Metal working process technology

Manufacturing Technology Delivering Safety to Society. Metal Processing Technology

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Abstract

The KOBELCO Group's metal materials and industrial machinery have played a significant role in supporting people's safe and secure lives. The manufacturing process of metal materials typically involves hot processes such as "rolling" and "forging." These processes shape the materials and enhance their performance and quality. Additionally, high-precision shapes are achieved through "forming" and "machining" processes. This paper explains the core processing technologies that are indispensable in KOBELCO Group's manufacturing, including "rolling," "forging," "forming," and "machining." It provides an overview of these core technologies, complemented by descriptions of past technical developments and practical examples. Furthermore, it discusses new initiatives that contribute to the innovation of manufacturing, which is essential for realizing a safer and more secure society of the future.

Introduction

The KOBELCO Group's metal materials and industrial machinery are used in vehicles, aircraft, and other transportation equipment; high-rise buildings; compressors; and societal and industrial infrastructure. The group's products support safety and security everywhere they are used. All industrial machinery, advanced materials, and products made by the KOBELCO Group inherently require exceptional quality and a guaranteed customer-facing supply chain. Furthermore, demands related to material strength, size, and geometric complexity have advanced considerably in recent years. We employ continuous improvement in our manufacturing operations to meet these requirements.

Metal materials go through multiple processes in manufacturing. First, raw materials are obtained by methods such as melting, refining, and casting. The resulting materials then go through hot working processes such as rolling, extrusion, and forging as primary processing. Secondary processing via forming processes such as pressing, drawing, or cold forging is followed by machining to create finished products. It is often the case that not only the shape, but also the performance and quality of the product, are governed by hot working processes such as rolling and forging in this secondary processing stage. The final form of the product is then achieved through precision forming and machining processes. Kobe Steel has refined its processing technologies to improve the quality, functionality, and production stability of materials with growing demand such as steel, aluminum, copper, and titanium. However, increased functionality generally entails increased manufacturing complexity. As such, Kobe Steel develops proprietary manufacturing technologies for difficult-to-process materials. These technologies have become solutions in our customers' manufacturing operations, improving the usability of the materials they produce. We collaborate with our customers and capitalize on our bird's-eye view of manufacturing to develop technologies that overcome society's many challenges. This paper describes the KOBELCO Group's core technology of metal working process technology (rolling, forging, forming, and machining) which are indispensable in manufacturing, and covers examples of each. Also described are new initiatives that contribute to innovation in manufacturing, which is essential for a safer and more secure society of the future.

1. Rolling

1.1 Rolling technologies

Many Kobe Steel products made of metal materials, particularly those made of steel, go through a rolling process. Rolling is a process that forms materials into shapes such as plate and sheet, wire rod, steel bar, and structural steel. Material properties including shape, surface characteristics, and dimensions such as plate thickness are controlled as part of the rolling processes. Kobe Steel produces steel, aluminum, copper, and titanium plate and wire rod. With the introduction of new societal challenges such as carbon neutrality, we must improve our rolling technology to support the high-throughput, high-yield production of a wide range of products. This is why we have been advancing rolling technology through studies related to phenomena occurring on actual operations and rolling simulations that reproduce complex rolling phenomena.

This section introduces examples of Kobe Steel's rolling technologies that support the quality and production of our rolled products as well as future developments in rolling technology.

1.2 Rolling technologies supporting production

Challenges encountered in rolling technology development include controlling material properties and controlling plate thickness and surface properties. For thickness control when hot rolling aluminum, we used the finite element method (FEM) and experimental studies to develop a model that calculates rolling temperature and rolling load. This model improves yields by ensuring that the initial setup of the rolling mill is more precisely tuned for the desired final plate thickness.[1] For shape control, we used a simulation model that accounts for elastic, thermal, and material deformation in rolling to develop a software solution and a mechanical solution. Our Automatic Flatness Control System (AFC)[2] on the software side and multi-roll mill (KST/KT mill)[3] on the mechanical side, technologies we have cultivated as a rolling mill manufacturer, optimize operating conditions in the industry. For surface quality control, we began with root cause analysis, as the cause of surface defects is not always clear. Specifically, we conducted experimental studies to clarify the mechanisms behind scale and rolling deformation. We also developed three-dimensional rigid-plastic FEM analysis technology to derive an incidence index that predicts the likelihood of wrinkle defect development in wire rod rolling, thereby reducing the defect rate.[4] For grain refinement, we have developed rolling process-metallurgy technology for the steel plate rolling process. Our technology provides the accurate reduction in the proper temperature range to grains refinement while ensuring steel plate flatness.[5), 6)]

1.3 Development of rolling technology for future society

We are developing rolling technologies to support new challenges including carbon neutrality and new levels of performance and functionality.

