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Frontier & Platform Research for Social Innovation Business

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HITACHI'S Social Innovation Business is a leader in its field, combining a diverse portfolio of technologies in the natural, social, and system sciences. In 2009 when I edited a feature issue of Hitachi Review Vol. 58 No. 4 that focused on human-oriented research and development (R&D) in the social sciences, I defined human society in terms of different "spaces," specifically the virtual, physical, and human spaces and how they are tied together by transportation. Articles in that issue covered nine different areas of Hitachi's R&D, describing technologies that related directly or indirectly to the social sciences in these different spaces.

In this issue, we consider the advanced scientific technologies behind Hitachi's Social Innovation Business, grouping them into three categories. The first category is the use of electron microscopes to measure natural phenomena. Hitachi invented the technology behind spin-polarized scanning electron microscopes (spin SEMs), and one of the articles describes how they can be used to observe the spin direction (magnetic orientation) of domains on the surface of a magnetic material, with applications that include improving the efficiency of electric generators and electric motors (p. 264). A diffractive imaging technique is also presented for visualizing the three-dimensional structure of light-element materials such as carbon nanotubes, graphene, and magnesium oxide (p. 269).

The second category relates to the use of information technologies to model, simulate, and analyze natural phenomena. This includes state-of-the-art technologies for modeling and simulation of high functional materials (p. 239), fluid dynamics (p. 244), and welding (p. 249). These technologies are the result of synergies between R&D at different Hitachi businesses, from power plants and home appliances to supercomputer systems. Another article describes recent technological developments for managing the information technology (IT) resources used to analyze real-world Big Data (p. 279).

The third category deals with the control of natural phenomena in various manufacturing processes, for which Hitachi uses the Japanese term "monozukuri" (the art of manufacturing products). This includes a technique for modeling the propagation of problems in production at one or more factories (p. 274). Other articles on monozukuri deal with lithium-ion batteries and power inverters (p. 259 and p. 254).

Because social infrastructure is tied so closely to interactions between people, its human aspects increase exponentially with population growth. System sciences such as artificial intelligence provide effective tools for solving such non-polynomial-order problems. Hitachi is well placed to develop system science technologies through its work on constructing various advanced systems.

Through its R&D, Hitachi's Social Innovation Business seeks to play a leading role in building a sustainable human world by combining proprietary technologies in the natural, social, and system sciences.

Frontier & Platform Research for System Development and Monozukuri

Naoya Sasaki, Dr. Eng.
Akio Saito
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SYSTEM CONSIDERATIONS IN MONOZUKURI MANUFACTURING

THE modern world faces many very difficult challenges, including global warming, resource and energy depletion, and rapid socioeconomic change. At the same time, while rapid progress is being made on establishing the foundations of a prosperous society, there are also calls from around the world for highly reliable social infrastructure that provides safety and security while being conscious of the global environment, including the changes needed to bring about a low-carbon society. Future manufacturing will need to undertake design, development, and production based on a global overview of the overall system for product creation and supply.

For the platform technologies that support manufacturing, this will require moving beyond the focus on specific technologies adopted in the past toward a system-based approach, with technology able to provide low cost, high performance, and high reliability throughout all phases of the manufacturing process.

The following two factors are considered to be important for developing a wide range of systems and other products globally: (1) Integration of a diverse range of multidisciplinary technologies to complement the existing technologies, which include simulation, testing and measurement, and production. These multidisciplinary technologies include advanced information technology (IT), computational engineering, data analysis techniques, systems, and service technologies. (2) The development of techniques for understanding, predicting, and controlling complex phenomena that occur in systems through the integration of models of real-world phenomena that span different scales.

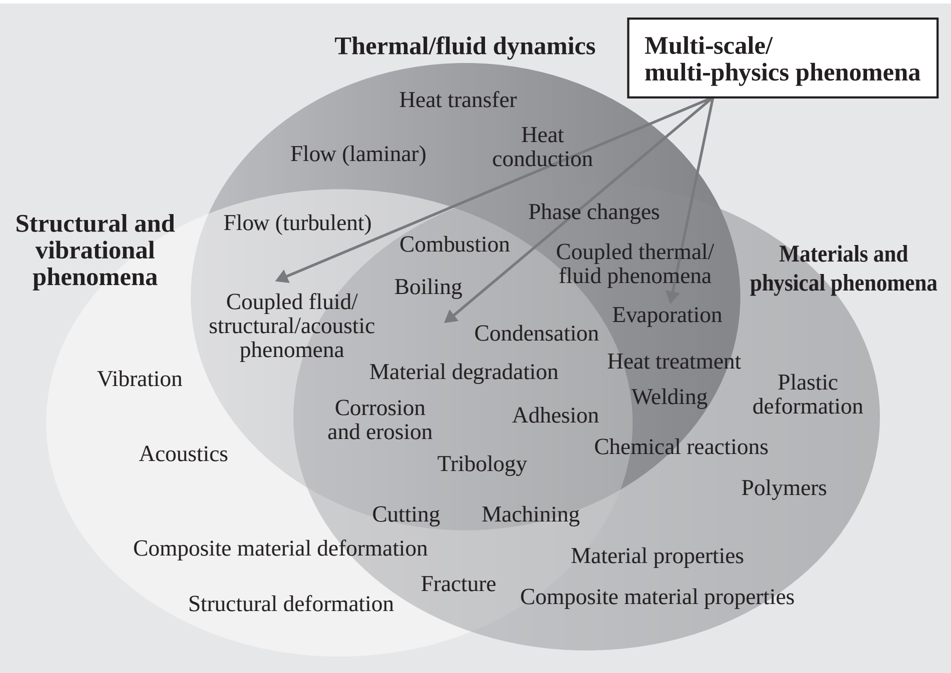

Fig. 1—Complex Multidisciplinary Coupling Phenomena in Mechanics and Materials.
There will be a need in the future to elucidate multi-scale and multi-physics phenomena that relate to a number of different fields. Examples include surface phenomena and coupled phenomena such as material degradation, corrosion, evaporation, and tribology.

ROLE OF PLATFORM TECHNOLOGIES

"Platform technologies" are common technologies that support a range of different manufacturing platforms. They cover a variety of fields, including simulation, measurement, and production technology. In particular, it will be essential in the future to deal with things like environmental problems and the greater diversity of requirements resulting from the globalization of markets.

Monozukuri in Social, Industrial, and Information Sectors

To accelerate the globalization of its products for the social, industrial, and information sectors, and improvements to their environmental performance, Hitachi recognizes a number of common core technologies as being platform technologies. These include analysis-led design techniques that use the latest simulation and measurement technologies, technologies for reducing the load on the environment, and production technologies that support globalization and improve productivity.

The fields in which these are applied include electric power, water and sewage supply and treatment, railways, automotive equipment, industrial and urban development systems, healthcare, information and telecommunication systems, and the advanced materials technologies, key devices, and other products that support these different sectors. Organically fusing the systems and technologies that Hitachi has built up in these diverse sectors will create an infrastructure that can act as the platform for a sustainable society able to reduce the load on the global environment while also providing a comfortable way of life and economic growth.

Platform Technologies from a Global Perspective

Because the product creation and supply system must operate in complex and diverse cultural and natural environments, managing a worldwide business requires a different approach to design than in the past. This involves more than just taking account of the complexity of the environment in which each product is used; it is also essential to achieve reliable cost and quality while also speeding up design, development, and production. A system-based approach to manufacturing is also needed. Together with extreme designs able to deliver high performance and low cost, this also calls for advanced platform technologies based on an understanding of complex phenomena.

Taking the mechanics and materials sector as an example, whereas in the past this sector tended to use models that represented phenomena in terms of a single field of study, the increasingly stringent demands being placed on product performance make it necessary to understand and control, as thoroughly as possible, multi-scale/multi-physics phenomena that inherently combine a number of different disciplines, such as tribology[(a)], material degradation, and coupled phenomena[(b)] (see Fig. 1).

The monozukuri approach to manufacturing also includes the following considerations.

(1) Succeed in staying ahead of rivals by improving, as far as possible, factors such as performance, quality, and cost for products that are based on existing concepts. For example, one approach is to develop next-generation products able to be used in harsher environments by improving materials, with any gains in performance also being important. Also, develop stand-out technology to keep ahead of similar products.

(2) Take a variety of approaches to resolving problems or satisfying needs, and develop products, systems, and services that use new technologies or concepts that implement these solutions.

However, using approach (1) on its own makes it difficult to differentiate products as technology matures. This means that combining both these approaches will be important in future research and development.

Given this background, in addition to manufacturing platforms based primarily on conventional production technology, what will also be required will be to construct a diverse infrastructure of platform technologies that are capable of working together. Examples of these include system platforms that incorporate control technology and involve performing design and operational simulation from a systems perspective, and information platforms that utilize

(a) Tribology
The Japanese Society of Tribologists (JAST) defines tribology as the science and technology of all phenomena that occur at the interface between two surfaces that interact through relative motion. This includes lubrication, friction, wear, seizure, and bearing design. The word derives from the Greek "tribos," meaning "to rub," and "ology," meaning "to study."

(b) Coupled phenomena
Phenomena or behaviors that involve the interaction of two or more features, such as structure, heat, flow, electric fields, magnetic fields, or acoustics, and therefore cannot be predicted based on consideration of a single feature on its own. The analysis of such phenomena is called coupled analysis.

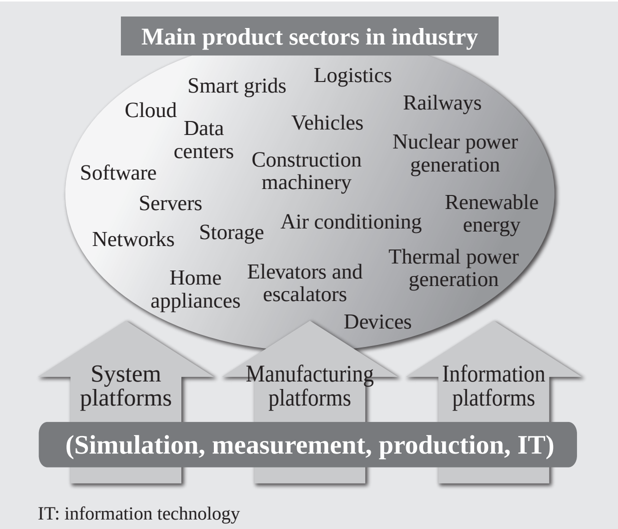

Fig. 2—Platform Technologies that Support Systems for Product Creation and Supply.
A wide range of platform technologies, including manufacturing platforms, system platforms, and information platforms, are used by industry to support the production of numerous different categories of product.

information science to deliver large-scale data processing and other solutions (see Fig. 2).

For example, system platforms include platform technologies such as simulators for the smart grids that will be needed in the future, operational simulations for railways and other applications, and model-based technologies that predict system functions. Examples of information platforms include large-scale data processing at data centers, encryption techniques for security, recognition techniques based on information science, and network, cloud and storage technologies. These will be essential platform technologies for supplying global systems and solutions (see Fig. 3).

Also needed will be the integration of different platforms, with technologies such as simulation, measurement, production, and IT acting as common cross-platform technologies.

USE OF PLATFORM TECHNOLOGIES IN SYSTEM-BASED MANUFACTURING

As described earlier, conducting manufacturing operations on a worldwide scale can be thought of as requiring complex perspectives and considerations, and this in turn requires the integration of multidisciplinary platform technologies that span different fields. Nevertheless, advanced and in-depth specialization in each field remains a prerequisite for achieving these diverse forms of integration.

The following sections give a broad overview of future developments in the simulation, measurement, and production technologies for manufacturing platforms in particular.

Simulation (Computational Engineering and Computational Science) Techniques

Improvements in computer performance have made it possible to conduct large and complex simulations. In the field of thermal fluid and structural analysis, these include coupled analyses of fluids, structures, and noise; coupled analyses of electromagnetic fields and circuits; and whole-product simulations[1]. Meanwhile, material simulations are inching closer to an understanding of complex systems, including simulations of microstructural changes in metals and those that use physical properties data to combine macro-scale phenomena with micro-scale analysis of atoms and molecules[1]. However, the current state of technology is still unable to make accurate predictions

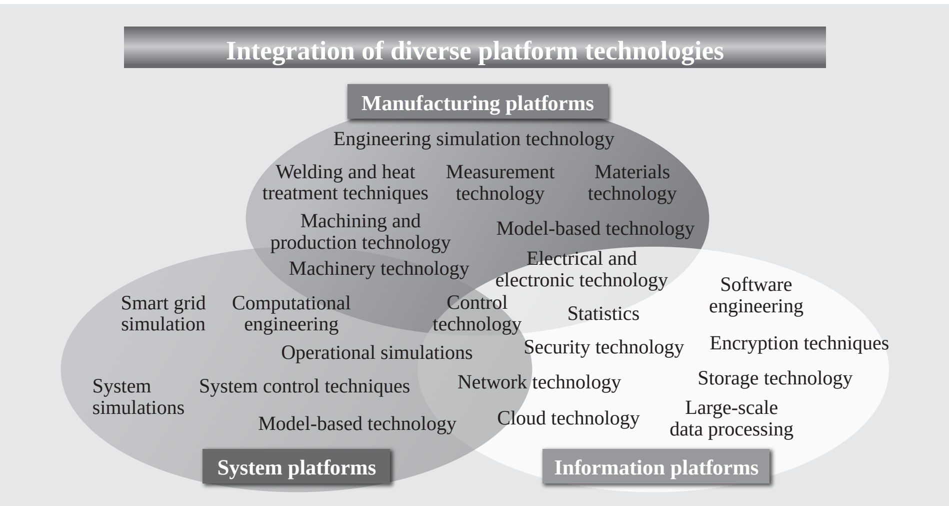

Fig. 3—Diverse Platform Technologies and their Integration.
The integration of platform technologies such as those for manufacturing, systems, and information will be vital for supplying global solutions.

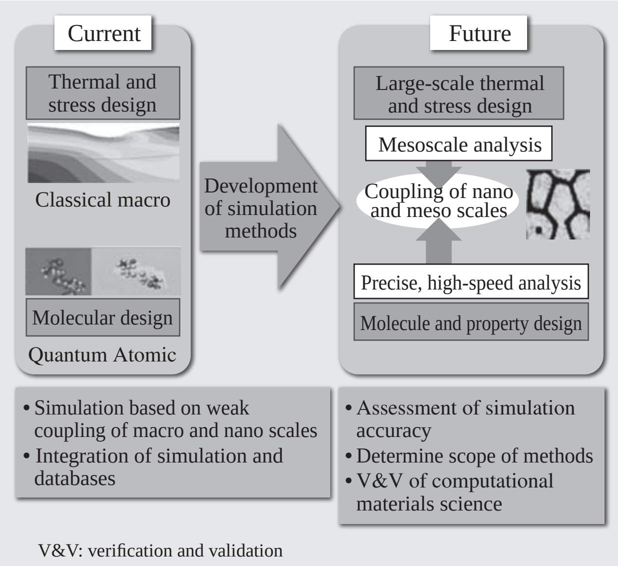

Fig. 4—Need for Mesoscale Material Simulations.
Modern material design and development requires the development of mesoscale models that take account of nano-scale properties, and their use for analysis.

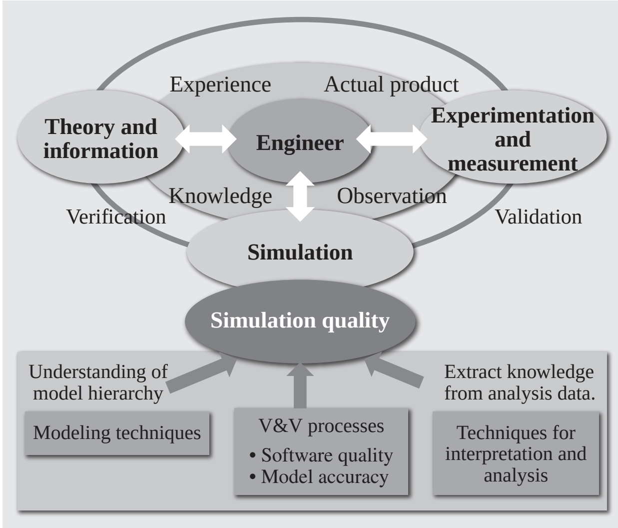

Fig. 5—Concept of Simulation Quality.
Advanced techniques such as modeling, V&V processes, and the interpretation of analysis results are required to improve simulation quality.

of complex phenomena. Examples include unsteady phenomena in fluid machinery, combustion involving complex reactions, and the machining, welding, lubrication, corrosion, and other processes associated with materials. Also of importance for material simulations are mesoscale[(c)] analysis techniques for predicting the influence that micro-scale material properties have on macro-scale product performance (see Fig. 4).

To increase the number of product functions and satisfy diverse needs, it is also necessary to obtain multipurpose and appropriate solutions. A number of optimization techniques are being developed for this purpose[(1)]. As relying solely on simulations based on physics and chemistry to achieve this, as in the past, will be difficult, it will be important in the future to incorporate approaches based on optimization, computational engineering, and information science.

It is anticipated that the elucidation and control of phenomena that are diverse and difficult to predict will occur in a global environment. What will be even more important in the future will be establishing the concepts and processes of V&V[(d)] for interpreting the suitability and guaranteeing the accuracy of the techniques used to simulate the complex phenomena involved[(2)]. To achieve this, it will be necessary to establish the processes of verification (for determining whether the computational models used for the phenomena being dealt with are appropriate in theoretical and mathematical terms) and validation (the use of advanced measurement techniques, comparison with actual phenomena, and other means to assess the suitability of analytical models), and to integrate them with other platform technologies, such as those for measurement and production (see Fig. 5).

Also, as it is impossible to predict the behavior of practical systems using simulation alone, it will also be necessary to develop modeling methods that successfully integrate with measurement technology, large-scale data processing, and other approaches. In the field of weather forecasting, for example, new integration techniques such as data assimilation[(3)] are being developed, and their use in industry is also anticipated.

The key requirements for the future use of simulation are as follows.
(1) Precise modeling of large and complex phenomena
(2) Interpretation of large data sets containing analysis results

(c) Mesoscale
The prefix “meso” means “intermediate” and the term mesoscale refers to spatial scales midway between the nano and millimeter range. This range includes structures that play an important role in determining material properties. As the mesoscale is midway between the realms of classical and quantum mechanics, analysis of phenomena at this scale requires the design of models that take account of both types of behavior.

(d) V&V
Abbreviation of “verification and validation.” A method for ensuring the quality of systems, services, and other products. In product development, for example, V&V may refer to an assessment (involving both verification and validation) of whether the development, design, production, and other processes are appropriate in order to determine whether the resulting product will be fit for purpose.

