image processing technology is also more robust than previous solutions. Specifically, it responds dynamically to factors that can cause variation in inspection results, such as deterioration of the UV light source over time and fluctuations in magnetic particle concentration. Additionally, high inspection accuracy is achieved by skillfully incorporating the latest technological advances from around the world, such as sensors with increased sensitivity and functionality, high-output light sources, and computers with powerful processors.[4)]

Recent technological progress in software and AI has been remarkable. Kobe Steel leverages AI decision-making to enhance inspection technology and thus achieve ever-higher product quality.[5)]

2. Process measurement technology

Kobe Steel first deployed its process measurement technology within the Steel Business Division, later applying the resulting innovations to the manufacture of non-ferrous metals such as aluminum, copper, and titanium. The company then focused on developing advanced products in the Machinery Business Division and bringing the

KOBELCO Group's measurement and inspection equipment to market.[6)]

Unlike measurement in an ideal environment such as a laboratory, measurement in a manufacturing process is subject to various inherent interferences and restrictions. For example, steel processing generally precludes the use of off-the-shelf all-purpose sensors because of installation constraints and temperatures exceeding 1000℃. Kobe Steel has overcome these parameters by creating technologies that are serviceable, accurate, reliable, and environmentally robust. Methods used include heat-resistant design, cooling equipment to protect sensors from thermal radiation, and air purging functionality to protect sensors and preserve field of view and range in a dusty, humid environment. Many of our proprietary measurement technology under special conditions are the first of their kind, which is an element of our competitive edge.

Some of our process innovations are based on information gained over the course of developing new measurement technologies. The following section introduces process measurement technology supporting blast furnace CO_2 reduction for contributing to a green society.

2.1 Continuous hot metal temperature measurement technology supporting high-volume charging of HBI in blast furnaces

Kobe Steel's blast furnaces operate at a remarkably high performance level because of numerous proprietary measurement technologies[7)] for purposes such as center coke charging,[8)] the use of pellets manufactured in house, and temperature distribution measurement via an in-furnace descending probe.[9)] We have recently developed low-CO_2 operating technology by increasing the ratio of HBI charged into blast furnaces. These efforts support a green society and our 2030 CO_2 reduction target (30 - 40% reduction from 2013). We conducted a month-long proof-of-concept at Kakogawa Works' No.3 blast furnace in October 2020. This demonstration revealed that the reducing agent ratio, which governs the CO_2 emissions of a blast furnace, can be reduced from 518 kg/t to 415 kg/t (20% reduction in CO_2 emissions). We also achieved the world's lowest coke rate (239 kg/t of hot metal).

High-volume charging of HBI in blast furnaces requires a combination of the KOBELCO Group's key technologies. These include HBI manufacturing via our MIDREX® Process alongside our steel operation's unique blast furnace operating technology. Under these umbrellas are Kobe Steel's technologies for HBI blast furnace charging, AI-based furnace operation, and pelletizing.

Our AI-based furnace operation technology predicts hot metal temperature five hours in advance to forecast sudden changes in furnace temperature and react appropriately. The key to accurate prediction in this technology is the continuous measurement of hot metal temperature. **Fig. 4** depicts our method of achieving this. A high-speed camera captures imaging of the mixed-phase jet of hot metal and molten slag (hereinafter, tapping stream) that is discharged from the blast furnace tap hole at several meters per second. The system uses pyrometry to continuously measure the temperature of the hot metal. The difference in emissivity between the slag and the hot molten metal gives the tapping stream a marbled appearance, as shown in the thermal image in Fig. 4. Image analysis extracts the brighter areas to identity and measure the temperature of the hot molten iron.

One source of temperature measurement interference is the reflection of smoke at the blast furnace tap hole. Smoke causes the hot metal to appear artificially darker on the thermal image, creating a temperature measurement error. However, image processing compensates the readout by analyzing the rate of fluctuation in the brightness of the hot metal, which increases as the smoke pattern changes.