One such development is rolling transfer technology. Microscopic surface roughness can support surface functions such as water repellency, heat transfer, and optical properties, as exemplified in biomimetic materials. Kobe Steel developed rolling transfer technology that transfers microscopic irregularities to the surface of a sheet. This technology capitalizes on the advantages of rolling, such as large surface area, high throughput, and low cost. We used this technology to develop HEET™ (**Fig. 1**), our high-heat-transfer titanium sheet. This sheet is being used in a demonstration plant in Japan for ocean thermal energy conversion (OTEC), which is attracting attention as a form of renewable energy.[7] In addition to OTEC applications, this product is also being considered for use in heat exchangers that use seawater for cooling and heating in chemical plants, power generation facilities, and large transport ships.

Another development in our rolling technology is the flexible tailored blank rolling. Reducing vehicle weight necessitates different properties (strength and ductility) within different components. We demonstrated that it is possible to control mechanical properties in the longitudinal direction by cold-rolling and joining three types of aluminum and controlling the tension during rolling. As a result, we were able to control the cladding ratio (proportion of each layer's plate thickness) (**Fig. 2**).[8] This technology will lead to developments in and broader use of composite materials.

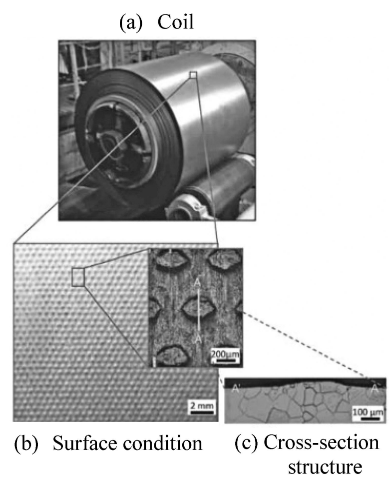


Fig. 1 High-heat-transfer titanium sheet, HEET™

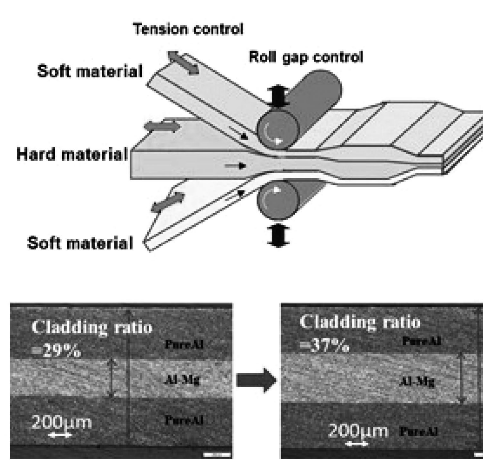


Fig. 2 Control of cladding ratio of aluminum-clad material

2. Forging

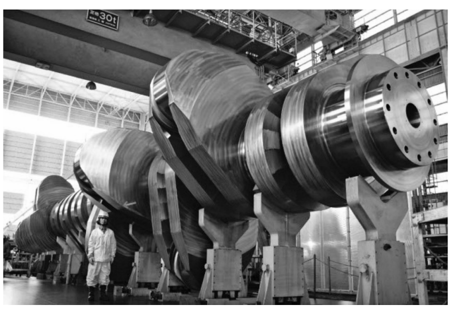
2.1 Forging technologies

Fig. 3 shows examples of the typical products Kobe Steel manufacture. We hold the top global market share for marine crankshafts[9] and the top market share in Japan for aluminum forged parts for automobile suspensions.[10] Furthermore, we have been supplying titanium alloy aircraft parts[11] for over 30 years. Kobe Steel uses Japan's largest presses to forge critical parts for transportation equipment such as ships, vehicles, and aircraft.

Forging is the process of deforming a material using a die to achieve the desired shape. This process is key to altering the microstructure created by casting to establish uniformity of the microstructure and shape the product. Kobe Steel uses hot forging process, in which a material is heated to a specified temperature and then forged. Hot forging process affects the material yield and the cost of subsequent processing. Therefore, the geometries of the material and die must be in line with the total delivered cost.