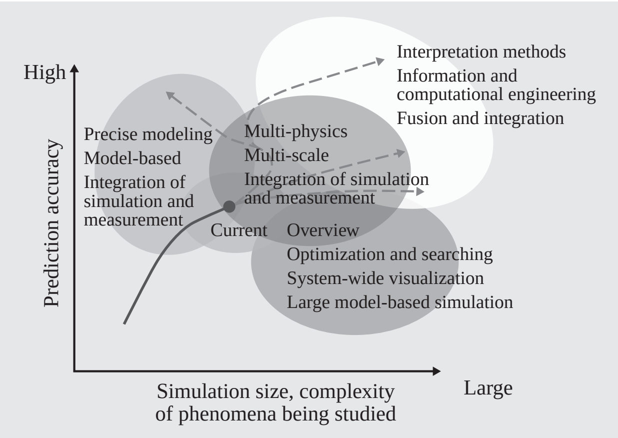

Fig. 6—Diverse Approaches to Computational Engineering.
A diverse range of optimum approaches to simulation (computational engineering) exist depending on factors such as prediction accuracy and the complexity of the phenomena being studied.

(3) Precise modeling of phenomena that have not been well understood in the past
(4) Taking account of scatter, variation, and other random factors that influence analysis

As the product creation and supply system becomes more complex, the quantity of data produced by simulations is growing. In an increasing number of cases, this is making the interpretation of analysis results more difficult. In situations such as these, even when simulation is being used, it is important to select analysis methods that are appropriate to the complexity of the phenomena being studied, as well as in terms of accuracy and other factors (see Fig. 6).

Measurement Technologies

Measurement lies at the heart of science and technology, which advances through a repeated process of theoretical prediction and experimental verification. As the natural world still contains many phenomena that are difficult to measure or visualize, even more advanced measurement technologies are needed. Meanwhile, of increasing importance for the products that play a fundamental role in society, such as vehicles and industrial plants, are initiatives that provide ways for Japanese companies to differentiate themselves against a background in which costs are falling globally, such as using measurement to underpin reliability and the modeling of complex phenomena.

The current issues for measurement technology can be broadly divided into the following three. As an example, Fig. 7 shows the requirements for measurement and evaluation in electronics manufacturing.

(1) Soft materials and water-containing materials play a large role in the field of environmental and biological materials. A common challenge for these is to perform measurements in a way that produces an efficient signal, but with low damage and without disturbing the state of the specimen. In the case of graphene, polymers, and many biological specimens,

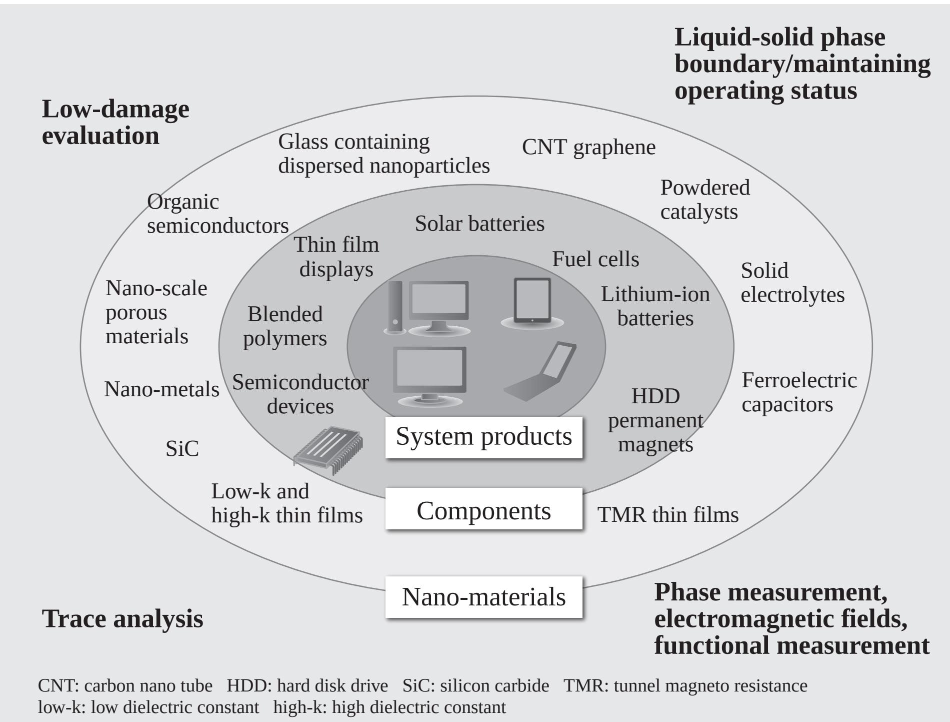

Fig. 7—Diverse Requirements for Measurement and Evaluation in Manufacturing (Electronics Industry Example).
The electronics industry has diverse and wide-ranging requirements extending from system products to individual components and nano-materials.

materials that are damaged even by exposure to light are becoming increasingly common. When testing the electrode materials used in lithium-ion batteries, it is necessary to study the liquid-solid phase boundary at the nanometer level as they undergo changes if removed from the electrolyte. Similarly, measurements of functional particles such as catalysts need to be performed at the gas phase boundary, which is where they are used.

(2) A wide range of medium to large products such as industrial plants, vehicles, construction machinery, electric motors, and materials require non-destructive, non-contact, and non-contaminating measurements, as well as portable, low-cost measurements that can be used in the field. The technical challenges to visualizing three-dimensional distributions and internal structures with high spatial resolution remain numerous. Similarly, on-site measurements are required for situations such as combustion phenomena in boilers or the flow rates and pressures in the complex rotating flow fields in fluid machinery.

(3) High-speed inspection techniques for applications such as detecting contaminants or agricultural chemical residues in foods are another pressing issue. This will be an important area of activity in the future, and will need to cope with different national regulations and other laws as well as challenging throughput and cost requirements. Measurement technology will also need to support material development to help with the move away from using rare earth elements.

The following lists the measurement platform technologies that will need to be considered in the future to respond to the above challenges.

(1) Techniques for controlling and detecting phase are important when electron beams are used for measurement. Platform technologies that will be important include electron optics that allow atomic-scale observations to be made using low-energy electron beams, detectors and analyzers able to discriminate between different signals, and high-intensity pulsed electron guns. These will allow for innovation in material and device development using soft materials based on light elements, specimens of which produce weak signals.

(2) Probe microscopy works by scanning a fine probe over the sample. Because it does not require a vacuum, probe microscopy can be used for highly efficient nano-spectroscopy[(e)] using near-field light[(f)], and to analyze the properties of liquid-solid phase boundaries. This represents a breakthrough in the structural analysis of water-containing specimens, proteins, and genes.

(3) Measurements performed at large facilities, such as those involving synchrotron radiation or neutron beams, can be used for non-destructive structural analysis at the atomic level. Successful results have been reported for a wide range of applications. Examples include evaluating the structure of electrodes in actual lithium-ion batteries without having to open up the battery package, evaluating the internal stresses in products, and evaluating the magnetic domains in a permanent magnet using beams of polarized light. Also measurements that use a pulsed beam to improve time resolution can be used to study transient phenomena such as chemical reactions and changes in molecular structure. It is anticipated that this technique will open up new possibilities in fields such as molecular material design and drug development.

(4) Medium-sized and large products require non-destructive testing techniques to ensure their reliability. Penetrant inspection and length measurement techniques have been commercialized using X-rays, ultrasonic wave, eddy current, laser beams, and other methods, and active progress is being made in areas such as the three-dimensional representation of information and making measuring instruments smaller and more portable.

Future applications are anticipated in areas such as resource mapping. In the case of thermal fluid and acoustic field measurement, technologies are needed that can integrate with simulations and measure entire specimens.

Production Technology

With the globalization of business, overseas production (particularly in Asia) is becoming essential for achieving cost-competitiveness.

Japanese manufacturing has led the world through globally superior technology, including production systems and integral manufacturing in the production workplace. However, these will not necessarily

(e) Nano-spectroscopy
A technique for analyzing structures by measuring how a specimen responds to light (including absorption, reflection, refraction, and dispersion) on the nano-scale. Traditionally, the spatial resolution of spectroscopy has been limited to approximately the wavelength of the light being used (several hundred nanometers in the case of visible light). Using near-field light, however, it is possible to achieve nano-scale spatial resolutions that exceed the diffraction limit of the light.

(f) Near-field light
A special type of light that is produced when light is applied to physical structures such as very narrow apertures or edges that are smaller than the light's wavelength. This near-field light does not propagate beyond the immediate vicinity of the surface of the structure. Because it has a wavelength shorter than visible light and is able to exceed the diffraction limit, it can be used to dramatically enhance the spatial resolution of optical microscopes.

function effectively if transplanted directly into overseas production sites, and it has become clear from actual experience of overseas production that the issues facing the manufacturing workplace cover a wide range. All of these issues, which include workers, procurement, supply chain, local infrastructure, local regulatory and commercial practices, and intellectual property, take considerable time and effort to resolve. Furthermore, remaining cost-competitive takes more than just focusing efforts on the manufacturing workplace, and the need for innovation in upstream processes such as product planning and design has already been discussed.

Accordingly, thinking about production technology for global manufacturing must go beyond just the technology at the manufacturing workplace and encompass a major conceptual change from a global perspective. The following seven topics represent the key considerations for achieving this.

(1) Trouble-free construction of factories, plants, and other facilities
(2) Establishing a supply chain, including procurement
(3) Optimization of factory production lines
(4) Workers
(5) Procurement (how to respond to variations in quality, delivery times, and other disruptions)
(6) Optimization of production across multiple sites spread over a wide area
(7) Optimization of maintenance and support

While these include some elements that are not part of conventional production technology, Hitachi believes that they are all appropriate subjects for research and development and represent production technologies for responding to the challenges of global manufacturing.

Among these, use of simulation is a particularly important platform technology (see Fig. 8).

The following sections describe the production technologies of global manufacturing for each of the above seven topics, considered primarily from this perspective.

(1) Construction of factories and plants needs to be thought of as comprising two stages: design and execution. Important technologies for the design stage include multi-dimensional computer-aided design (CAD) and simulation, which are used for tasks such as site selection, design of the plant layout, and logistics design. The execution stage requires techniques for managing schedules, cost, and resources across the entire construction project, taking account of a large number of considerations and constraints, and techniques for overall planning of material procurement, transportation, and site delivery.

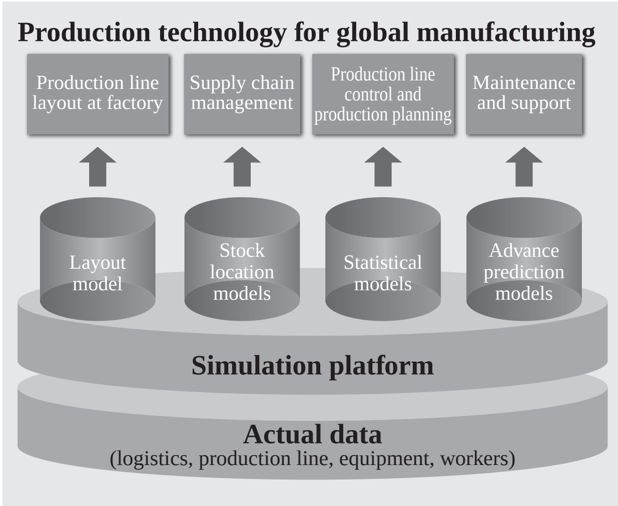

Fig. 8—Use of Simulation to Support Global Production Technology.
Use of simulation techniques that combine with statistical models, stock location models, and similar will be essential in the future.

(2) The importance to manufacturing of the global supply chain (including procurement), and its fragility, were exposed by the earthquake and flooding disasters of 2011. Use of simulation is essential to study how to achieve a smooth supply chain based on an accurate appreciation of the actual conditions in each country and region obtained in advance.

(3) While manufacturing process design based on the structure of the product being produced and the planned production volume has a fundamental role in determining production line layout, establishing production equipment layouts, worker deployments, space designs, and internal factory logistics that achieve high efficiency for a low investment requires digital factory technology (combining simulation and animation) that can determine in advance whether designs are optimal and achievable.

(4) Techniques such as automatically generating easily understood work instructions or taking steps at the design stage to simplify assembly are an effective way of dealing with workers whose skills are lacking. The "assembly reliability evaluation method"[(4)] is an effective technique for use with designs that simplify assembly. This evaluation method quantifies the ease of assembly of proposed designs. It considers the ease of assembly of each component, one at a time, and estimates the rate of assembly defects by quantitatively assessing the working capabilities of each production site.

(5) While encouraging improvements by suppliers is a necessary part of procurement, it is also important from a production perspective to adopt robust machining and assembly techniques that assume a degree of variability in supplied parts. Variability in part delivery times is also to be expected and this requires realtime production management techniques.
(6) The important factors for optimizing production across multiple sites spread over a wide area are to adopt realtime practices and improve the accuracy of production line control and production planning, and to establish a supply chain that operates in synchronization with production. Detailed simulation is key to both of these objectives and the use of more advanced techniques is essential.
(7) Reductions in the cost of reliable maintenance and support can be achieved through an accurate appreciation of maintenance intervals acquired by taking note of warning signs.

Extending these production technology concepts makes a systems-based approach more important, and the development of more advanced simulation techniques can be seen as a major technical challenge.

While this article has so far considered production technology from a systems perspective, improvements in hardware technology are also important. In particular, the phenomena associated with platform technologies that support highly reliable systems such as machining, welding, lubrication, and surface treatment are complex, and this is a field in which modeling is not yet well established. Meanwhile, the aging of staff with a high level of skills is depleting their numbers, and this is a particularly significant problem for global production. This is a field in which it is desirable to combine simulation, measurement, and other techniques to encourage the formalization of knowledge, or what is often referred to by the term "know-how."

EXAMPLES OF HITACHI'S ACTIVITIES

This section summarizes each of the nine articles in this issue and explains how they relate to Hitachi's activities. Each article describes an example application of simulation, measurement, or production technology, with a particular focus on manufacturing platforms, and also on how they integrate with information and system platforms.

Applications for Simulation Techniques

"Material Property Simulations for Efficient Design of Environmentally Conscious Functional Materials" describes a simulation technique for predicting material properties from first principles at the level of electrons and atoms.

As global environmental problems become more severe, there is an urgent need to develop environmentally conscious materials. In the past, the development of new materials such as these often involved repeated trial-and-error testing of prototypes. However, because this approach was very time consuming, it was considered desirable to shift to an analysis-led approach to material design by using computer simulations to perform design efficiently.

Using anode materials for high-performance lithium-ion batteries, piezoelectric materials that do not contain lead, and recyclable plastics as examples, this article describes example applications for molecular simulation using a combination of analysis techniques to determine the overall behavior of the material at two different scales, namely the use of quantum mechanics to calculate the behavior of electrons and classical mechanics to calculate the behavior of atoms.

"Platform Technology for Computational Fluid Dynamics Supporting Design of System Products—from Power Plants and Industrial Machinery to Home Appliances" describes examples in which large-scale fluid dynamics simulations are used to predict complex fluid phenomena, an application that will be needed in the future.

The pursuit of greater energy efficiency is an important consideration in the development of many different products, from home appliances to power plants and industrial machinery. Pumps, fans, and other fluid devices are used in many of these systems, and computational fluid dynamics (CFD) has for some time been successfully used as a core technology in the design of many products. Ensuring competitive product development in the future will require, among other things, devising new ways of using fluid dynamics in design, and measures aimed at elucidating phenomena that are not amenable to conventional analysis.

This article includes an example of how Hitachi is utilizing collaborations between industry and academia to work on large-scale analyses that use fluid dynamics to study phenomena that could not previously be tackled, and how it is applying multi-objective design optimization and cavitation analysis techniques in its product design.

"Welding Simulation Technologies for Highly Efficient Production of High-quality Social Infrastructure Products" describes welding distortion simulations for large structures.

Large welded structures are used extensively in power plants, industrial machinery, construction machinery, rolling stock, and other types of products, and welding accounts for a large proportion of the overall manufacturing process. Hitachi has developed techniques for improving analysis speed and accuracy, and also a database of material property values that takes account of factors such as material, structure, and environment based on past finite element method (FEM) analyses.

This article describes the state of progress for the technology used in the development of a deformation simulation technique that combines a high level of precision and speed, and examples of its application to the fabrication of large structures.

“Next-generation Inverter Technology for Environmentally Conscious Vehicles” describes the structure of next-generation inverters, and power modules that allow fast and highly efficient switching.

Amid calls for a reduction in carbon dioxide (CO_2) emissions to help realize a sustainable society, use of hybrid electric vehicles (HEVs) and electric vehicles (EVs) is growing. Meanwhile, the construction of large power generation systems is being hastened to increase the amount of power produced from renewable energy sources such as wind and photovoltaic power generation. Small and highly efficient inverter systems will be essential for achieving this low-carbon society.

Inverters are one of the components of the power electronics systems that support this sector, and this article describes analysis and design techniques that use specific technologies needed to reduce inverter size and improve power density, including physical circuit design methods, cooling, and anti-vibration analysis.

Applications for Measurement Techniques

“Lifetime Prediction for Heavy-duty Industrial Lithium-ion Batteries that Enables Highly Reliable System Design” describes a technique for predicting the operating lifetime of lithium-ion batteries with a high degree of accuracy.

The anticipated uses of lithium-ion batteries include energy storage systems such as backup power supplies, and reducing fluctuations in the output of renewable energy generation systems. Being able to reliably predict the lifetimes of the batteries used in these applications makes energy storage systems more affordable and gives greater confidence in the estimated operating life of the systems.

This article describes how experimental measurement techniques and a theoretical model were used to formulate a lifetime prediction equation that incorporates terms corresponding to the square root function law, Arrhenius law, and additive law methods used in the past. It also describes the resulting lifetime prediction technique that considers the number of cycles, operating time, and ambient temperature to improve lifetime prediction accuracy.

“Development of Spin SEM Technology for Observation of Magnetic Domains” describes the electron microscopes used to study various different magnetic materials, including hard disk drives (HDDs) and permanent magnets, with a particular emphasis on spin-polarized scanning electron microscopes (spin SEMs).

By taking advantage of their features, which include being able to study the magnetic structure of a device at the nanometer scale, perform three-dimensional analyses of magnetic orientation, and analyze magnetization and shape information separately, spin SEMs are already being used in applications such as evaluating the shape of storage bits on magnetic media.

This article includes example applications and describes how analysis of a wider range of materials, including permanent magnets, has been made possible by the development of a new mechanism that allows high-temperature observations of a heated sample, and another that shields magnetic stray fields on the sample surface to allow observation of samples with remanent magnetization.

“Low-energy Electron Diffractive Imaging for Three-dimensional Light-element Materials” describes an electron diffraction microscope created by retrofitting an SEM with a high-resolution imaging function that reconstructs the phase information from a diffraction pattern in order to allow diffractive imaging to be used with a low-energy electron beam.

Electron microscopes are already used in the development of materials and devices, particularly in semiconductor manufacturing, and they have also been used extensively in research aimed at identifying the structure of dislocations in metals. However, developments in recent years, such as the extensive use of carbon-based materials as battery electrodes, including in lithium-ion batteries, have seen growing demand for analysis of lighter element materials. This article describes how images of the atomic structure of single-wall carbon nanotubes (comprising a single loop of graphene sheet) were obtained from their diffraction pattern using computer processing.

Applications for Production Technologies Using Statistical Models

"Production Control System to Visualize Future Effects by Production Trouble" describes a production control system able to make highly accurate predictions of the variations in production volume that result from the sort of problems that occur in a supply chain, such as component shortages or equipment failure.