Furthermore, thermal radiation from hot metal and other hot materials, airborne debris, and dust create an adverse measuring environment. Malfunctions can delay the retrieval of thermal images from all-purpose cameras by several days. Thermal radiation causes overtemperature of the camera, and dust and other particles adhere to and damage the optics. Kobe Steel has added a unique camera cooling function and an air purge function to blow away debris and dust.

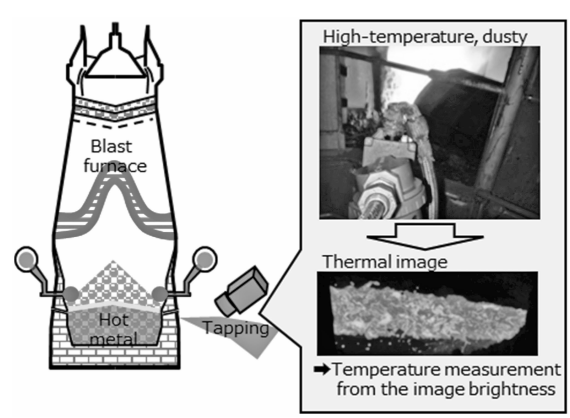


Fig. 4 Continuous measurement of hot metal temperature in blast furnace

These innovations have resulted in a system that produces high-quality thermal images and stable temperature measurement without maintenance for more than six months. **Fig. 5** shows that the results from pyrometry correlate well with thermocouple readings, for a temperature measurement accuracy within 10℃.

3. Inspection and measurement technologies supporting transformation of methods and processes

The labor shortage caused by the shrinking workforce has affected the manufacturing industry more than other industries. This critical development necessitates automation in manufacturing, particularly for the skilled tasks of inspection and measurement, from a perspective of business security. Kobe Steel has been working to automate such tasks to improve productivity, standardize results among workers, and improve safety. The following section introduces examples of our developments in automation, including ultrasonic testing of crankshafts, spark testing, and dimensional measurement of hot forgings.

3.1 Automatic ultrasonic testing of crankshafts

Kobe Steel produces two types of crankshafts: built-up type crankshafts, which are made by shrink-fitting an eccentric element called a throw onto a shaft element called a journal, and solid type crankshafts, which are forged from a round bar. Crankshafts must generally withstand long-term cyclic loads. The recent trend toward more powerful and compact engines necessitates strict quality control of the surface and interior of the crankpins and fillets of solid-type crankshafts. Crankshaft inspection has historically been a manual process. Proper inspection of all surfaces is time consuming as well as physically and mentally demanding. This led us to develop a self-propelled automatic ultrasonic testing device that scans the entire surface. This fast and consistent inspection technology records accurate inspection results to ensure the high reliability required of crankshafts (**Fig. 6**).[10]

The detection area of straight beam testing is limited to a relatively small point, necessitating certain operational considerations and thereby demonstrating the value of our innovation. For example, scanning in straight beam testing must