Designing a forging process requires prediction of the forging load and the forging shape, including underfills and defects. Recent advancements in computer processing power have made numerical simulation techniques more common. Because Kobe Steel handles a broad spectrum of shapes and materials, the focus has been to improve the prediction accuracy of numerical simulation technique and to implement process design methodologies based on this technology. At Kobe Steel, we have also spent recent years applying our numerical simulation technique to our customers' processes to respond to their trust in and expectations of our manufacturing capabilities.

This section introduces a case study of in-house process design for increased yield using numerical simulation technique.



(a) Built-up type crankshaft for large ships[9]

(b) Aluminum forged parts for automobile suspension[10]

(c) Titanium alloy aircraft landing gear parts[11]

Fig. 3 Representative products manufactured by Kobe Steel

2.2 Forging process design technology using numerical simulation technique [12), 13)]

Crankshafts used in marine engines, generators, etc. can be produced as solid type or built-up type crankshafts.

The shipping industry is striving to improve fuel efficiency by making engines more compact. The impetus to do so stems from increasingly stringent environmental regulations, the need to improve energy efficiency during operation, and the trend toward eco-ships. These demands necessitate lightweight components with high output and high strength.

Kobe Steel's solid type crankshafts constitute the solution here by capitalizing on our ultra-clean steel, our joint casting/forging/machining process, and the world's only near-net-shape RR forging operation.

Kobe Steel will collaborate with engine manufacturers to make ships lighter and more compact, thereby supporting our customers' development efforts.

Fig. 4 shows the deformation behavior that occurs in the RR forging method. In this method, a wedge converts the downward force of the press into a compressive force along the axis of the material in the die. Compression of the material in the axial direction results in barreling, creating a preliminary deformed part called the arm. Pressure is then introduced in the vertical direction to offset

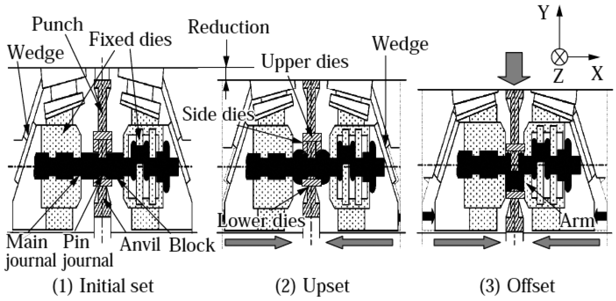


Fig. 4 Deformation behavior in RR forging method

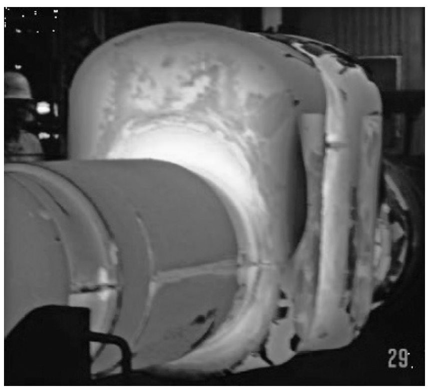


Fig. 5 Actual forging shape

the pin while axial compression remains applied, thus forging the pin, arm, and journal as a single unit. The RR forging method is characterized by extremely complex material flow.

Following is a description of a case study in which we used numerical simulation for material and die shape design to improve the yield from RR forging. For details, see references 12) and 13). **Fig. 5** shows a prototype produced by reducing the amount of material and optimizing the die shape. The results demonstrate that numerical simulation can reduce material consumption and optimize process design.

3. Sheet metal forming

3.1 Sheet metal forming technology

The main products in Kobe Steel's materials business, steel and aluminum sheet, are deeply seated in the automotive industry. We have achieved high functionality in our advanced automobile body parts through technological innovation. We have also developed indispensable forming technology for these materials. Our application and advancement of high-function materials have played a key role in improving safety and reducing weight in vehicles. Formed sheet metal products require formability, dimensional accuracy, and specific surface properties. They must also be economical, meet quality requirements, and lend themselves to mass production. Therefore, it is important to understand the behavior of sheet metal, changes in material properties, and deformation of tools during the forming process. Understanding these concepts enables optimal process design based on the quality parameters required by the customer.

This section introduces Kobe Steel's technological developments in sheet metal forming, which have supported vehicle safety and weight reduction by expanding the application range of high-function materials and improving the quality of sheet metal products.