In recent years, there has been a need for supply chains with the flexibility and resilience to minimize the impact when unexpected problems or disasters occur at the production sites and logistics operations that have spread throughout the world in conjunction with the globalization of business. This article describes a production control system that uses a statistical model for the highly accurate prediction of the variations in production volume that will occur in the manufacturing process after a problem occurs.

Applications for Information and IT

"IT Resource Management Technology for Reducing Operating Costs of Large Cloud Data Centers" describes IT resource management technology for the administrators who operate and manage cloud data centers, which are becoming increasingly larger.

Data centers provide the platform for cloud computing. The main problems facing these data centers in recent years have been the difficulty of centralized management of increasingly large data centers, the growing workload being placed on individual administrators due to the specialized nature of advanced management skills, and the increasing amount of time spent on coordinating administrators of different layer.

This article describes Hitachi's work on management repository technology that allows centralized administration of large-scale IT resources, root cause analysis technology that formalizes the advanced know-how of administrators in the form of structured knowledge, and virtual server and storage administration coordination technology that automates storage configuration and reduces the workload associated with coordinating different administrators.

PLATFORM TECHNOLOGIES THAT SUPPORT COMPLEX AND DIVERSE SYSTEMS

This article has described the future outlook for common platform technologies used in product development from a global and systems perspective.

Success in global competition requires a wide range of platform technologies that can predict and control various different phenomena in diverse and complex product environments, and also the ability to integrate these technologies. Technologies that can take on the challenges and take account of the risks associated with supporting complex and diverse systems can be recognized as the common platform technologies that will generate new value in the future.

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Material Property Simulations for Efficient Design of Environmentally Conscious Functional Materials

Tomio Iwasaki, Dr. Sc.
Shin Takahashi

OVERVIEW: With the aim of realizing a sustainable society, Hitachi has formulated an Environmental Vision directed toward overcoming the challenges facing the global environment, and based on the three pillars of Prevention of Global Warming, Conservation of Resources, and Preservation of Ecosystems. Applying this initiative in the field of material development, Hitachi is developing simulation technology that works from first principles at the level of electrons and atoms to provide comprehensive predictions of chemical properties, such as reactions involving the formation and breaking of chemical bonds; physical properties, such as optical electromagnetic, and diffusion characteristics; and mechanical properties, such as breaking strength and deformation characteristics. Through the application of this technology, Hitachi is working on material designs for the three pillars of its Environmental Vision. In the future, Hitachi intends to utilize this technology for the efficient design of a wide range of different environmentally conscious high functional materials that will enhance the products it develops.

INTRODUCTION

AS global environmental problems become more severe, there is a growing need to develop environmentally conscious materials, including materials that can help reduce emissions of carbon dioxide (CO_2) and other greenhouse gases, high functional materials that do not contain lead or other substances that are harmful to human health or the ecosystem, and materials that can be broken down and recycled after use. In the past, the development of new materials such as these often involved repeated trial-and-error testing of prototypes. However, because this approach was very time consuming, it was considered desirable to shift to an analysis-based approach to material design by using computer simulations to perform design efficiently. Against this background, Hitachi has developed simulation technology able to predict the physical properties of materials from first principles at the level of the electron and atom (see Fig. 1).

This article describes three examples of the application of material property simulation to environmentally conscious materials that support Hitachi's Environmental Vision: (1) anode material for lithium-ion batteries that help reduce exhaust gas emissions and fuel consumption in automobiles such as hybrid electric vehicles (HEVs), (2) piezoelectric materials that do not contain lead or other substances that are harmful to human health or the ecosystem, and (3) plastics that can be broken down and recycled after use.

PRINCIPLES OF MATERIAL PROPERTY SIMULATION

As macro-scale simulation based on continuum mechanics is insufficient on its own for the combined prediction of the chemical, physical, and mechanical properties of a material, analysis of the movement of each of the atoms is also required. When designing plastics that can be broken down after use to allow for recycling, for example, it is necessary to determine whether the chemical bonds between atoms (the overlap of electron clouds) will break or not, and this requires solving the equations of motion for the atoms.

As atoms are made up of a nucleus and its surrounding electrons, simulation involves calculating the states of the nucleus and electrons. While the atomic nucleus follows Newton's equation of motion (force = mass × acceleration), the fundamental equation of classical mechanics, it was determined in the early 20th century that this equation could not be used for the electron, which has a mass of less than a thousandth that of a nucleus. Instead, the more fundamental principles of quantum mechanics are required. In fact, like the electron, the physical properties that follow classical mechanics, such

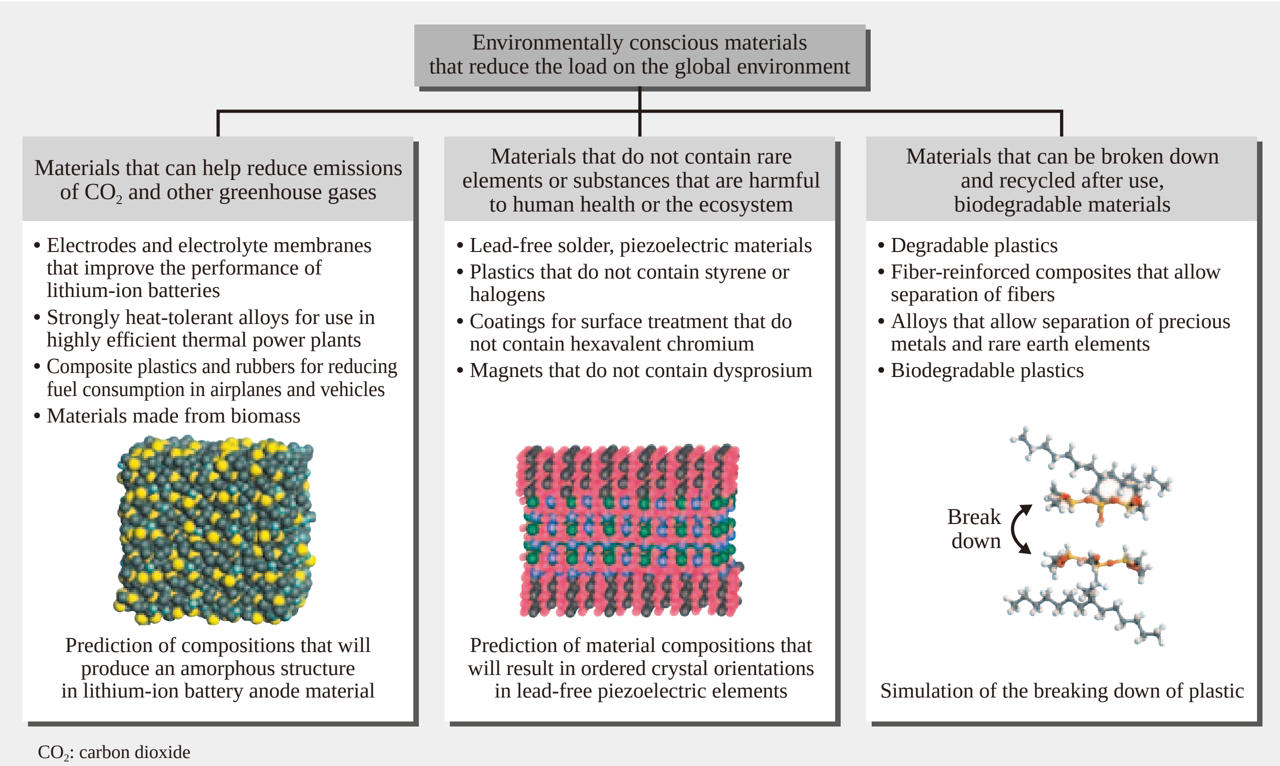

Fig. 1—Overview of Material Property Simulations for Efficient Design of Environmentally Conscious High Functional Materials.
These are examples of materials that reduce the load on the environment include materials that help reduce emissions of CO_2 and other greenhouse gases, materials that do not contain lead or other substances that are harmful to human health or the ecosystem, materials that can be broken down and recycled after use, and biodegradable materials.

as the atomic nucleus and the objects visible in the world around us, can also be described by the Schrödinger equation (the fundamental equation of quantum mechanics). However, when realistic approximations are made for objects with masses several thousand times or more that of an electron, it frequently turns out that Newton’s equation of motion closely approximates the Schrödinger equation and therefore that behaviors can be adequately expressed by classical mechanics.

The Schrödinger equation can be written as follows, where the states of electrons and other particles are represented as waves and described by a wave function, $\psi(r, t)$.

$$\{-\hbar^2/(2m)\}\partial^2\psi/\partial r^2+U\psi=i\hbar\partial\psi/\partial t \quad \ldots(1)$$

Here, m represents mass, r represents spatial coordinates, t represents time, U represents potential energy, i is the imaginary unit (square root of -1), and $\hbar$ is Planck’s constant ($\hbar=1.05457\times10^{-34}$ J·s). Omitting details, it can be demonstrated that the wave for a particle with a mass m that is several thousand times that of an electron can be represented as a spatially localized wave packet, and that the motion of this wave packet can be approximated by Newton’s equation of motion. This means that an atomic nucleus or objects visible in the world around us can be represented using Newton’s equation of motion. Even though we now understand that quantum mechanics provides the fundamental underpinning, Newton’s equation of motion from classical mechanics still retains an important role in describing the behavior of physical objects.

The following sections describe examples of the design of environmentally conscious materials based on predictions of their physical properties obtained by using molecular simulation technology. This technology determines the overall material behavior by combining the use of quantum mechanics to solve for electron behavior with the use of classical mechanics to solve for atomic nuclei behavior (see Fig. 2)[1].

DESIGN OF ANODE MATERIAL FOR NEXT-GENERATION LITHIUM-ION BATTERIES

The most common anode materials currently used in lithium-ion batteries are graphite and amorphous carbon. Commercial lithium-ion batteries that mix additives such as tin (Sn) alloy or silicon into carbon anodes to achieve higher capacity[2] are also available,

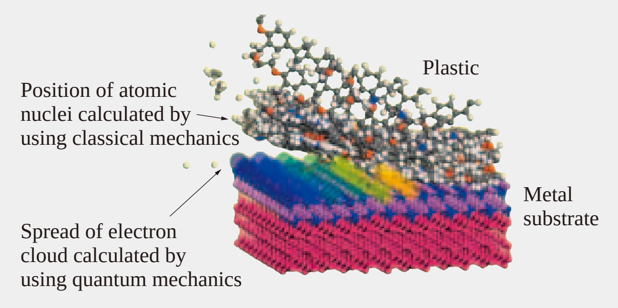

Fig. 2—Overview of Molecular Simulation.
This overview of molecular simulation shows an example of a peel test in which an external force is applied to peel off a plastic material bonded to a metal substrate.

and studies are being carried out on materials that use carbon nanotubes (see "Low-energy Electron Diffractive Imaging for Three-dimensional Light-element Materials" in this issue). To provide these batteries with the performance and reliability for use in future HEVs or electric vehicles (EVs), they will require both higher capacity and longer life. However, if their atomic arrangements retain a regular crystalline state, new materials such as Sn alloys are prone to degrading due to the large expansion and contraction strains that result from the absorption and release of lithium during charging and discharging, and this makes extending their operating life more difficult (see "Lifetime Prediction for Heavy-duty Industrial Lithium-ion Batteries that Enables Highly Reliable System Design" in this issue for an explanation of battery life prediction technology when using carbon).

Therefore, to prevent the generation of the large strains associated with the absorption and release of lithium, it is necessary to transform the alloy into an amorphous state (in which the atomic arrangement is disordered). Normally, metal alloys tend to adopt a crystalline state and often will not adopt an amorphous state even if melted and rapidly cooled. In response, Hitachi applied the molecular simulation technology described above to analyze what alloying elements should be added to achieve an amorphous state alloy capable of being used as the anode material in a lithium-ion battery.

Fig. 3 shows the atomic arrangement obtained by a simulation of the rapid cooling of a molten alloy consisting of equal quantities of Sn, cobalt (Co), and bismuth (Bi). The figure shows an ordered atomic arrangement indicating that the alloy has adopted a crystalline state. Fig. 4, meanwhile, shows the atomic arrangement obtained by a simulation of the rapid cooling of a molten alloy consisting of equal quantities of Sn, Co, and zirconium (Zr). Unlike in Fig. 3, no ordered arrangement of atoms is evident, indicating that an amorphous state has been achieved.

In this way, the mix of elements needed to produce an amorphous state alloy suitable for use as an anode material in next-generation lithium-ion batteries can be calculated based on knowledge from simulations.

DESIGN OF LEAD-FREE PIEZOELECTRIC MATERIAL

Uses for piezoelectric elements made from piezoelectric material sandwiched between electrodes include actuators that convert voltage into force and sensors that convert force into voltage. Currently, lead zirconate titanate [Pb(Zr,Ti)O_3, also known as PZT] is used as the piezoelectric material, and palladium (Pd) or platinum (Pt) are used as the electrodes. However, because lead is harmful to human health and the ecosystem, work is in progress on developing alternative lead-free piezoelectric materials. Examples include the development of materials made by

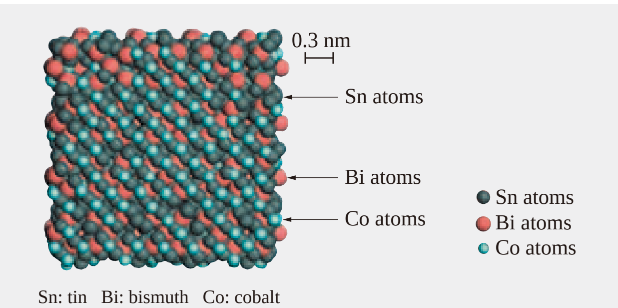

Fig. 3—Atomic Arrangement Obtained by Simulation of Rapidly Cooled Molten SnCoBi Alloy.
The alloy adopts a crystalline state characterized by an ordered atomic arrangement, making it unsuitable for use as the anode material in a lithium-ion battery.

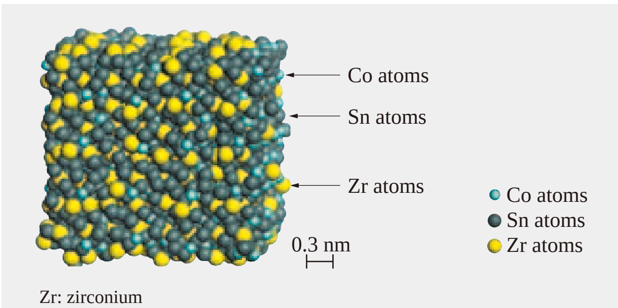

Fig. 4—Atomic Arrangement Obtained by Simulation of Rapidly Cooled Molten SnCoZr Alloy.
The alloy adopts an amorphous state characterized by a disordered atomic arrangement, making it suitable for use as the anode material in a lithium-ion battery.

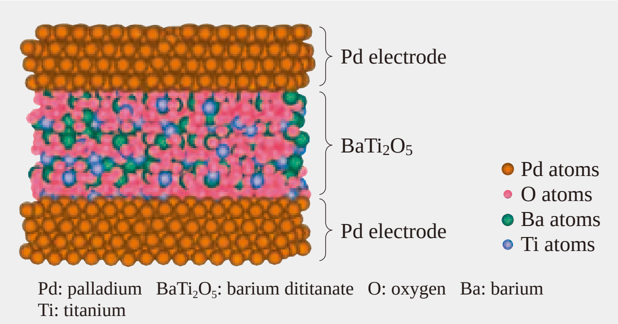

Fig. 5—Atomic Arrangement of $BaTi_2O_5$ Sandwiched between Pd Electrodes.
The disordered atomic arrangement of $BaTi_2O_5$ indicates it will not have adequate piezoelectric properties.

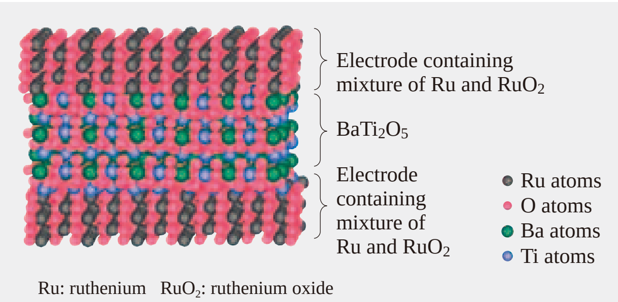

Fig. 6—Atomic Arrangement of $BaTi_2O_5$ Sandwiched between Electrodes of Mixed Ru and RuO_2.
The ordered atomic arrangement of $BaTi_2O_5$ indicates it will have excellent piezoelectric properties.

adding iron (Fe) to the currently used barium titanate ($BaTiO_3$), or materials in which another form of barium dititanate ($BaTi_2O_5$) or a niobium oxide such as (potassium, sodium) niobium oxide [(K, Na) NbO_3] are the main components. However, it remains unclear whether these materials can exhibit a higher level of piezoelectric properties than lead zirconate titanate (which contains lead). In response, studies are currently being conducted aimed at improving the level of piezoelectric properties by changing not only the piezoelectric material but also the material used for the electrodes between which the piezoelectric material is sandwiched.

$BaTi_2O_5$ is being studied as a potential lead-free piezoelectric material. Fig. 5 shows the analysis result for a molecular simulation of the atomic arrangement when this material is used with conventional Pd electrodes. The atomic arrangement of $BaTi_2O_5$ is disordered causing the force generated by the voltage to be dispersed and resulting in inadequate piezoelectric properties. In contrast, Fig. 6 shows the analysis result for a molecular simulation of the atomic arrangement when $BaTi_2O_5$ is sandwiched between electrodes made of a mixture of ruthenium (Ru) and ruthenium oxide (RuO_2). Unlike in Fig. 5, the material has an ordered atomic arrangement. Without going into details, this ordered structure means that the force generated by the voltage will not be dispersed and the material will have a high level of piezoelectric properties.

This shows how the piezoelectric properties of a material are determined in combination with the electrode material and not by the piezoelectric material alone, and indicates that an electrode material made from a mixture of Ru and RuO_2 is suitable for use with $BaTi_2O_5$.

In this way, molecular simulation can be used to identify lead-free piezoelectric materials that exhibit a high level of piezoelectric properties in conjunction with their electrode material.

DESIGN OF PLASTICS THAT CAN BE BROKEN DOWN FOR RECYCLING

The use of plastics to reduce weight in airplanes, vehicles, and other machinery has become common as a way of cutting their exhaust gas emissions and improving fuel consumption. Plastics are often reinforced by incorporating ceramic, carbon, or other types of fibers to produce composites, and there is a growing need to design plastics capable of being broken down to extract the plastic raw material and fiber for reuse. As producing prototypes and then conducting experiments to determine whether the material can be broken down is very time consuming, the molecular simulation technique described above provides an effective alternative means for achieving this.