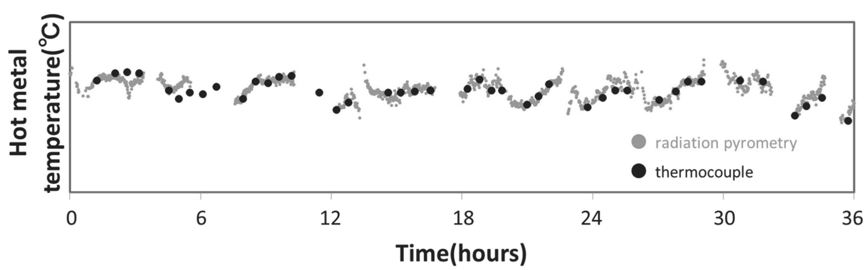


Fig. 5 Continuous temperature measurement results in actual blast furnace

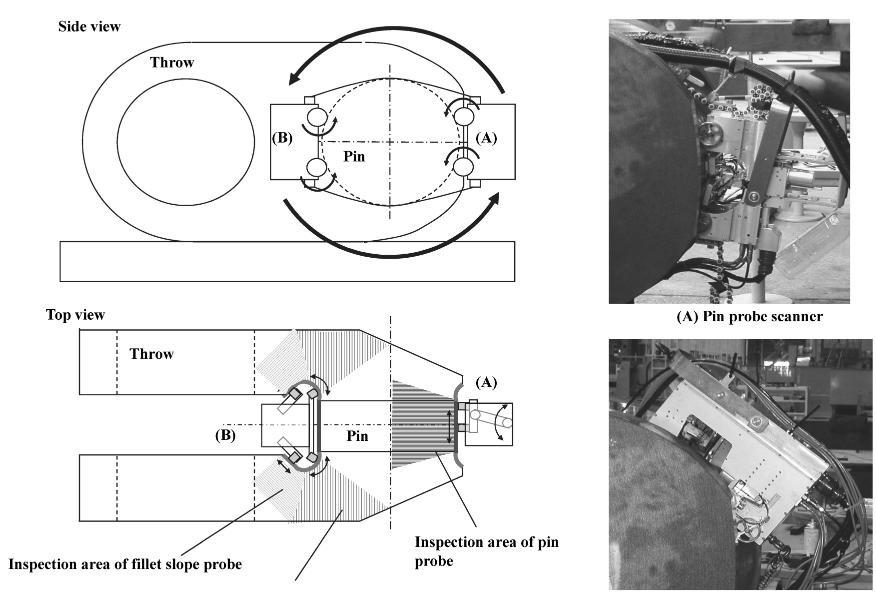


Fig. 6 Automatic ultrasonic testing system being used on built-up type crankshaft throw[10]

occur at a slow rate, and the limited accessibility of the probe makes it difficult to inspect areas of the fillet with small curvatures. To ease the demand placed on inspectors, we developed a unique ultrasonic probe and associated scanning mechanism that employs the phased-array method. Even if the inspection surface is curved, it is possible to detect a reflective source with a 0.5 mm diameter flat-bottom hole from the surface via an electronic method called sector scanning. **Fig. 7** shows a conceptual diagram.[11)]

3.2 Spark testing

AI image recognition has evolved rapidly in recent years. We have capitalized on this in the development of AI-based spark testing technology in our efforts to automate highly technical inspection processes. Different types and compositions of steel produce different spark characteristics when pressed against a grinder. Spark testing involves the evaluation of grinding sparks by a trained person to determine the type of steel. As a test requiring visual evaluation by an expert, this long-used manner of determining steel type was in great need of automation. Previous efforts have estimated carbon content by using a camera to capture images of sparks alongside rule-based image processing (e.g., pattern matching) to detect forks and lines in the images. However, rule-based image processing has limitations when it comes to identifying the types of various alloy steels, such as those containing the alloying elements S, Cr, Mo, and Ni. To address this issue, Kobe Steel developed AI image recognition technology that both estimates the carbon content of steel[12)] and determines the type of alloy steel[13)] to digitally transform and automate skilled techniques. **Fig. 8** shows a flow diagram of the steel identification process. A convolutional neural network uses the spark image to first estimate carbon content and then identify the type of alloy steel, thereby achieving a highly accurate determination of steel type.

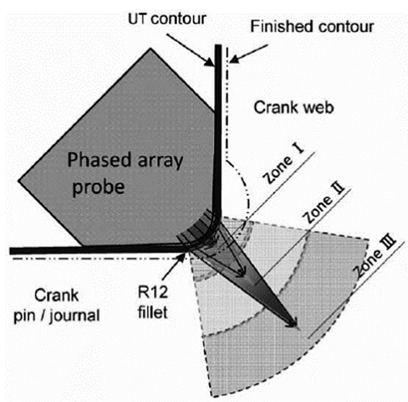


Fig. 7 Focus pattern diagram of phased array[11)]