3.2 Kobe Steel's technological developments in sheet metal forming

Kobe Steel proposes the use of ultra-high-tensile strength steel sheet for body frame components and aluminum sheet for exterior panels, which takes advantage of each material's characteristics.[14] Cracking and wrinkling during forming are quality issues common to both materials. Additional challenges applicable to ultra-high-tensile strength steel include dimensional accuracy and tool durability; challenges associated with aluminum sheet are related to surface quality and design.[15] We develop forming and evaluation technologies that safeguard quality in all components. Following are recent examples of Kobe Steel's proposals for improving dimensional accuracy and formability prediction accuracy.

3.2.1 Improving formability prediction accuracy

CAE (computer-aided engineering) is seeing increased application in the quick resolution of quality challenges in automotive parts. Formability evaluation that incorporates the forming limit curve into the CAE model is one such example. Kobe Steel is working to refine the forming limit curve to reduce quality defects resulting from the actual machine. Two types of cracks occur in stretch flanging.[16] Additionally, the forming limit at the edge of the sheet metal, where a strain gradient occurs in the surface, depends on the mechanical properties of the material, the degree of the strain gradient, and the punching conditions.[17] Therefore, the forming limit at the edge of the material must be determined for each type of crack via a large database that accounts for a variety of processing conditions. Hence, we aim to improve formability prediction accuracy by deriving the forming limit curve for each type of crack.[18] **Fig. 6** contains an example of a forming limit curve we derived.

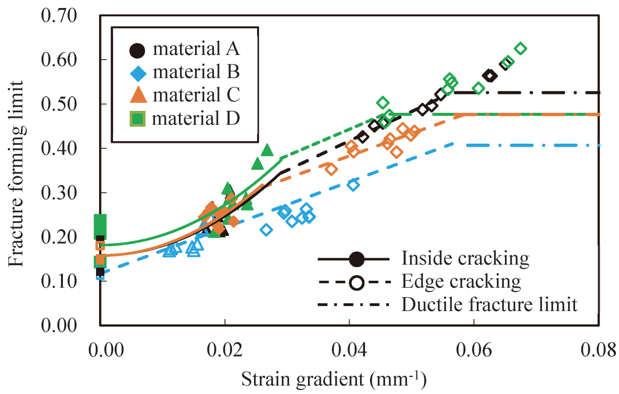


Fig. 6 Fracture forming limit in stretch flanging by fracture type

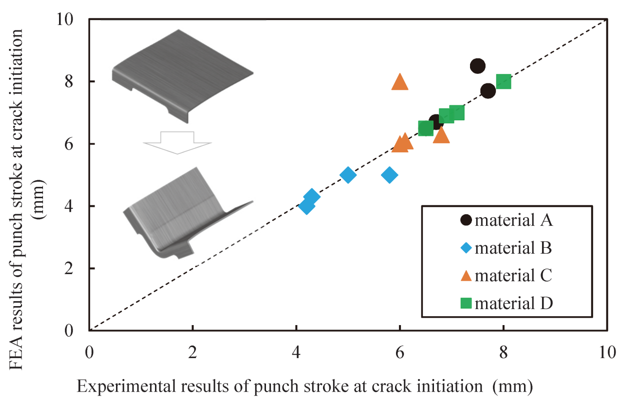


Fig. 7 Comparison of FEA and experimental punch stroke at crack initiation

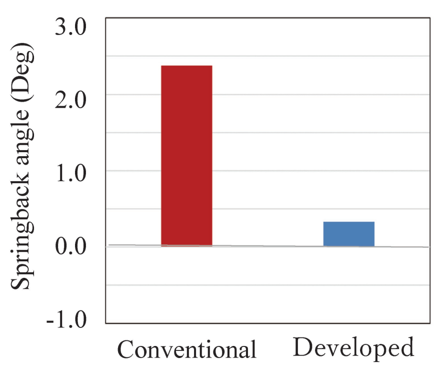


Fig. 9 Comparison of springback angle by conventional process and by developed process

Fig. 7 shows its use in predicting crack formation at the edge of the stretch-flanged sheet, including a comparison with experimental results. The graph confirms the high accuracy of the predicted values.