Fig. 7 shows the use of methanol (CH_3OH) at high temperature and pressure to break down a polyethylene containing siloxane (Si-O-Si) bonds. As indicated by the figure, the equation for the bond

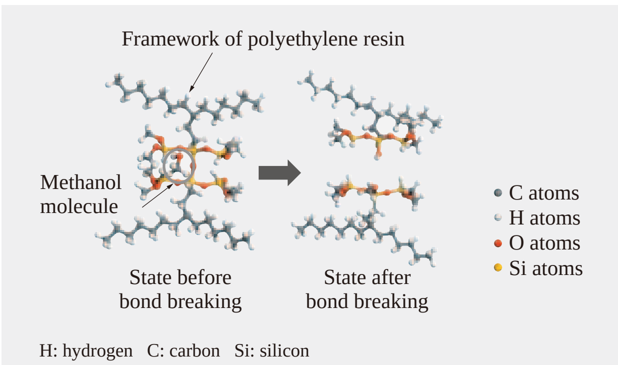

Fig. 7—Plastic being Broken Down by Methanol Molecule.
The figure shows how the siloxane bond is broken by methanol at high temperature and pressure, causing the plastic to break down.

breaking reaction is as follows.

-Si-O-Si- + $CH_3OH \rightarrow$ -Si-OCH_3 + HO-Si

In this way, molecular simulation can be used to determine whether a plastic can be broken down, enabling the design of materials that are easy to recycle.

CONCLUSIONS

This article has described material property simulation technology for designing environmentally conscious high functional materials, using as examples an anode material for lithium-ion batteries, a lead-free piezoelectric material, and plastics that can be broken down and recycled after use.

This technology is also suitable for use with a wider range of other environmentally conscious materials, including the design of materials that do not contain rare elements, such as magnets without dysprosium or transparent electrodes without indium, and of strongly heat-tolerant materials able to withstand high steam temperatures to improve the efficiency of thermal power plants. In the future, Hitachi plans to apply this technology in the design of a wide range of materials with the aim of improving the reliability and performance of various different products.

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Platform Technology for Computational Fluid Dynamics Supporting Design of System Products

—from Power Plants and Industrial Machinery to Home Appliances

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OVERVIEW: Pumps, fans, and other fluid devices are used in a wide range of system products, from power plants and industrial machinery to home appliances. Although CFD has been used in the design of these devices for some time, growing demands to reduce the load on the environment, to improve reliability and other aspects of product performance, and to cut costs are driving the need for analyses that cover a broad scope and achieve a high level of accuracy. On its own and through collaborations between industry and academia, Hitachi is responding to this need by working on large-scale analyses using fluid dynamics to study phenomena that could not previously be tackled. Hitachi is also applying techniques such as multi-objective design optimization in situations where trade-offs exist between different objectives, and special cavitation analysis techniques.

INTRODUCTION

THE pursuit of greater energy efficiency is an important consideration in the development of many different products, from home appliances to power plants and industrial machinery. Competition on energy efficiency in the field of home appliances is becoming progressively more intense with each passing year, and development is ongoing with attention given to even the smallest of losses. As small differences in efficiency have a significant impact on power plants and industrial machinery, Hitachi recognizes the importance of developing products with superior efficiency to those of its competitors. Pumps, fans, and other fluid devices are used in many of these systems, and computational fluid dynamics (CFD) has for some time been successfully used as a core technology for their design.

However, as CFD comes to be used in routine design work, the development of distinctive products requires that further work be undertaken in areas such as techniques for applying CFD in design and in the study of phenomena that are not amenable to analysis by conventional techniques.

This article describes examples of the use by Hitachi of core CFD technologies, including the use of CFD by high performance computing for the visualization of noise sources and the study of unstable head curves in pumps, the use of multi-objective design optimization techniques for control of unstable phenomena and high efficiency in blowers, and the use of cavitation analysis to predict where erosion will occur on pump impellers and to determine how to improve residual stresses in the internal structure of nuclear reactors.

TECHNIQUES FOR CFD BY HIGH PERFORMANCE COMPUTING

The prediction of phenomena such as fan noise or the unstable head curves of pumps at low flow rates requires that detailed analyses be performed that treat the flow as an unsteady phenomenon. To predict these phenomena, Hitachi is working with The University of Tokyo on the development of technology for CFD by high performance computing. The following section describes analyses performed using free software called “FrontFlow/blue (FFB).” FFB is primarily

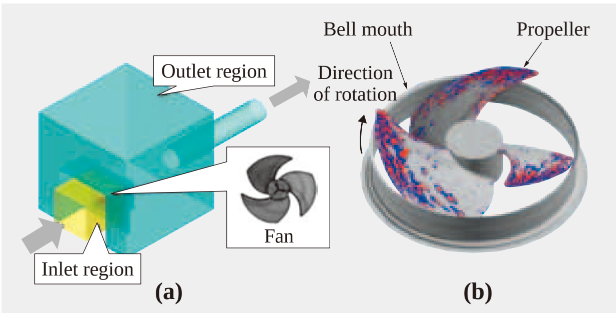

Fig. 1—Visualization of Fan Noise Source.
Diagram (a) shows the computational model, and diagram (b) shows a Powell noise source map. The computation was performed for a total of 16 million mesh elements, of which 2.8 million corresponded to the blade-to-blade region.

developed by The University of Tokyo, and is based on incompressible large eddy simulation (LES). FFB is therefore suitable for high performance computing.

Visualization of Fan Noise Sources

Reducing the aerodynamic noise produced by the fans used in products such as chillers and air conditioners, home appliances, and information technology (IT) equipment is an important consideration when seeking to improve comfort in the home, workplace, and other environments. The development of low-noise fans requires techniques for visualizing noise sources.

Fan noise is caused by phenomena such as flow separation and lift fluctuation due to vortices. Accordingly, it is necessary to capture the fluctuation of tip vortex and flow separation on the blade surface for the visualization of a noise source. The large-scale unsteady fluid analyses required to evaluate these phenomena can be performed by using FFB and super computer.

Fan noise source visualization[1] based on analysis results was performed to investigate location where aerodynamic noise generates (see Fig. 1). The Powell noise source referred to in the figure is an index that represents the noise source due to deformation of vortices [div($\omega \times v$), where ω is vorticity and v is velocity][2]. The figure shows how the noise sources are concentrated at the tips and around the leading edges, indicating that the tips and leading edges are influencing the noise. In this way, use of analysis to identify noise sources helps find ways to reduce fan noise.

Study of Unstable Head Curves in Pumps

When operating in their partial capacity range, pumps sometimes become unstable, resulting in pulsations in their flow rate and pressure. For this reason, it is necessary to develop pump design techniques (operating range enlargement) that will avoid unstable head curves and produce pumps capable of stable operation over a wide range of flow rates.

Causes of an unstable head curve include flow separation from the blade. Accordingly, the prediction of unstable head curves requires the execution of large-scale unsteady fluid analyses by using LES, a technique capable of predicting the behavior of unsteady and complex flows.

Working with The University of Tokyo, Hitachi undertook a study of the causes of unstable head curves using CFD by high performance computing with 78 million mesh elements[3] (see Fig. 2). The figure shows how localized pressure increases occurred along the trailing edges of the blades, and that these pressure increases caused flow separation to occur. The results demonstrated that the influence of this flow separation extended to the adjacent blade and that these phenomena were the cause of the unstable head curve. Hitachi is studying complex flow phenomena through detailed analyses such as this to devise new design method.

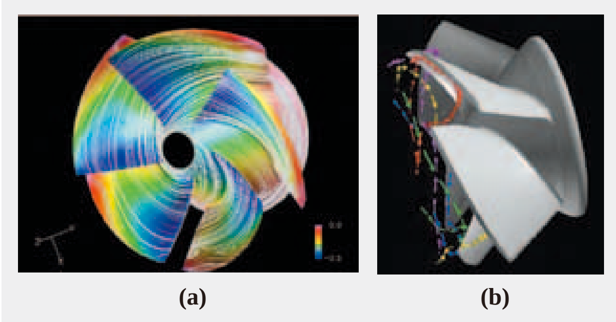

Fig. 2—Results of Analyzing Pump Operating in Partial Capacity Range.
The figures show the distribution of pressure on the blade surface (a) and the stream lines on the suction side of the blades (b). Computational fluid dynamics (CFD) by high performance computing can be used to perform detailed analyses.

MULTI-OBJECTIVE DESIGN OPTIMIZATION TECHNIQUES

Multi-objective optimization is a technique for evaluating the trade-offs between several product characteristics (objective functions). The multi-objective genetic algorithm (MOGA) is one of the multi-objective optimization techniques, and Hitachi has developed an optimization method that combines MOGA with CFD and applied it to the development of products such as vacuum cleaner fans[4]. The following is an example that achieved higher efficiency and wider operating range in centrifugal blowers for sewage aeration using this method.

Definition of Multi-objective Optimization Problem for Centrifugal Blower Impeller

Centrifugal blowers are widely used in products that require liquid or gas to have relatively high pressure and a low flow-rate. Centrifugal impellers are one of the components of centrifugal blowers and require higher design-point efficiency and, like the pump described above, wider operating range. In general, design-point efficiency and operating range are in a trade-off relationship. Therefore, adjustment of this trade-off is important in impeller design.

Performing multi-objective optimization using CFD results at the design and some low-flow-rate points is a simple method for evaluating the impeller operating range. However, this approach is very time-consuming. As an alternative, Hitachi developed a technique for evaluating the impeller operating range only from the CFD result at the design point.

Senoo et al.[5] reported that an increase of the relative velocity deceleration ratio from the inlet to the throat of an impeller causes an increase in the boundary layer thickness near the throat and flow separation. Here, the throat of the impeller is defined as the section where the sectional area of the blade-to-blade passage becomes narrowest. In our preliminary investigation, the flow separation near the throat occurred in several impellers analyzed by CFD. Moreover, in these impellers, the larger the throat deceleration ratio ($W_1/W_{th,s}$) at the design point, the higher the flow-rate at which the flow separation occurred [see Fig. 3 (a)]. In other words, a reduction of $W_1/W_{th,s}$ at the design point decreases the flow-rate at which flow separation and impeller stall occurs and improves the operating range.

Accordingly, an impeller shape optimization using the adiabatic efficiency (η_{imp}) and $W_1/W_{th,s}$ derived from CFD at the design point as the objective functions was performed[6].

Optimization Results

The distribution of solutions obtained from the optimization result shows the trade-off relationship between these two objective functions clearly [see Fig. 3 (b)]. The solution that showed the best balance between η_{imp} and $W_1/W_{th,s}$ was selected as the optimized shape. The results of a detailed analysis indicated that the optimized shape achieved 1.8% higher efficiency and 5% wider operating range than the conventional one [see Fig. 3 (c)].

In this way, it was confirmed that selecting appropriate evaluation indices (objective functions) could expand the scope of application of multi-objective optimization. Hitachi considers that the applications of design optimization can be further expanded by finding new evaluation indices using CFD by high-performance computing as described earlier in this article.

CAVITATION ANALYSIS TECHNIQUE

Cavitation is a phenomenon of bubble generation in low-pressure regions in a liquid. When the bubbles collapse, a high level of impact energy is released to the surrounding area under certain conditions. While this impact energy applied to the material can cause erosion, it can also be utilized for improving residual stress. Hitachi, therefore, has developed an analysis technique that considers the pressure interaction between flow and bubbles at a scale factor of 10^6. This analysis technique can be used both to predict the behavior of bubbles that expand and contract on the order of a microsecond and to estimate the impact energy[7]. The sections below describe the application of this cavitation analysis technique to a large industrial pump and to a preventive maintenance technology for nuclear power plants.

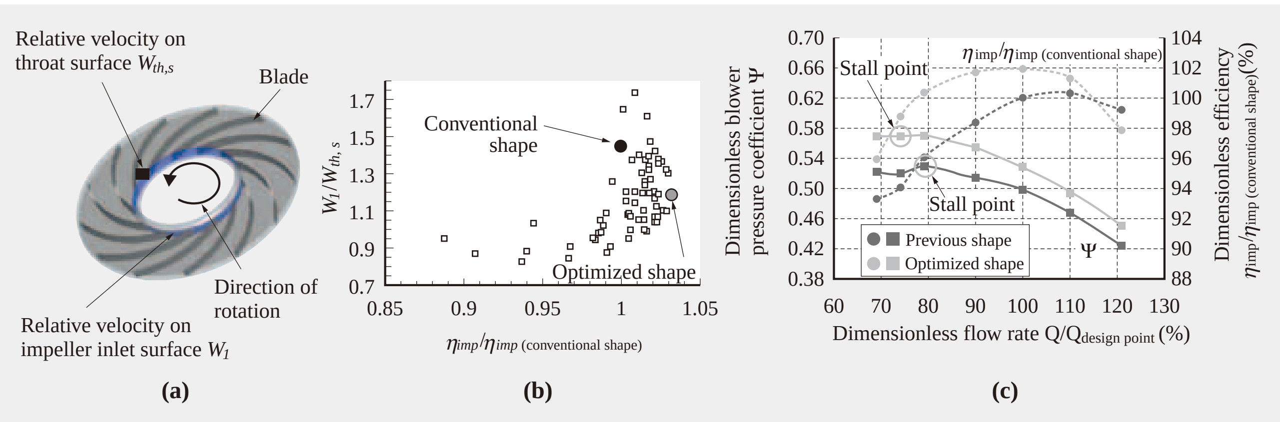

Fig. 3—Multi-objective Optimization of Centrifugal Blower Design.
Diagram (a) shows the impeller. The operating range of the centrifugal impeller can be estimated from the throat deceleration ratio at the design point. Graph (b) shows the results of design optimization. The vertical axis represents the throat deceleration ratio and the horizontal axis represents the dimensionless efficiency, such that points at the bottom right corner of the graph indicate superior performance. The detailed analysis results in graph (c) show how the selected optimum shape has improved efficiency and shifted the point at which stalling occurs to a lower flow rate, indicating a wider operating range.

Prediction of Erosion Location on Pump Impeller

Pumps are a form of fluid machinery that is used extensively in social infrastructure such as industrial plants, water treatment and sewage plants, and vehicles. Ensuring the reliability of pumps is an important mission. If it becomes possible to predict whether and where cavitation erosion occurs in a pump, it is possible to take measures to prevent it at the design stage.

In the past, the detection of the erosion location in a large pump was done by making a small model pump for experimental tests. After the impeller was painted and the pump was operated for a certain period of time, the location of erosion could be identified by noting where paint peeling occurred, which indicates where the impact energy was high. By using the new analysis technique, Hitachi achieved a world-first prediction of the expansion and contraction of large numbers of bubbles in a rotational flow field, and the distribution of bubble nuclei. The predicted bubble behavior was then used to estimate the distribution of impact energy(7). This allowed the design to be completed in a short period of time taking account of reliability as well as performance (see Fig. 4).

Prediction of Residual Stress Improvement on Structure Surface in Nuclear Reactor

Tensile residual stress occurs on weld surfaces of the internal structure of nuclear reactors at nuclear power plants. The tensile residual stress can be a cause of stress corrosion cracking when combined with sensitization of materials and a corrosive environment.

Water jet peening (WJP) is a preventive maintenance technology for mitigating stress corrosion cracking.

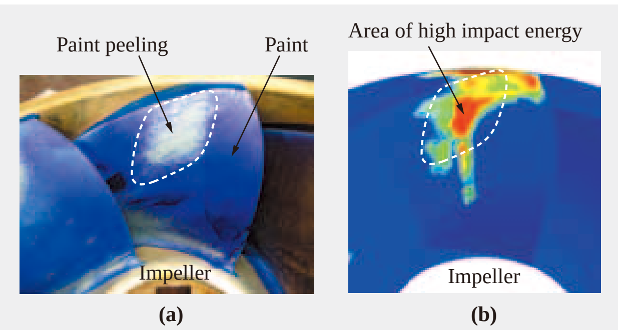

Fig. 4—Location of Cavitation Erosion on Pump Impeller.
Diagram (a) shows the result of a paint test on a small model pump, and diagram (b) shows the impact energy distribution determined by the analysis. The results show a good agreement between the area where the cavitation caused the paint peeling and the area of high impact energy.

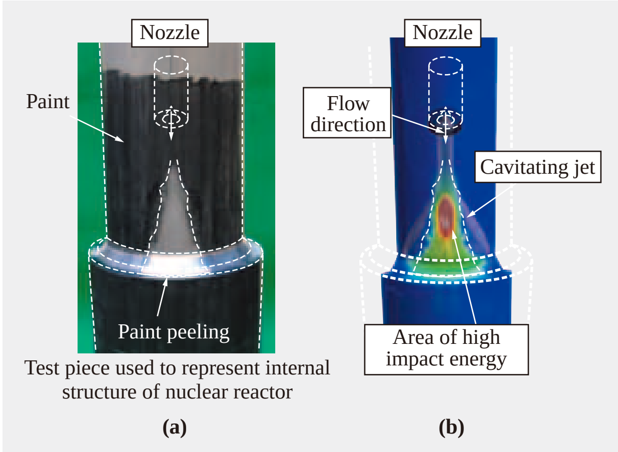

Fig. 5—Residual Stress Improvement on Internal Structure Surface in Nuclear Reactor.
Diagram (a) shows the results of a paint test using a mockup of the internal structure in a nuclear reactor. High compressive residual stress was measured in the region where the paint was peeled due to cavitation. Diagram (b), meanwhile, shows the impact energy distribution determined by the analysis. The results show a good agreement between the area where the paint was peeled and the area of high impact energy.

It reduces the risk of stress corrosion cracking by applying a cavitating jet from an underwater nozzle to welds so that the impact energy converts the residual stress from tensile to compressive.

In the past, the nozzle locations were selected by operating WJP on mockups of the internal structure and measuring the distribution of the residual stress after WJP. However, by quantifying the strong correlation between the impact energy and the residual stress, the developed analysis is able to estimate the residual stress from the impact energy(8). As a result, it is now possible to investigate the operating conditions of WJP in detail at low cost (see Fig. 5).

CONCLUSIONS

This article has described examples of the use by Hitachi of core CFD technologies for product design.

While CFD already has a long history of use in product design, the development of new analysis techniques and other improvements such as in computer performance mean that routine design work can now take advantage of more advanced types of analysis. These practical applications in turn bring about new challenges and requirements. In response to these challenges, and to take advantage of technical innovations in product development, Hitachi believes that continuing to seek innovations in core CFD technologies is important, and that this represents a foundational technology for Hitachi.

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Welding Simulation Technologies for Highly Efficient Production of High-quality Social Infrastructure Products

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OVERVIEW: Welding makes up a large proportion of the processes involved in the manufacture of social infrastructure products, and greater use of global procurement and production practices is making weld quality assurance and welding efficiency improvements more important. Hitachi has developed technology for simulating the welding of large structures to improve their reliability and to shorten production times by predicting the behavior of the welding process. Hitachi is using this technology to establish appropriate designs and placements for welding jigs, as well as welding procedures and other operational requirements.

INTRODUCTION

LARGE welded structures are used extensively in power plants, industrial machinery, construction machinery, rolling stock, and other types of products, and welding accounts for a large proportion of the overall manufacturing process. In most cases, welds are made at a number of different locations. Typically, practices such as welding procedures and the design and placement of the welding jigs used to minimize the distortion that occurs during welding are determined based on experience, and a considerable amount of time is spent on subsequent remedial work. Greater diversity in materials procurement and production sites is also raising other concerns, such as variations in weld quality caused by differences in material properties and defects caused by inexperienced welders. To overcome these problems, Hitachi is working on the development of a support system that uses simulation to predict weld quality (execution of weld) and that can determine appropriate material selections and other operational requirements.