3.3 Dimensional measurement of hot forgings

Measurement technology also contributes to safety and countermeasure implementation in extremely hot environments. Kobe Steel's large forgings, such as shell rings (4 to 6 m in diameter) used in oil refinery pressure vessels (reactors), are forged into the specified shape by an 8,000-ton press at our forging plant (**Fig. 9** (1)) and then machined into the shape of the final product. The conventional

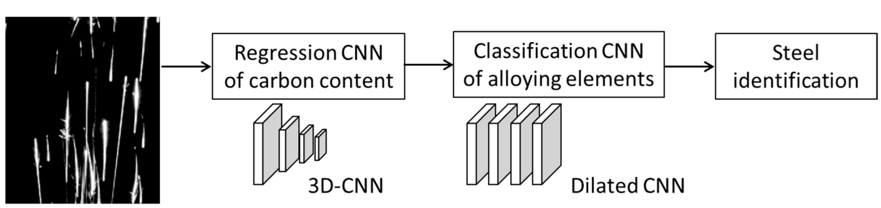
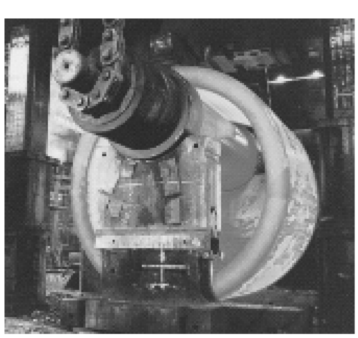
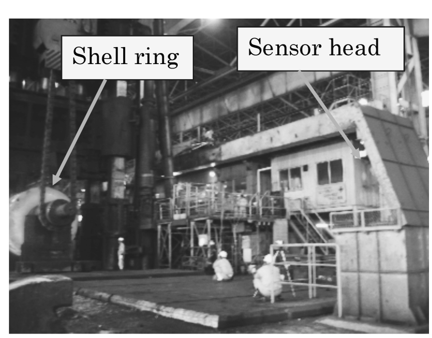


Fig. 8 Flow diagram of steel identification from spark images[13)]


(1) shell ring forging



(2) place of sensor head

Fig. 9 Shell ring diameter measurement equipment[14)] method of checking shape during pressing involves accessing the hot forged workpiece (500 to 900℃) from under the press and measuring its dimensions using calipers. Extreme heat makes this process very physically demanding, and there is great variability in measurement from person to person. This led us to establish a method for measuring shell ring diameter safely, remotely, quickly, and accurately via stereoscopic image measuring (Fig. 9 (2)).[14] We are also working on technology for automatic on-demand measurement of the dimensions of other hot forged products.[15]

Conclusions

This paper has introduced Kobe Steel's technologies in NDT and process measurement as well as the company's inspection and measurement technologies that support automation. This paper also describes how our measurement technology under special conditions serve as core technologies that support safe and reliable products and sustainable manufacturing.

Major changes in manufacturing toward the advancement of a sustainable society are anticipated, and at an accelerating pace. The steel industry, for example, is expected to reduce CO_2 emissions generated by the production process through efforts such as switching to electric furnaces. As part of this endeavor, we will help transform manufacturing through top-level integration of advanced measurement technologies in areas including intelligence, fundamental scientific theory of new processes, and operations.

Additionally, both the recent trend toward DX and the projected decline in labor force numbers are creating an ever-increasing need for automation. Kobe Steel's manufacturing operations require precise control in adverse environments, leading us to make maximum use of inspection and measurement technologies. Dramatic advances in robotics and AI in recent years have expanded the possibilities for capturing and exploiting operational knowledge previously thought to be attainable only by humans. At the same time, as processes continue to change, the adaptability and creativity unique to humankind are gaining importance. Wisdom and ingenuity are particularly valued at Kobe Steel, a provider of a wide range of key components that support the world's infrastructure. These characteristics will enable us to meet the growing demand for high-added value by combining human knowledge with the latest inspection and measurement technologies.

We will advance measurement technology to provide a stable supply of key components and products that support the foundations of society. We will meet the ever-increasing demands for quality, functionality, and performance. And we will taking on the challenge of realizing carbon neutrality and a sustainable society.

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