3.2.2 Countermeasures for improving dimensional accuracy

Dimensional accuracy is lost to internal stresses caused by the complex hysteresis from forming followed by elastic recovery during release from the die. Because the degree of elastic recovery increases in proportion to the yield point, dimensional inaccuracy is a serious problem that limits the usability of high-strength materials.[19] Therefore, controlling or offsetting stress in the sheet metal is a countermeasure against dimensional inaccuracy. Kobe Steel is working on developments to control stress in the forming process with the end goal of improving dimensional accuracy.[20] **Fig. 8** shows an example of a bent part for which dimensional accuracy (camber springback) was improved.[21] The figure shows the distribution of longitudinal stress within the formed sheet, which is the driving force behind deformation after release from the die. Here, we identified tensile stress in the top surface of the curved section and compressive stress in its flange as the main causes of dimensional inaccuracy before release from the die. We controlled material behavior during intermediate processing to reduce these stresses. As shown in **Fig. 9**, this reduced the degree of camber springback.

4. Machining

4.1 Machining technology

Parts for equipment such as aircraft and vehicles require exceptional quality and precision. Manufacturing such parts requires machining processes that offer an excellent balance between productivity, precision, and cost. Kobe Steel has spent decades collaborating with customers to

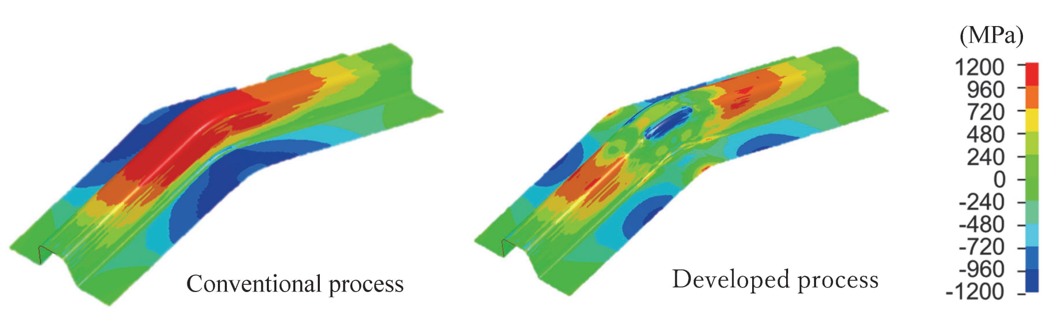


Fig. 8 Comparison of stress distribution by conventional process and by developed process (longitudinal direction)

create effective solutions in machining technology, compressors, and drilling equipment. Meanwhile, parts that go through a machining process have recently entered a period of great change. The material composition must result in lighter and stronger parts and foster the electrification of vehicles in support of carbon neutrality. Technological advancements in data analysis and AI are changing the technical side of machining as well. Kobe Steel has responded by developing various machining simulation technologies for purposes such as analyzing cutting-edge phenomena via FEM, predicting chatter based on vibration theory, and performing evaluations through prototype testing.[22] This section introduces examples of each technology.

4.2 Advancing machining technology via data analysis and simulations

4.2.1 Chip breaking prediction technology for turning operations

Turning inevitably generates chips. Results of chips remaining in the equipment or not being broken include hindered automation, a flawed machined surface, and tool damage. Therefore, it is necessary to select materials, cutting conditions, and tool shapes (chip breakers) that generate chips that are easy to break and manage. Kobe Steel has developed easy-to-implement chip breaking prediction technology in support of this need.

A chip breaker, an uneven surface on the rake surface of the tool, bends the chip. When the bending strain in the chip exceeds the critical fracture strain εc, the chip breaks off. Based on this principle, we developed a method to calculate chip shape based on cutting conditions and chip breaker shape, and to predict whether a chip will break under each cutting condition. The contour plot in **Fig.10** depicts a sample of our results.

The experimental results (○, △, ×) correlate strongly with the prediction that anything above and to the right of the red dashed line indicates separation, and anything below and to left indicates continuity. Therefore, this is an effective prediction technology. This technology makes it possible to quickly select cutting conditions, tools, and chip control solutions applicable to any given cutting operation.

4.2.2 Machining error prediction technology based on power consumption of the spindle motor

Kobe Steel manufactures industrial air compressors. The cast iron materials used in these compressors vary in hardness. Even under the same cutting conditions, machining inaccuracy occurs because of material variation. This necessitates corrective machining, generally reducing throughput. Forecasting machining error before finishing provides control over the variability in machining accuracy by enabling appropriate adjustment of cutting parameters. Therefore, as shown in **Fig.11**, we estimated material hardness based on the power consumption of the spindle motor during drilling. We used these data to predict the degree of machining error during finish boring. Feed rates were adjusted to achieve the target machined shape based on the predicted machining error (**Fig.12**). This technology enables automatic correction to achieve high-precision machining on the order of a few microns. Eliminating the need for rework reduces manufacturing costs and the headcount required for the manufacturing process.