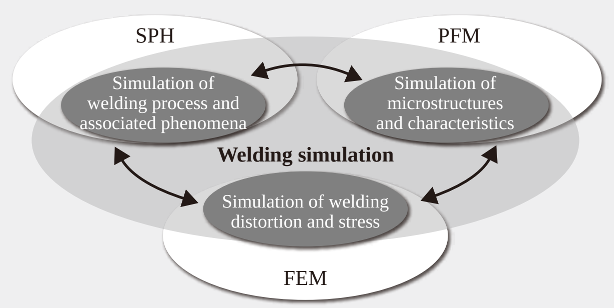
This article describes welding simulation technologies for the highly efficient production of high-quality social infrastructure products.

DEVELOPMENTS IN WELDING SIMULATION TECHNOLOGY

As welding is an extremely complex process that resists systematization as a topic of study, it is not possible to predict all welding phenomena and other outcomes from a single simulation. Accordingly, a range of different simulation methods are used to suit different objectives.

Overview of Progress in Welding Simulation

Fig. 1 shows the main research topics and analysis techniques associated with welding simulation. In broad terms, the commonly used methods can be divided into simulations of welding distortion and stress that use techniques such as the finite element method (FEM)(1), simulations of the welding process and associated phenomena that use techniques such as smoothed particle hydrodynamics (SPH)(2), and simulations of the microstructure of weld metal and its properties that use techniques such as the phase field method (PFM)(3). Essentially, the FEM and SPH methods are discrete numerical techniques for solving equations that describe a continuous body in terms of its dynamics. PFM on the other hand is a thermodynamics-based technique for simulating



SPH: smoothed particle hydrodynamics PFM: phase field method
FEM: finite element method

Fig. 1—Research Topics and Analysis Techniques for Welding Simulation.
A range of different simulation techniques are used to suit different objectives, including analyses of welding distortion and stress, the welding process and its associated phenomena, and weld microstructures and characteristics.

phenomena such as the segregation of elements and the evolution of the microstructure in the material. The calculation accuracy and computational speed of techniques for simulating distortion and stress that were first used in the 1970s have been improved markedly, and these are now used in a wide range of fields. Attention in recent years has been directed toward areas such as research into the use of SPH for welding process simulations that include the flow of material, and the use of PFM to simulate the various different microstructural changes that occur in the material.

Current Status of Welding Simulation Research at Hitachi

Hitachi has developed techniques for improving analysis speed and accuracy, and also a database of properties material that takes account of factors such as material, structure, and environment based on past FEM analyses of heat transfer and structure. Hitachi has also worked on estimating weld life and on predicting welding distortion in actual products as well as residual stress and crack propagation in welds[(4), (5)]. Recently, Hitachi has also been actively working on SPH and PFM techniques for simulating the welding process as well as weld microstructures and properties, and is developing integrated simulation techniques that also incorporate FEM.

The following sections describe the development of a technique for simulating welding distortion in large structures, and examples of its application.

DEVELOPMENT OF WELDING DISTORTION SIMULATION TECHNIQUE

Basic Methodology of Welding Distortion Simulation

Use of FEM for welding distortion simulation can be broadly divided into the thermo elastic plastic (TEP) method and the inherent strain method of elastic analysis. TEP analysis starts with an analysis of transient heat conduction to obtain the thermal history of the welds in the welded structure being analyzed. Then, TEP analysis is used to calculate the strain and stress history. Because it divides the period from the start to the end of the welding process into small time intervals, this method allows highly accurate simulations to be performed that closely model the thermal and deformation history of actual welds. In the case of large-scale welding structures, however, the long calculation time required to combine an analysis of a moving heat source with a TEP analysis makes this impractical in many cases.

The inherent strain method uses elastic analysis to calculate the welding distortion from the response of the welded structure to the inherent strains generated in the weld and surrounding areas. The inherent strain resulting from a weld is the elastic strain subtracted from the apparent strain, which by solid mechanics is equal to the residual plastic strain. The inherent strain is obtained either from strain measurements in welding experiments or from the plastic strain calculated by TEP analysis using a model of a specific region. Because it allows the deformation of a structure to be obtained by using only elastic analysis, the inherent strain method significantly shortens the calculation time. On the other hand, its inability to track the time evolution of an actual weld means its application in high-precision simulation is limited.

More Advanced Simulation of Distortion in Large-scale Welding Structures

For simulating the distortion of large structures, Hitachi has been developing a technique suitable for use on actual products. Past activities have involved selecting suitable techniques based on the requirements of the product concerned and the purpose of the simulation, and developing techniques for optimizing the analysis model together with experimental and measurement technology. Hitachi has also been working on joint research with universities aimed at developing distortion simulation techniques that combine higher accuracy with faster calculation speed.

While use of the TEP method is desirable when simulating the deformation of large structures with small numbers of welds that require appropriate welding conditions, one problem with this is the calculation time that is needed. Accordingly, Hitachi is working to reduce the calculation time by combining an elastic analysis of the entire structure with a TEP analysis of the weld and adjacent areas based on elastic analysis using the inherent strain method. When constructing analysis models that take account of the characteristics of the actual structure, Hitachi uses a three-dimensional solid model in regions where a TEP analysis is required and a two-dimensional shell model in regions where elastic analysis is required. Meanwhile, to improve the analysis accuracy, Hitachi has also conducted experimental testing to measure inherent strain and other material characteristics, and utilized this information in the analysis models to fine-tune the analysis conditions.

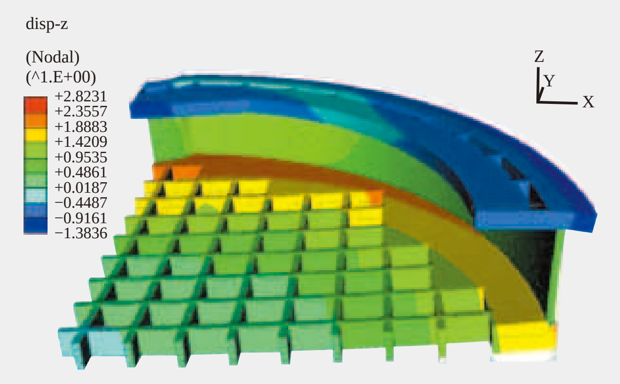


Fig. 2—Example Simulation of Deformation in Large-scale Welding Structure.
The structure has a radius of about 3 m and a height of about 1.2 m.

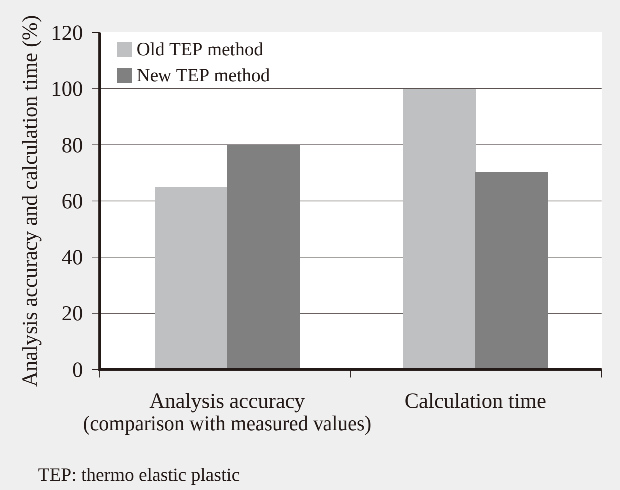


Fig. 3—Comparison of New and Old Methods.
The newly developed method achieved an improvement in accuracy of more than 10% while reducing calculation time by about 30%.

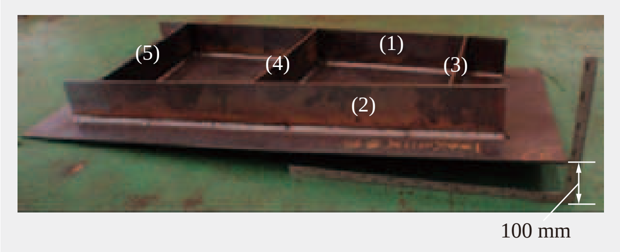


Fig. 4—Welding Structure Used for Experimental Testing.
This structure with a length of 1,200 mm and width of 600 mm was fabricated by welding sheet with a thickness of 6 mm [parts (1) to (5) in the photograph]. Welding resulted in a large deformation of approximately 100 mm.

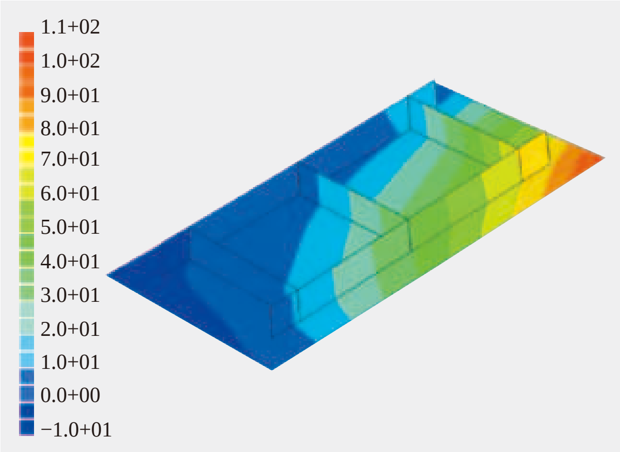


Fig. 5—Results of Analysis Using Inherent Strain Method.
By using a nonlinear version of the inherent strain method that took account of the large deformation, the simulation was able to reproduce with high accuracy the large deformation observed in the experimental test.

By combining a number of different methods in this way, it is possible to simulate the deformation in large-scale welding structures with high accuracy and speed. Fig. 2 shows example calculation results (distribution of deformation) of a welding distortion simulation of a large structure, and Fig. 3 shows a comparison of the previous and newly developed TEP analysis methods.

When simulating deformation in welded structures with a large number of welds with the same joint shape and welding conditions, emphasis is placed on using the inherent strain method and improving accuracy. The factors that influence the simulation accuracy are the inherent strain distribution that results from performing the weld and the specific dynamic characteristics of the structure. To obtain accurate estimates of inherent strain, the TEP method is used in conjunction with experimental testing to calculate the strain distribution. In the case of the specific dynamic characteristics of the structure, a separate method is used to assess the potential for a large deformation to occur, and then either a linear or nonlinear version of the inherent strain method is used, depending on the result.

Fig. 4 and Fig. 5 show an example of the inherent strain method for the case when a large deformation occurs. A test structure with a length of 1,200 mm and width of 600 mm was fabricated by welding sheet with a thickness of 6 mm [see (1) to (5) in Fig. 4]. This welding left behind a large deformation of approximately 100 mm. As running a TEP calculation for such a structure would be very time consuming, the inherent strain method was used instead. However, the version of the inherent strain method used in the past was a linear one that was unable to reproduce the large deformation, resulting in an error of up to 90% between the actual and predicted results.

On the other hand, when the results of analyzing the specific dynamic characteristics of the structure were incorporated, and a nonlinear version of the inherent strain method was adopted that took account of the large deformation, the simulation was able to reproduce with high accuracy this large deformation observed in the experimental test. Fig. 5 shows the analysis result taking account of the large deformation. This shows that the results of analysis and experiment agree, both in terms of the tendency for distortion to occur and the maximum size of the deformation[(6)].

USE OF WELDING DISTORTION SIMULATION TO ENHANCE PRODUCTION PROCESS

This section describes examples of applying welding distortion simulation to large structures.

Elimination of Welding Jig for Large Structures

A method used to minimize welding distortion in large reactor core internal structures (stainless steel) for nuclear power plants is to enclose them in a restraining ring. Using the welding simulation techniques described above, Hitachi has conducted a study into the influence that the type of restraint used has on welding distortion. The results were then used to fine-tune the use of welding jigs during the production of welded structures (to simplify the jig or eliminate it entirely), and to rationalize the production process by reducing the volume of work required for fabrication (see Fig. 6).

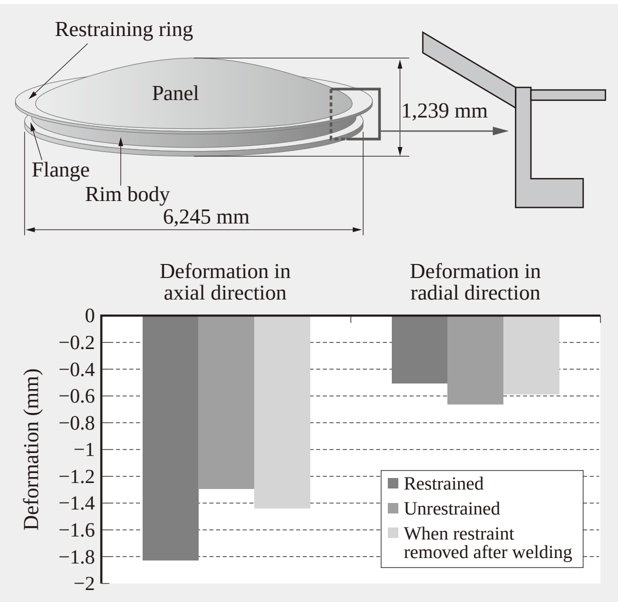


Fig. 6—Example of Welding Distortion in Large Structure.
It is possible to reduce the work associated with attaching the large welding jig used to reduce welding distortion.

Minimizing Welding Distortion

This section describes the use of welding simulation to study the effect that welding methods and the sequence of welding steps have on welding distortion with the aim of reducing work volume (time spent of remediation of welding distortion) and improving weld quality (in terms of welding distortion).

A study of the vertical welding of thick plate, aimed at predicting welding distortion and rationalizing the deformed areas, used a TEP analysis of a moving heat source to investigate the effect that the sequence and direction of weld passes had on welding distortion. The results showed good agreement between the actual and predicted deformation when welding was performed using the method that produced the minimum amount of welding distortion (see Fig. 7).

The effectiveness of the welding distortion simulation technique was also demonstrated in the development of a laser welding technique for reactor core internal structures. This involved a study of the factors that influence the amount of deformation (such as the sequence of laser welding passes) and a comparison with the distortion in arc welding.

CONCLUSIONS

This article has described welding simulation technologies for the highly efficient production of high-quality social infrastructure products.

Welding is a dynamic process made up of a complex combination of different phenomena, making it difficult to simulate in its entirety. As the progress

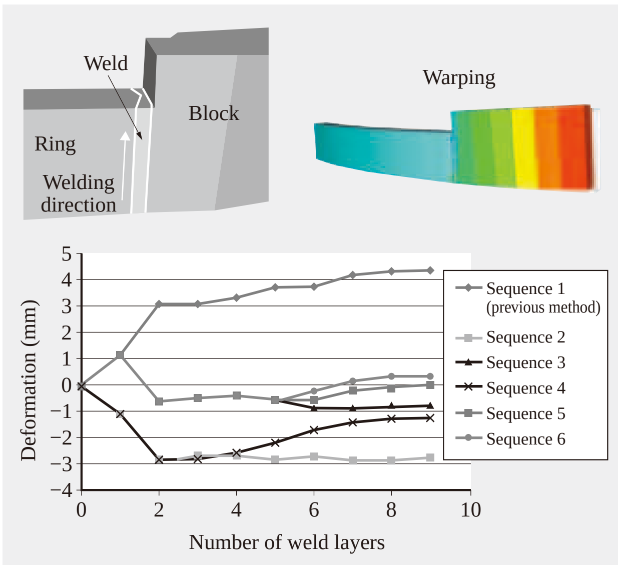


Fig. 7—Example of Reduction in Welding Distortion.
This work aims to use the sequence of successive weld layers to minimize welding distortion.

of technology in recent years has made it possible to analyze the stresses and deformations that result from welding with a level of accuracy and calculation time suitable for practical industrial applications, it is anticipated that its use as a tool for design and production will become more widespread in the future. Although still at the research and development stage, also required will be ways of fine tuning weld designs, operating practices, and similar by using simulation to predict in advance the occurrence of defects caused by the welding process.

In the future, Hitachi intends to continue working on the implementation of computer aided engineering (CAE) systems for welding that support more advanced analysis-driven welding design and process development.

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Next-generation Inverter Technology for Environmentally Conscious Vehicles

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OVERVIEW: Realizing a sustainable society will require a reduction in CO_2 emissions, and energy efficiency is being urged on many different sectors of the economy, including the electric power business, industry, and consumer and transportation businesses. In the transportation sector, in particular, environmentally conscious vehicles that use power electronics will be essential as replacements for conventional vehicles powered by internal combustion engines. The main components used in power electronics include inverters, batteries, and electric motors, and Hitachi is working on the development of specific technologies intended to make these components even smaller and more efficient than before.

INTRODUCTION

WITH steps being taken to reduce carbon dioxide (CO_2) emissions to help achieve a sustainable society, the transportation sector is seeking to improve energy efficiency and reduce CO_2 emissions by switching from conventional vehicles powered by internal combustion engines to hybrid electric vehicles (HEVs) and electric vehicles (EVs). Meanwhile, the power generation sector that produces electric power from primary energy sources is hastening the construction of large power generation systems to increase the amount of power produced from renewable energy sources such as wind and photovoltaic power generation. The construction of smart cities capable of making efficient use of clean and renewable primary energy sources such as these for transportation, industry, and consumer purposes will require small, highly efficient inverter systems, as well as battery systems that will be available when needed for regenerated energy and other surplus electric power (see Fig. 1).

Inverter systems in particular can convert direct-current (DC) electric power from batteries or other sources into alternating-current (AC) electric power, generate this power at the frequency needed for the vehicle speed and other system control requirements at the time of conversion, and accelerate or decelerate the vehicle by controlling the motor revolutions per minute (RPM), torque, power consumption, and other parameters. The features required by electric drive systems such as these in HEVs, EVs, and other vehicles include small size to make them easier to fit inside the vehicle, high efficiency to extend the

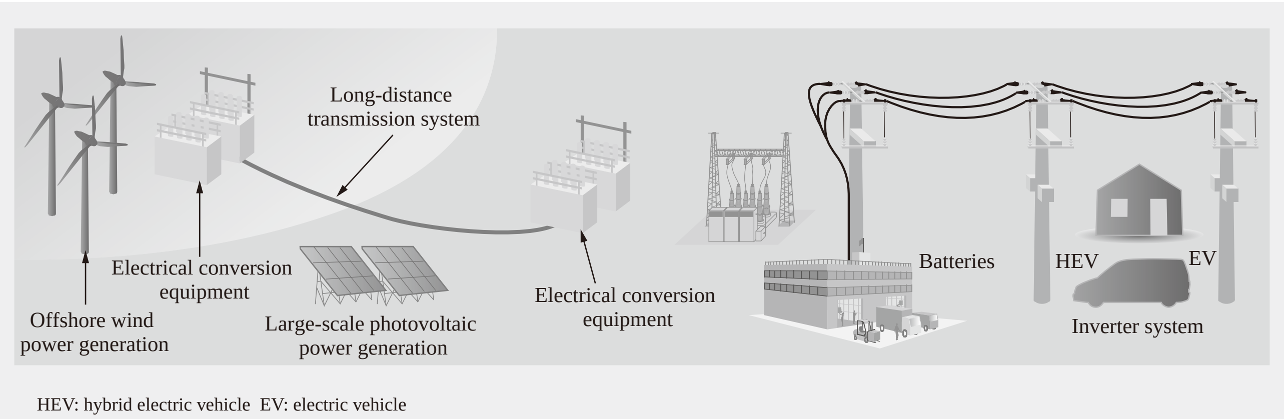

Fig. 1—Inverter Systems Using Renewable Energy.
Smart cities capable of making efficient use of clean and renewable primary energy for transportation, industry, and consumer purposes require small, highly efficient inverter systems and battery systems able to store regenerated energy and other surplus electric power.

vehicle's range, high output to enhance the vehicle's performance, and high reliability to withstand the harsh automotive environment[(1), (2)].

To satisfy these diverse requirements, Hitachi developed direct water cooling in 2007 and succeeded in achieving higher inverter performance and smaller size by utilizing implementation and analysis techniques it had built up in numerous other fields such as the electric power, industrial, and consumer sectors. This development has continued, with ongoing work aimed at making further reductions in the size of electric power conversion equipment by using direct, double-sided water cooling in which the entire cooling fin surface is immersed in coolant[(3), (4)] (see Fig. 2).

This article describes the physical circuit designs needed to make the inverters used for control of electric power smaller and more efficient, and analysis and design techniques that achieve a high level of reliability, including cooling and vibration resistance.

NEXT-GENERATION INVERTER

The challenges to be overcome in achieving higher inverter performance and smaller size include designing electric power wiring that is compact and highly flexible, reducing losses in the power modules, improving cooling system performance, and providing greater reliability, including for the circuit board that contains the control computer. The following sections describe the electric power wiring layout of the next-generation inverter together with a power module design that allows highly efficient, high-speed switching.

Use of Compact Electric Power Wiring to Reduce Inverter Size

The inverters used in HEV systems are typically mounted in the restricted space of the engine compartment, and this often results in more complex internal routing of electric power and a larger housing size in order to improve the ease of connection to the battery, electric motor, and other components. The ideal electric power wiring layout is one that allows the relative positions of the motor and battery wiring to be easily modified, and minimizes the influence of factors such as conversion losses and noise (see Fig. 3).

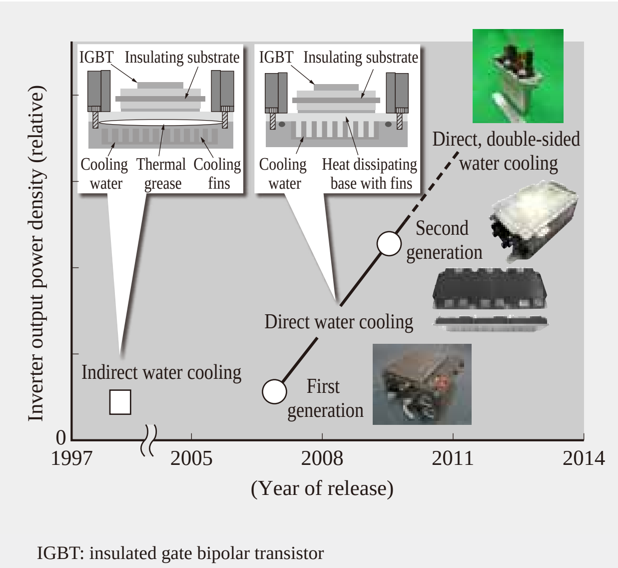

Fig. 2—Development Roadmap for HEV and EV Inverters.
To satisfy the diverse requirements associated with use in a vehicle, Hitachi has developed direct water cooling to achieve smaller size and higher performance by utilizing implementation and analysis techniques derived from numerous other fields, such as the electric power, industrial, and consumer sectors.

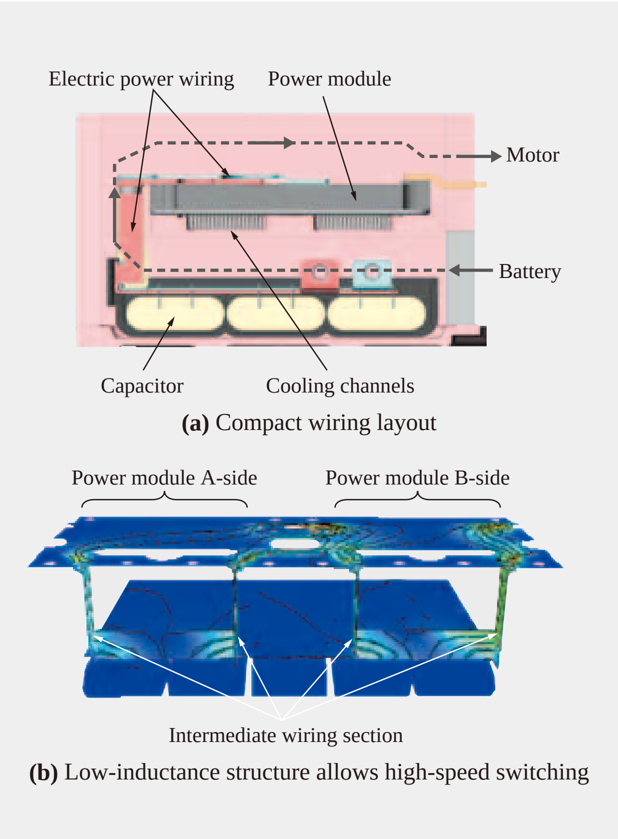

Fig. 3—Wiring Layout and Low-inductance Structure of Next-generation Inverter.
The inverter consists of three areas with cooling water channels running down the center. The design significantly reduces the area required for wiring by providing a compact flow of electric current in the housing. It also provides more flexibility for attaching external connections, and reduces inductance by controlling the current density distribution in the intermediate wiring section.

Fig. 3 (a) shows an outline of how electric power is routed in the second generation inverter developed by Hitachi. A feature of this inverter is that it is made up of three areas, including cooling channels that run down the center, a capacitor underneath, and a power module on top, with the capacitor area providing a highly flexible layout for connection of the battery wiring. This design significantly reduces the wiring area by providing a compact flow of electric current through the housing, as indicated by the dotted line, while also improving the inverter output power density and the flexibility with which the battery wiring can be connected. This increases the inverter output and reduces its size by a factor of more than three compared to the previous model.

Power Module Capable of High-speed Switching

To reduce inverter losses, it is necessary to reduce the power module conduction loss and the switching loss caused by transient changes in voltage and current. In turn, reducing switching loss requires that the inductance of the electric power wiring be reduced to allow high-speed switching(5). Typically, inductance can be reduced by adopting a parallel board layout so that the currents for opposing phases cancel out the magnetic flux. However, connecting the capacitors and power modules to a pair of parallel boards tends to make the housing larger. In response, to reduce the size of the second-generation inverter, Hitachi succeeded in reducing the inductance to the A- and B-side power modules by splitting the electric power wiring between the capacitor area and power module area, connecting four pairs of intermediate wiring to form a small parallel board arrangement between these areas, and providing adequate spacing between them. Fig. 3 (b) shows the results of a current distribution analysis for the electric power wiring. The analysis demonstrated that the effect of the intermediate wiring was to reduce the inductance by spreading the current across the full extent of the electric power wiring in each area, thereby reducing power module losses and minimizing surge voltage, a cause of noise.

OPTIMUM DESIGN TECHNIQUE FOR PIN FIN HEAT SINKS

To cool the power semiconductors and improve reliability, most automotive inverters fitted in vehicles use cooling water to carry the generated heat to the radiator at the front of the vehicle so that it can be dissipated into the air. Especially in the case of HEV and EV inverters that required smaller size and higher performance, the heat generated by the power module is greater relative to volume than it is in industrial and other systems, and therefore a high-performance cooling system is required to remove the heat from the power module. Accordingly, direct cooling is used whereby pin-shaped fins that have excellent heat transfer characteristics with respect to cooling water are formed directly on the heat-dissipating base of the power module.

The challenges for this pin fin heat-dissipating base are how to improve the efficiency of the vehicle's overall cooling system, and how to combine low pressure losses with a high rate of heat transfer from the fins. The performance of the pin fins is largely determined by the shape of the fins, and it is necessary to optimize the fin's shape parameters to satisfy the specifications for both pressure loss and heat transfer rate. The design technique used in the past required a very large number of different combinations to be tested, resulting in a considerable amount of work. In this case, a multi-objective optimization technique was used to improve the performance of the pin fin heat-dissipating base.

To use this multi-objective optimization technique, it is necessary to define objective functions. In the case of the power module, the thermal resistance (R) and pressure loss (P) provided suitable objective functions. Similarly, the pin fin shape parameters served as the design variables. The four variables were height (H), diameter (D), flow-parallel pitch (X/D), and flow-perpendicular pitch (Y/D) (see Fig. 4). The analysis also specified fin height $H < 8$ mm and minimum fin spacing > 1 mm as constraints. The analysis involved varying the design variables within the above constraints to find a shape that satisfied the objective functions for both R and P.

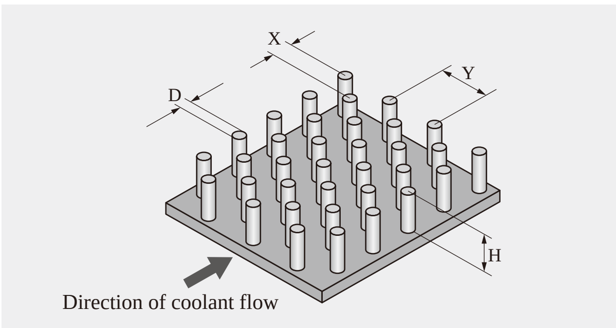

Fig. 4—Definition of Heat Sink Design Variables with Respect to Direction of Coolant Flow.
The variables are the pin height (H), diameter (D), and the pitches in the directions parallel and perpendicular to the flow (X and Y respectively).

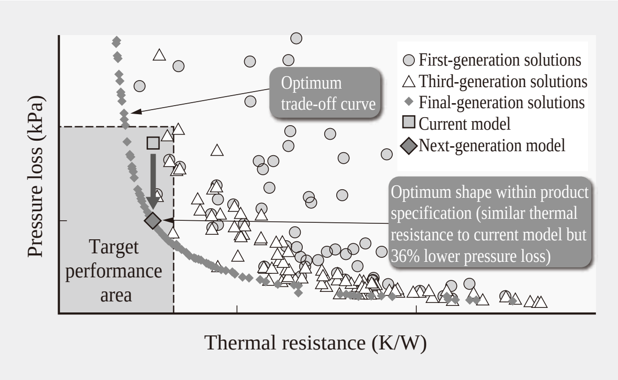

Fig. 5—Results of Multi-objective Optimization Calculation.
A genetic algorithm was used to perform an analysis to minimize the trade-off between pressure loss and thermal resistance. The graph in the figure plots the characteristics of different shapes. While the solutions for the first generation were widely scattered, they had started to concentrate at the bottom left by the third generation. When the process of natural selection was repeated and analysis continued to the final generation, the set of solutions that remained formed a curve representing the optimum trade-off.

The search used a genetic algorithm that repeated 100 iterations of 100 pairs of combinations over the entire analysis range. The result of automatic calculation was to obtain a solution with a thermal resistance (R) similar to that of the heat sink produced by the previous design technique and a pressure loss that was roughly 36% lower. In addition to improving the performance of the cooling system, this technique is also making a major contribution to shortening the design time in ways that include being able to respond quickly to specification changes (see Fig. 5).

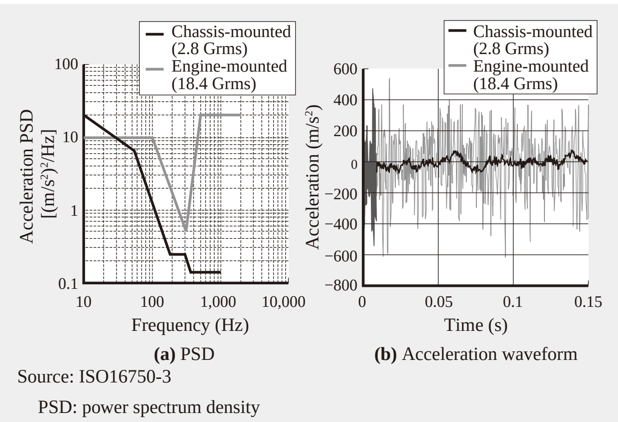

Fig. 6—PSD Representing Intensity at Each Frequency of Random Wave, and Example of Actual Acceleration Waveform.
The vibrations to which an inverter is subject differ significantly depending on factors such as where it is mounted, whether the vehicle has an engine, the engine type, and suspension performance.

TECHNIQUE FOR ASSESSING VIBRATION RELIABILITY

Inverters for HEVs or EVs need to achieve high reliability in the harsh environment inside a motor vehicle. Also, to make effective use of the limited space inside the vehicle, the inverter and other electrical components need to be fitted close to the engine or transmission, both major sources of vibration. This means that the key factor when seeking to design an inverter able to withstand vibration is to make it reliable with respect to vibration while also dealing with the heat, electric power, and other challenges within the confined space available. The vibrations to which an inverter is subject can be broadly divided into: (1) The predominantly sinusoidal vibrations generated by large vehicle components such as the engine or transmission, and (2) The predominantly random vibrations associated with road noise. To improve vibration reliability, it is necessary to assess the influence of both types of vibration. Many car makers use random vibration testing schemes based on standards for vibration testing of automotive parts such as ISO16750-3 and JIS-D1601 (see Fig. 6).

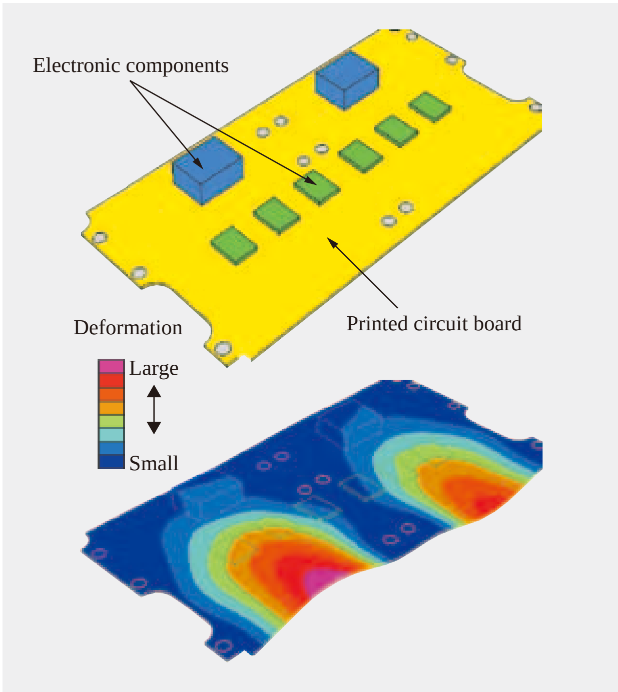

Fig. 7—Vibration Analysis of Inverter Printed Circuit Board.
Used in conjunction with three-dimensional computer-aided design (3D-CAD) software, the technique provides a designer working at a desktop with a workflow that proceeds from shape design to analysis and then uses the assessment results as feedback to the shape.

To allow a range of different types of random vibration to be used, Hitachi has developed an analysis-based random vibration simulation and reliability assessment technique based on vibration simulation techniques that Hitachi has been developing for some time for use with railway, nuclear power plant, and other equipment (see Fig. 7). When combined with three-dimensional computer-aided design (3D-CAD) software, this technique allows the vibration reliability of the inverter to be assessed under a wide range of different vibration conditions. It provides a designer working from a desktop with a workflow in which simulation is used to perform reliability assessments based on shape changes made in the 3D-CAD system, and then this information is used as feedback for the 3D-CAD shape. The technique assesses vibration reliability based on the resonant frequency, deformation, stress frequency characteristics, and other results obtained from the simulation. This assessment can then be used as feedback to the design, including designing appropriate attachment points to minimize unwanted resonance, modifying the structural design to reduce stresses, and vibration isolation design using vibration reduction rubber mounts.

CONCLUSIONS

This article has described the use of Hitachi's analysis techniques for electric power, heat, and vibration to reduce the size and improve the reliability of inverters, a key component of environmentally conscious vehicles.

By making further improvements to these analysis techniques in the future, Hitachi intends to continue working toward achieving a sustainable society by supplying power electronics systems with benefits that include helping to boost the performance of overall systems while reducing the load they impose on the environment.

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Lifetime Prediction for Heavy-duty Industrial Lithium-ion Batteries that Enables Highly Reliable System Design

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Shingo Ito
Tadashi Yoshiura

OVERVIEW: The operating life of the batteries is a major factor in the reliability and cost of energy storage systems such as those used as backup power supplies or for the reduction of generated power fluctuations from renewable energy sources. This article describes research aimed at improving the accuracy of lifetime prediction for lithium-ion batteries by devising a lifetime prediction technique able to handle three variables simultaneously (number of cycles, operating time, and ambient temperature). The work included formulating a new lifetime prediction equation that combines the square root function law, Arrhenius law, and additive law approaches used in the past. The benefits of this prediction technique include both reducing system cost by minimizing the number of batteries required, and improving reliability by providing a clearer understanding of the margin for error. Use of this technique to predict the operating life of batteries in energy storage systems contributes to reduced costs, improved reliability, and other benefits.

INTRODUCTION

THE high energy density and compact and lightweight construction of lithium-ion batteries (“batteries”) make them candidates for use in energy storage systems such as those used as backup power supplies or for the reduction of generated power fluctuations from renewable energy power generation systems. Being able to reliably predict the lifetimes of the batteries used in these applications makes energy storage systems more affordable and gives greater confidence in the estimated operating life of the systems. However, previous techniques were unable to consider three relevant variables for predicting lifetimes simultaneously, namely, the number of cycles, operating time, and ambient temperature, and this made them inadequate for providing accurate predictions of battery lifetime.

In response, Hitachi has formulated a prediction equation that incorporates all three of these variables, and has developed a technique able to predict battery lifetimes accurately.

This article describes a lifetime prediction technique for heavy-duty industrial lithium-ion batteries that allows highly reliable system design.

BATTERY LIFETIME AND PREVIOUS PREDICTION TECHNIQUE

Repeated charging and discharging of batteries causes a gradual decay in their capacity (see Fig. 1). When designing energy storage systems, it is necessary to take this decay into account when selecting the initial capacities to ensure that the batteries continue to satisfy the required design capacity throughout their operating lives. To achieve this, it is important to have a technique available that can accurately predict battery lifetime (the point in the battery’s life when its capacity falls to the level of the design capacity). In turn, accurate prediction of lifetime requires an understanding of the processes

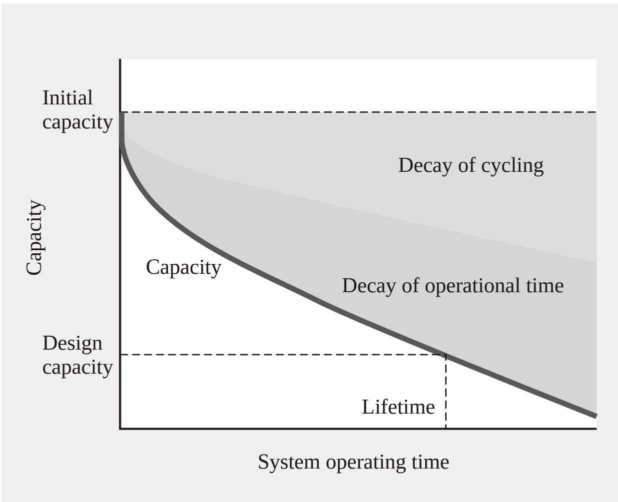

Fig. 1—Battery Lifetime Definition and Capacity Degradation.
Repeated charging and discharging of batteries causes their capacity to deteriorate. The rates of progress of the two different forms of degradation, “decay of cycling” and “decay of operational time,” are considered independent of each other.

that cause capacity to decay, and the formulation of a prediction equation that uses appropriate variables.