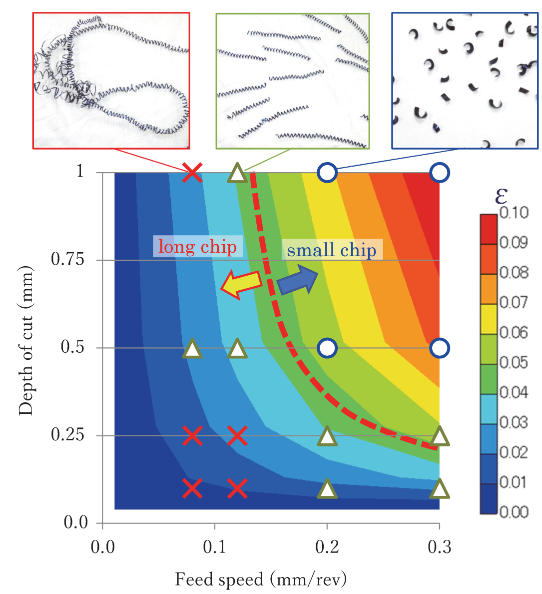


Fig.10 Comparison of chip breaking prediction results and experimental results

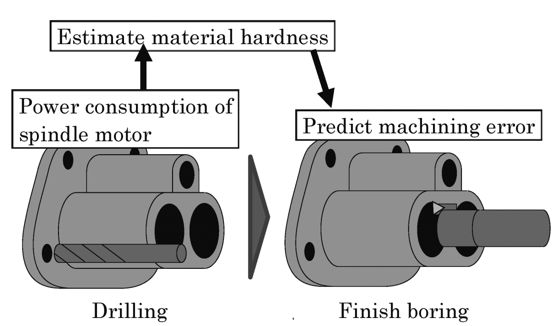


Fig.11 Overview of machining error prediction technology

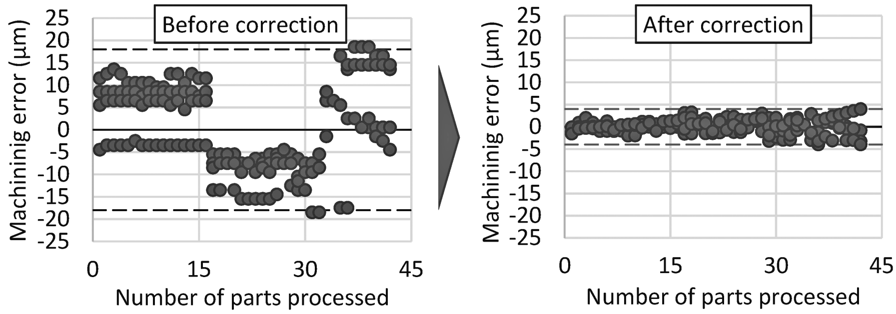


Fig.12 Effect of high-precision machining by automatic correction

Conclusions

Technological developments around the world are anticipated in the near future, which is an impetus to continue developing technologies for processing high-function materials and products with exceptional quality, yield, productivity, and added value. As such, Kobe Steel will use and refine the processing technologies covered throughout this article to create new functional materials for carbon-neutral and energy-related products.

Additionally, ever-shorter product development cycles are driving a need to optimize process design and machining both within Kobe Steel and among its customers. However, the anticipated decrease in the working population owing to the declining birth rate will make it more challenging to implement sophisticated machining process design methods, traditionally based on the experience of engineers. Overcoming this challenge will require sensing and simulation technologies to visualize phenomena that are difficult to grasp using conventional methods. Technologies that can capitalize on this vast amount of information to create new value will be critical. Big data and AI/MI will likely enable tailored process design, such as by determining the material shapes and cutting tools that maximize both yield and the functionality that the final product geometry can achieve. Big data and AI/MI will also likely support traceability as well as abnormality detection and prevention in equipment and in machining processes, an innovation that is beginning to see practical use. However, achieving exceptional process design presents many challenges, such as handling new materials and machining geometries. To overcome these challenges, Kobe Steel plans to integrate the computational science methods and numerical simulation technologies amassed over the years.

Kobe Steel will also contribute to a safe and secure society and carbon neutrality through a variety of digital transformation projects and will continue refining each of its core technologies.

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