It is understood that two processes in particular account for the decay in battery capacity. The first is the degradation caused by expansion and contraction of the anode and cathode materials during charging and discharging (called “decay of cycling”), which progresses with each charge/discharge cycle. The second is degradation due to chemical reactions inside the battery (called “decay of operational time”), which progresses over time regardless of whether the battery is charged and discharged. It is believed that these two types of degradation are largely independent of each other, and that the overall decay in battery capacity is the sum of the two effects. This means that the battery’s operating time needs to be considered as well as the number of cycles.

As it is known that both “decay of cycling” and “decay of operational time” proceed more rapidly at higher temperatures, the ambient temperature also needs to be taken into account.

Therefore, accurate prediction of battery lifetime requires a prediction equation based on three variables: number of cycles, operating time, and ambient temperature.

The following describes the three main prediction techniques used in the past.

Prediction based on the square root function law estimates the contribution of “decay of cycling” to the battery lifetime by extrapolating capacity based on the assumption that the decay in battery capacity is proportional to the square root of the number of cycles[(1)]. The square root function law method can also estimate the contribution of “decay of operational time” to the battery lifetime by assuming that the decay in battery capacity is proportional to the square root of the operating time.

Prediction of battery lifetime based on the Arrhenius law uses a square root function law to approximate the battery’s capacity decay at different temperatures and assumes that the coefficient of the square root function law at each temperature is proportional to an exponential function of temperature[(2)].

Prediction of battery lifetime based on an additive law adds together the contributions of the “decay of operational time” and “decay of cycling” obtained using the square root function laws[(3)].

Prediction using a square root function law on its own can only deal with one or other of “decay of cycling” and “decay of operational time,” and is unable to take account of the increase in each type of deterioration caused by higher temperature. Similarly, the Arrhenius law and additive law methods are also unable to deal with all three variables (number of cycles, operating time, and ambient temperature) at the same time. This makes these past techniques inadequate for the accurate prediction of battery lifetime. In response, in the work described in this article, Hitachi developed a technique for the accurate prediction of battery lifetime by combining these previous techniques to formulate a new lifetime prediction equation that uses all three variables.

DEVELOPMENT OF LIFETIME PREDICTION TECHNIQUE

Formulation of Lifetime Prediction Equation

The new lifetime prediction equation combines the concepts from the previous techniques (see Fig. 2). The equation represents the “decay of operational time” as a function of the square root of operating time, and the “decay of cycling” as a function of the square root of the number of cycles. The ambient temperature T is one of the factors that determines the rate at which the “decay of operational time” and “decay of cycling” occur, and is represented in the equation as an Arrhenius (exponential) function. The equation calculates the values for “decay of operational time” and “decay of cycling” separately and then subtracts their sum from 1 to express the battery capacity as a capacity retention ratio (proportion of the battery’s initial 100% capacity).

The variables in the equation are the number of cycles (N_{cyc}), operating time (N_p), and temperature (T), and the result is the capacity retention ratio (Q_R). The constants in the equation are the gas constant (R) and four constants (A_p, A_{cyc}, E_p, and E_{cyc}) that characterize the rates for “decay of operational time” and “decay of cycling.” These latter four constants are determined by battery testing, consisting of storage tests to determine the constants for “decay of operational time” and cycle tests to determine the constants for “decay of cycling,” each of which is conducted for three different ambient temperatures (25°C, 35°C, and 45°C).

$$Q_R = 1 - \Big(\underbrace{A_P \cdot e^{-\frac{E_P}{RT}} \cdot \sqrt{N_P}}_{\text{Decay of operational time}} + \underbrace{A_{cyc} \cdot e^{-\frac{E_{cyc}}{RT}} \cdot \sqrt{N_{cyc}}}_{\text{Decay of cycling}} \Big)$$

Fig. 2—New Lifetime Prediction Equation.
The equation calculates the capacity retention ratio (Q_R) from the number of cycles (N_{cyc}), operating time (N_p), and temperature (T).

To obtain the *Ap* and *Ep* constants for the "decay of operational time," the results of the storage tests at each temperature were approximated by a square root function law and plotted on an Arrhenius plot with the logarithm of the square root function law coefficient as the vertical axis and the inverse of temperature as the horizontal axis.

The results of the cycle tests were analyzed in the same way to obtain the constants for "decay of cycling." However, because the time taken to perform a cycle test means that the results also include a "decay of operational time" component in addition to the "decay of cycling," the results were adjusted to include the "decay of cycling" component only when calculating the constants. To obtain this component, the time required for the cycle test was substituted into the equation for "decay of operational time" described above (see Fig. 2) to calculate the "decay of operational time," and this value was then subtracted from the cycle test results. Using the "decay of cycling" component obtained from this calculation, the "decay of cycling" constants (A_{cyc} and E_{cyc}) were then obtained using the same procedure as for "decay of operational time."

Comparison of Lifetime Prediction Equation with Test Measurements

The suitability of the lifetime prediction equation was verified by comparing it against the results of a long-term cycle test. The long-term cycle test ran for two and a half years, during which the batteries experienced 6,000 cycles. Fig. 3 shows the actual measurement results from the long-term cycle test as white dots and the predictions as a gray line. The results show a close agreement between the measured and predicted trend in the capacity retention ratio, indicating that the newly developed lifetime prediction equation is suitable for use.

EXAMPLE APPLICATIONS OF LIFETIME PREDICTION

The new lifetime prediction technique can be used to reduce system costs because it allows the installed battery capacity to be minimized in systems that in the past would have required a large safety margin. Furthermore, an understanding of how much margin to allow for factors such as the number of cycles and ambient temperature provides benefits such as higher system reliability. The following sections describe some actual implementations of the technique.

Lifetime Prediction

Fig. 4 shows battery lifetime predictions for a constant ambient temperature (25°C) and number of cycles (four per day). Under these conditions, the predicted capacity retention ratio after 10 years was 75%.

This result can be used to determine the battery capacity required by an energy storage system. For example, if the design capacity of a system were

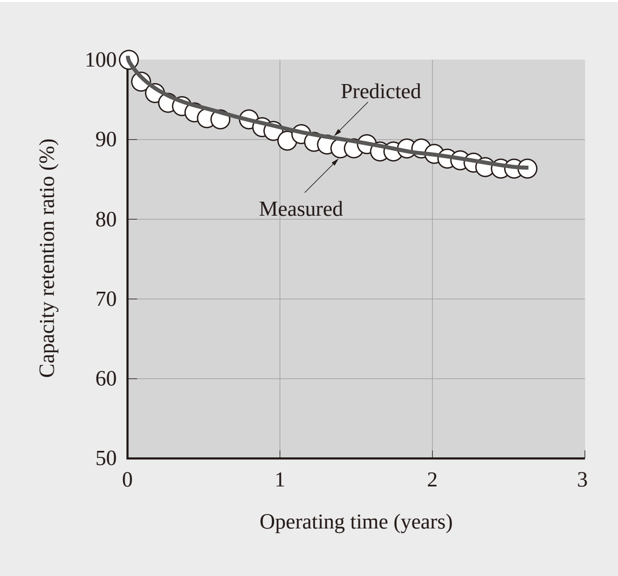

Fig. 3—Results of Battery Testing.
The graph shows close agreement between the predicted and actual results of a long-term cycle test.

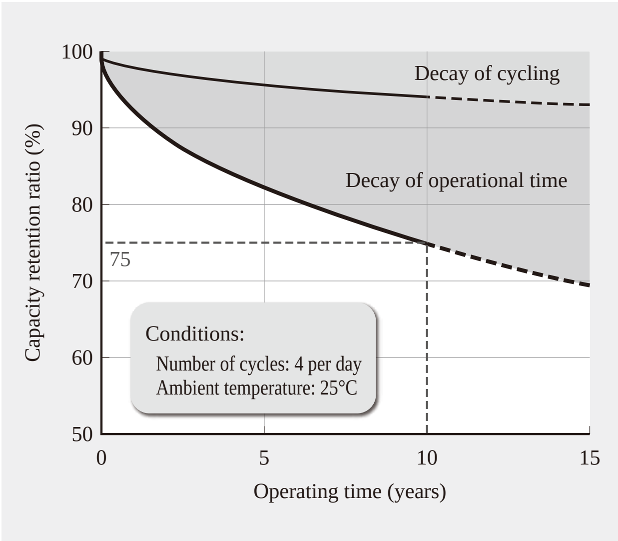

Fig. 4—Results of Lifetime Prediction.
The graph shows the predicted lifetime under standard conditions for ambient temperature and number of cycles. Accurate prediction of battery lifetime reduces the system cost.

chosen to correspond to a capacity retention ratio of 75%, ensuring that this level of minimum capacity is maintained over a period of 10 years would require an initial capacity equal to 1.33 times the design capacity (1.33 being the inverse of 75%).

As indicated by this example, an accurate prediction of battery lifetime reduces the system cost by allowing the installed capacity to be minimized, instead of requiring a large safety margin as was the case in the past.

The lifetime prediction equation also allows the relative proportions of the "decay of operational time" and "decay of cycling" to be compared. In the example shown in Fig. 4, the comparison indicates that the "decay of operational time" predominates over the "decay of cycling."

Margin Allowance

Fig. 5 shows comparisons of the prediction results for cases when either the ambient temperature or the number of cycles was held constant and the other parameter varied.

The study found that varying the number of cycles from four to eight per day at an ambient temperature of 25°C had little effect on the behavior of the capacity retention ratio. On the other hand, when the batteries were subjected to four cycles per day, the capacity retention ratio after 10 years fell to 75% for an ambient temperature of 25°C, but to 60% for an ambient temperature of 32°C.

As this example indicates, an understanding of how much margin to allow for the number of cycles and ambient temperature helps enhance system reliability because it allows the system to be designed in a way that maintains the design capacity even when these parameters vary from day to day.

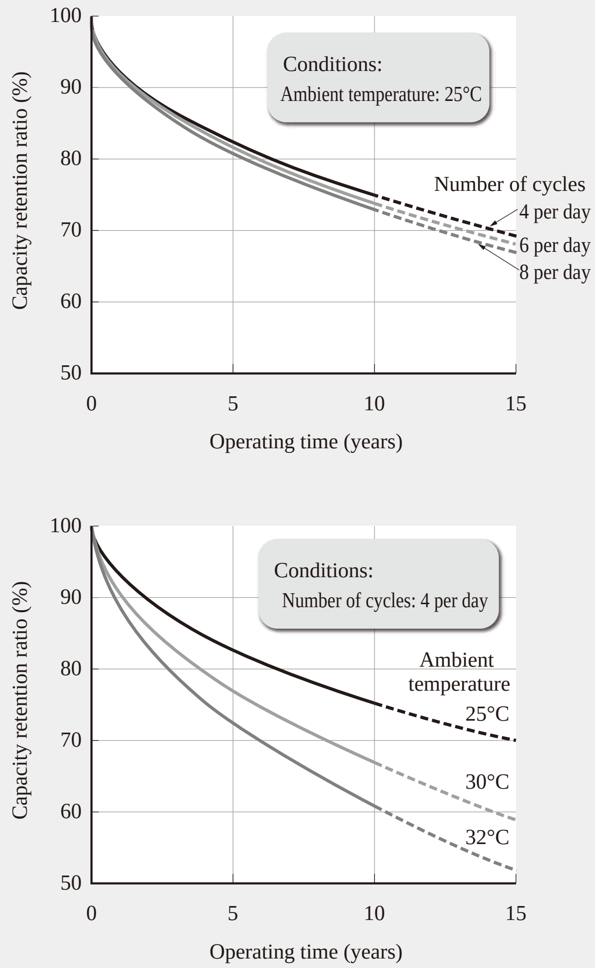

Fig. 5—Margin Allowance.
The graphs show the results for cases when either the ambient temperature or the number of cycles was held constant and the other parameter varied. An understanding of how much margin to allow for the number of cycles and ambient temperature helps enhance system reliability.

CONCLUSIONS

This article has described a lifetime prediction technique for heavy-duty industrial lithium-ion batteries that allows highly reliable system design.

Hitachi has developed a lifetime prediction technique that takes account of three variables at once, namely, number of cycles, operating time, and ambient temperature. Use of this new technique reduces the system cost by allowing the installed battery capacity to be minimized, instead of requiring a large safety margin as was the case in the past. Furthermore, an understanding of how much margin to allow for factors such as the number of cycles and ambient temperature provides benefits such as higher system reliability. In the future, Hitachi intends to use this technique to predict battery lifetimes in energy storage systems to help make them more affordable and reliable.

While ambient temperature is one of the variables considered by the prediction, heat generated in the battery itself means that the ambient temperature and battery temperature are not necessarily the same. Therefore, it is also necessary to consider the amount of generated heat, which is dependent on operating conditions. Also, it is not possible to take account of factors such as causes of capacity degradation that occur unpredictably in battery operation. It will be necessary in the future to expand the scope of lifetime prediction by developing prediction equations that take account of these factors.

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Development of Spin SEM Technology for Observation of Magnetic Domains

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OVERVIEW: Electron microscope technology developed by Hitachi is used for testing and analysis of a wide range of semiconductors and other hardware devices. Spin SEMs are able to observe the magnetic structure of a device at the nanometer scale and are already used for applications such as evaluating the shape of storage bits on magnetic media. Hitachi has succeeded in implementing two new observation techniques in order to deal with the increasingly diverse range of device functions and evaluation criteria, namely observation of structural changes in magnetic domains at high temperatures (up to 500°C) and observation of samples with remanent magnetization resulting in magnetic stray fields. It is anticipated that these observation techniques will contribute to improvements in the performance of magnetic devices, including playing a role in the development of powerful new magnetic materials.

INTRODUCTION

BECAUSE high-resolution observation of magnetic domains allows device characteristics to be analyzed at the micro level, it is an effective technique for the evaluation of magnetic devices as they continue to improve in performance. Electron spin is a physical quantity, and the spin-polarized scanning electron microscope (spin SEM) is an instrument for the observation of magnetic domains that works by detecting and imaging the spin of electrons inside ferromagnetic samples (see Fig. 1).

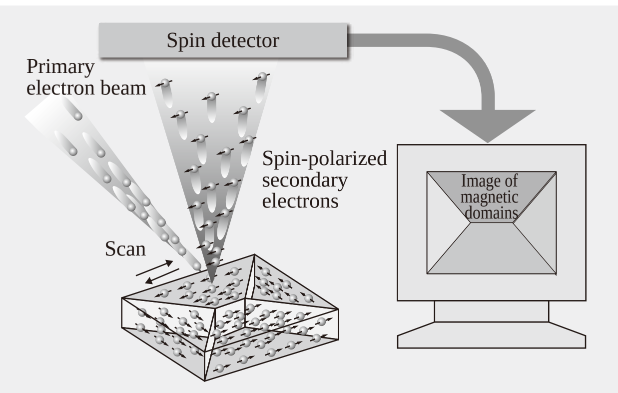

Fig. 1—Diagram of Magnetic Domain Observation Using Spin SEM.
By exposing a sample to a primary electron beam and detecting the spin polarization of the emitted secondary electrons, the magnetic orientation at that point on the sample can be determined. This primary electron beam can then be scanned over the sample to build up an image of its magnetic domains.

A common cause of magnetism is when the electron spins inside a sample of magnetic material become aligned (polarized). It is known that, if an electron beam is applied to a sample and it causes electrons from inside the sample to be emitted, those electrons will retain this spin polarization. Accordingly, if a tightly focused primary electron beam is applied to the sample and a detector is used to measure the spin polarization of the emitted secondary electrons, the magnetic orientation at the point from which the secondary electrons were emitted can be determined. By progressively scanning the primary electron beam across the surface of the sample, an image of its magnetic domains can be obtained. The key feature of this instrument is the spin detector for measuring the electron spin polarization.

It works by Mott scattering whereby spin-polarized electrons incident on a thin metal foil result in an asymmetric pattern of scattering directions[1]. This principle can be exploited to obtain a quantitative, three-dimensional map of a material’s magnetic orientations, with characteristics that include an excellent ability to handle any sample shapes and the ability to get an information about magnetization separately from physical shape. Hitachi led the world in developing spin SEMs[1], and since then has made continued improvements to sensitivity and resolution[2],[3], utilizing the instrument to measure the characteristics of a wide range of different magnetic devices.

In the past, spin SEM measurement has not been well suited to observation of permanent magnets and other materials with strong remanent magnetization, and examples of such use have been rare. This is because the magnetic stray field from such samples affects both the incident primary electron beam and the emitted secondary electrons that constitute the signal, degrading performance characteristics such as the resolution and signal-to-noise (S/N) ratio of the image. Similarly, experiments that involve raising a sample to high temperature can have a strong influence on things like vacuum integrity and electron lensing. Consequently, reports of such use in the literature are all but non-existent. In recent years, however, performance improvements and a greater diversity in the nature of magnetic devices have made these types of observations more important. They are including observations of changes in magnetic domains caused by temperature and external magnetic fields, and also observations of the structure of magnetic domains in materials with remanent magnetization, such as permanent magnets. Accordingly, we have developed new mechanisms that allow a spin SEM to be used for observations of samples that have been raised to 500°C, and samples with a magnetic field of 80 kA/m at the material surface.

These mechanisms are described here, together with example applications.

SAMPLE STAGE INCORPORATING HEATING AND MAGNETIC STRAY FIELD SHIELDING MECHANISMS

This section describes the design of a sample holder that incorporates the mechanisms referred to above. Sample heating is performed using a pyrolytic boron nitride (PBN) ceramic heater. Fig. 2 shows how the different parts are positioned in the sample holder. Fig. 2 (a) shows a plan view and (b) shows a lateral cross section. Although not described here, a mechanism for applying a magnetic field to the sample was developed in parallel. As this involves locating a magnet directly under the sample to provide the magnetic field, the placement of the heater needed to leave a gap of approximately 10 mm for this purpose. The heat from the heater is conveyed to the sample via a thermally conductive copper sheet. As overheating the under-sample magnet would degrade its magnetism, a thermally insulating plate (stainless steel) is positioned between it and the heater. This design succeeded in minimizing the locations that are raised to a high temperature and limited any negative effects of sample heating, such as loss of vacuum or impairment of the electron lensing apparatus located just above the sample.

For observations of material with remanent magnetization, a magnetic shield is required that can block the magnetic stray field and reduce its influence on the primary and secondary electron beams. This mechanism was designed and developed using a three-dimensional simulation of the electron path. The magnetic shield was made from 0.5-mm permalloy sheet cut to size so that it could be placed like a shroud over the top of the sample holder, and cut with a slit 5 mm long and 1 mm wide. The shield was then positioned so that the slit aligned with the region of sample surface to be observed. The probe electron beam passes through the slit to the sample surface,

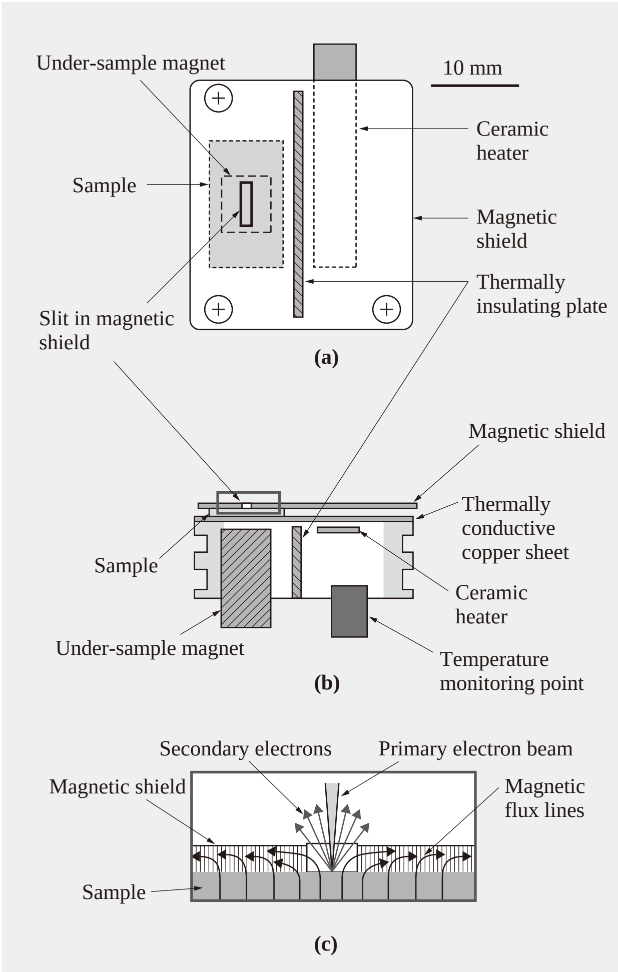

Fig. 2—Plan View (a), Lateral Cross Section (b), and Detail (c) of Sample Holder.
Diagrams (a) and (b) show the relative positions of the sample, heater, under-sample magnet, and magnetic shield in the mechanism for sample heating and observing samples with remanent magnetization. Diagram (c) is an enlargement of the gray box in diagram (b) and shows how the magnetic shield blocks the magnetic stray field from the sample.

and the secondary electrons are also captured by the detector through the slit. As the magnetic stray field from the sample is blocked by the magnetic shield, as shown in Fig. 2 (c), its influence on the primary electron beam and secondary electrons is significantly reduced. The mechanism was fabricated and then tested on material with a magnetic stray field to demonstrate that the shielding functioned adequately.

SAMPLE HEATING TESTS

Using the sample heating mechanism described above, high-temperature observations were made of the magnetic domains on the surface of a cobalt (Co) singlecrystal (0001). Fig. 3 shows the images captured at 100°C intervals from 100°C up to 500°C.

While the sample has a magnetic easy axis (axis at which the material is easily magnetized) perpendicular to its surface [the (0001) axis], it is also known that its structure is characterized by closure magnetic domains on its surface due to magnetostatic energy. As the observations show only a small component perpendicular to the surface, the images in Fig. 3 were produced by color-coding the result of calculating the magnetic orientations that lay on the sample surface.

The 100°C image shows magnetic domains with a size of 2 to 3 µm, reflecting the symmetry of the crystal structure. While any change in domain shape as the temperature increases remained comparatively small up to 200°C, the small domains had all disappeared by 300°C as the structure changed to one with large magnetic domains of 10 µm or more. As the temperature rose further from 400°C to 500°C, the formation of small new domains with sizes of 2 to 3 µm was observed to occur inside the large domains.

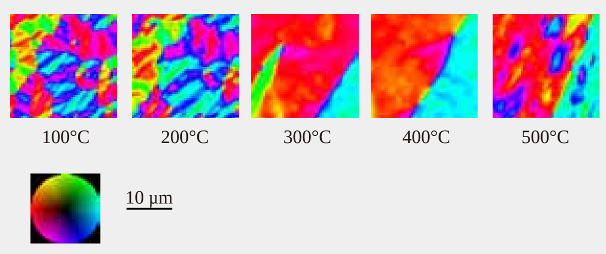

Fig. 3—Changes in Magnetic Domains with Rising Temperature in Co (0001).
The images were color coded to indicate the magnetization vector (as indicated by the color circle on the bottom left). Major changes in magnetic domain structure were evident between 200°C and 300°C, and between 400°C and 500°C. These are believed to correspond to changes in the magnetic anisotropy and in the crystal structure that occurred between these temperatures.

It is known that the magnetic easy axis in the (0001) orientation that exists in the Co singlecrystal at room temperature changes to a (0001) in-plane orientation at temperatures above the phase transition that occurs around 200°C. At temperatures below the phase transition, therefore, the magnetization inside the sample is oriented in the (0001) axis, whereas magnetostatic energy causes the structure on the sample surface to be characterized by small closure magnetic domains. At temperatures above the phase transition, on the other hand, the (0001) in-plane orientation (that is, an orientation along the surface) becomes an easy axis and therefore large stable domains oriented along in-surface axes form both in the interior and on the surface of the sample. In this experiment, it is assumed that this phase transition was the cause of the major change in magnetic domains that occurred between 200°C and 300°C. Similarly, as Co singlecrystal changes from an hcp structure to an fcc structure at around 450°C, it is assumed that this was the reason for the second change in domain structure. Using the spin SEM in this way to observe the magnetic domains of a Co (0001) surface allowed direct observations to be made of the magnetic domain changes associated with phase transitions reported in the literature, and therefore it demonstrated that the newly developed sample heating mechanism was working correctly.

The intention is to use this technology for the observation of magnetic devices, the high-temperature magnetic properties of which are a subject of interest. In the case of the powerful neodymium-iron-boron (NdFeB) magnets used in the electric motors that drive hybrid cars, for example, there is a need to assess changes in magnetic domains at high temperatures in order to make further improvements in the magnets' high-temperature coercivity (resistance to becoming demagnetized).

EXAMPLE OBSERVATIONS OF REMANENT MAGNETIZATION

This section describes observations of a permanent magnet (a material with remanent magnetization)[4]. The sample was a NdFeB magnet with fine-grained anisotropic crystals and the experiment, described below, studied the relationship between changes in the magnetic domains and crystal grain shape. First, spin SEM images of the magnetic domains and surface shape were obtained for the magnet in a thermally demagnetized state (in which it had zero magnetization). The sample was then removed and placed in a separate apparatus where it was exposed to a magnetic field of 80 kA/m. After the magnetic field was turned off, leaving the material in a state of remanent magnetization, the sample was then returned to the spin SEM and further observations were made. This procedure was then repeated with the applied magnetic field increased by 80 kA/m each time until the magnetization became identical in the field of view. The changes in the remanent magnetization of the magnetic domains at each stage were observed.

Images (a) to (k) in Fig. 4 show some example results. The images are oriented so that the magnetic easy axes of the crystal grains point upwards. In the thermally demagnetized state shown in image (a), the bands of light and dark represent the magnetic domains. The light regions indicate an upward orientation, the dark regions a downward orientation, and non-magnetic regions (corresponding to impurities, etc.) appear gray. The areas of the light and dark regions in this view are roughly equal.

Image (b) shows the shape for the same area as image (a). A crack can be seen running up the left side of the image and an impurity with a size slightly less than 1 μm is visible on the right. The granular structures with sizes in the 0.3 to 0.5-μm range observable elsewhere in the image as thin lines contrasted against the background correspond to the individual crystals that make up the magnet. As the contrast is inadequate in some places, not all the crystals can be resolved.

To investigate the relationship between the shape image and magnetic domain walls, image (c) was generated by overlaying the magnetic domain walls obtained from image (a) on image (b). This shows some places where the magnetic domain walls coincide with the crystal grain boundaries as well as some places where they do not. As the magnetic domain walls tend to run in straight lines in order to minimize their area, they sometimes transect crystal grains. Grains where this occurs have multiple magnetic domains, which means they have two different directions of magnetization within the same grain. As the spin SEM can be used in this way to study shape and magnetization in parallel, it provides a way to analyze the relationship between crystal shapes and magnetic domain walls.

Images (d) to (k) in Fig. 4 show the magnetic domains for the sample in a state of remanent magnetization resulting from the successive exposure of magnetic fields oriented in the upward direction. As exposure of the magnetic fields required the sample to be removed from the microscope, the crack and impurities visible in the shape image (b) were used as landmarks to align the viewpoints for each observation. The position of a particular crystal grain at the bottom left of the shape image (b) is enclosed by a white border and indicated by an arrow. The same crystal grain is also shown in the magnetic domain images to indicate the relationship between the viewpoints in each image.

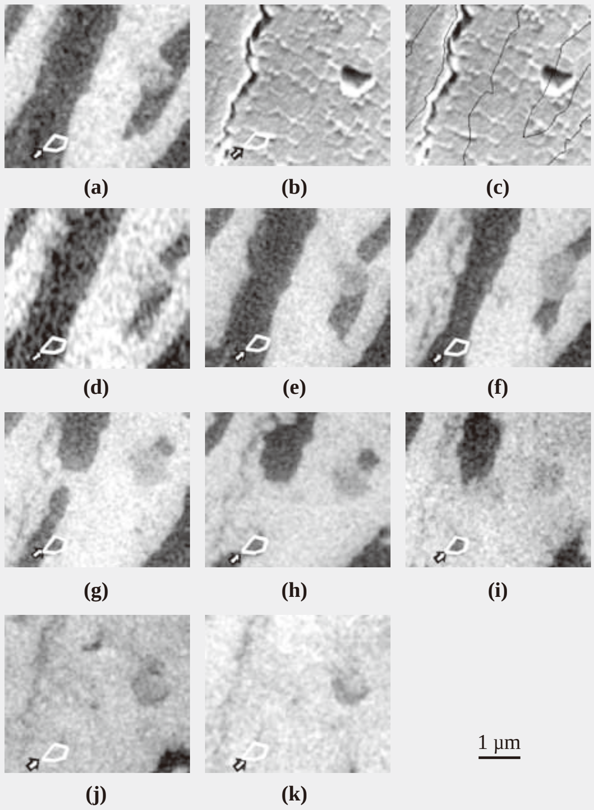

Fig. 4—Spin SEM Images of Sample at Varying Degrees of Magnetization.
The images show the magnetic domains and shape respectively at varying degrees of magnetization, from a thermally demagnetized state up to remanent magnetization after exposure of a field of 640 kA/m. Images (a) and (b) show the magnetic domains and shape images respectively when the sample was in a thermally demagnetized state, and image (c) shows the magnetic domain walls overlaid on image (b). Images (d) to (k) show the magnetic domains for the sample in a state of remanent magnetization after exposure of increasingly strong magnetic fields, the respective field strengths being: 80 kA/m (d), 160 kA/m (e), 240 kA/m (f), 320 kA/m (g), 400 kA/m (h), 480 kA/m (i), 560 kA/m (j), and 640 kA/m (k). In the magnetic domain images, the light regions indicate an upward magnetic orientation and the dark regions a downward magnetic orientation. Although the viewpoint shifts slightly in the images that show the sample in a state of remanent magnetization, the position of a particular crystal grain is enclosed by a white border and highlighted by an arrow. Reprinted with permission from the Journal of The Magnetics Society of Japan(4).

Looking at the shapes of the magnetic domains, no major changes are evident between the thermally demagnetized sample in image (a) and the 240-kA/m image (f), except for a gradual thinning of the dark regions and an expansion of the light regions. In the 320-kA/m remanent magnetization image (g), the large dark magnetic domain visible in the earlier images has shrunk and split in two, and this shrinkage becomes rapidly more pronounced in images (h) through (j) (400 to 560 kA/m) until it is seen to disappear.

Through this process, the shapes of the magnetic domain walls can be observed changing from smooth and linear in the thermally demagnetized image (a) to more complex and undulating lines in the images for 320 kA/m and higher. At around 0.3 to 0.5 μm, the size of these undulations is similar to that of the crystal grains, suggesting that the magnetic orientation is being determined at the level of single grains. For example, the crystal grain highlighted at the bottom-left of the magnetic domain images remains part of the large dark domain from the thermally demagnetized image (a) up to the 240-kA/m remanent magnetization image (f). In the 320-kA/m image (g), this crystal grain still retains its magnetic orientation but the magnetization of part of the surrounding area has flipped polarity, leaving this crystal grain protruding from the area of dark magnetic domain and causing the magnetic domain wall to take on an undulating shape. In the 400-kA/m image (h), the flipping of polarity in the surrounding area is more advanced, and by the 480-kA/m image (i) the crystal grain has become its own isolated magnetic domain. Finally, in the 560-kA/m image (j), the magnetic polarity of this crystal grain also flips.

These results show how the retention and flipping of magnetic polarity occur at the level of crystal grains and are different to the multi-domain structure suggested by the sample when it was in a thermally demagnetized state. Also flipping of the magnetization polarity occurs at the level of individual crystal grains at different magnetic fields. The use of data such as these to provide pointers on how to improve the coercivity of the magnet will be a topic for future work.

During this experiment, the remanent magnetization of the sample was progressively increased until it finally reached more than 0.2 T. While there were concerns about the magnetic stray field at the surface of the sample, the measures described earlier meant that magnetic domain images could be obtained without magnetic stray fields influencing the results.

The research described in this article was conducted jointly with the NEOMAX Company, Hitachi Metals, Ltd.

CONCLUSIONS

Nearly 30 years after the spin SEM was first developed, advances in this field continue to be made. This article has described an observation technique for investigating changes in magnetic domains. Meanwhile, further planned developments include work on achieving higher resolutions and on satisfying user demands such as the ability to make observations of the grain boundary regions in NdFeB magnets. Hitachi aims to continue contributing to improvements in magnetic device performance through the use of microscopic analysis, while also making enhancements to detector sensitivity and other aspects of microscope technology.

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Low-energy Electron Diffractive Imaging for Three-dimensional Light-element Materials

Osamu Kamimura, Ph. D.
Takashi Dobashi

OVERVIEW: Hitachi has been developing a diffractive imaging technique capable of high-resolution imaging without causing serious damage to the specimen in collaboration with Hokkaido University. The technique has growing applications in the fields of environmental engineering, sustainable energy, and life science. Using a low-energy (30-keV) electron beam, images of the atomic structure of SWCNTs with a resolution of 0.12 nm were successfully reconstructed by digitally processing diffraction patterns recorded with a new dedicated electron diffraction microscope (a scanning electron microscope with a diffraction recording function). Using this technique, the microscope can obtain high-resolution images of light-element materials with complex three-dimensional structures without specimen damage. The technique is suitable for use in material and device development in various fields.

INTRODUCTION

USE of electron microscopes for the development of materials and devices has occurred most commonly in the field of semiconductors, where they have frequently been used to identify the structure of dislocations in metals. Recently, demand for electron microscopy has also been increasing in the fields of environment engineering, sustainable energy, and life science. Light-element materials such as the carbon electrodes of lithium-ion batteries are important in these fields.

The need to make observations of different materials can be a driver of innovation in analysis technology. While observations with atomic-scale resolution are usually performed using transmission electron microscopes (TEMs) with high-energy electron beams, light-element materials tend to be

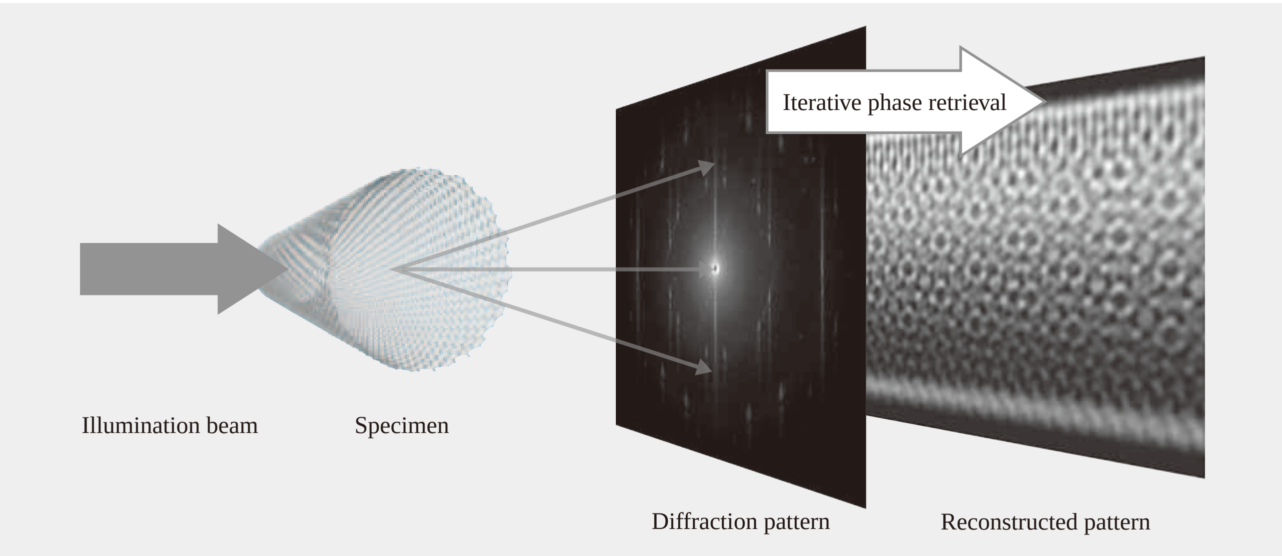


Fig. 1—Schematic Diagram of Diffractive Imaging.
The microscope illuminates the specimen with a parallel electron beam and records the resulting diffraction pattern. The structure of the specimen (reconstructed pattern) is then obtained by using iterative phase retrieval to retrieve the phase information lost when the diffraction pattern was recorded. The diffraction pattern and reconstructed pattern shown here are actual patterns obtained from observation of a single-wall carbon nanotube.

sensitive to radiation damage. The level of knock-on radiation damage caused by incident high-energy electrons pushing atoms in the specimen out of place is sufficiently severe that it is necessary to limit the observation time when using a conventional 200-keV TEM. Using an electron beam with lower energy is one solution to this problem of short observation time, but lens aberrations make it difficult to obtain atomic-scale resolution when using low-energy electron microscopy. Accordingly, the growing demand for analysis of light-element materials has created a need for an imaging technique capable of atomic-scale resolution that does not damage the specimen.

A new technique called diffractive imaging has been attracting interest as a potential solution to this problem. Diffractive imaging reconstructs an image of the specimen structure from its diffraction pattern. Unlike conventional electron microscopy, in which the resolution is restricted by lens aberrations, the resolution of diffractive imaging depends on the size of the diffraction pattern that can be acquired (the wider the diffraction angle, the higher the resolution). This means it is possible to obtain high-resolution images without being limited by lens aberrations. In addition, whereas conventional analysis of crystal structures assumes a periodic structure, this technique can also be used for imaging materials with a non-periodic structure. Hitachi has developed an analysis technique that combines a low-energy electron beam with diffractive imaging, and has tested its performance when used for imaging with atomic-scale resolution.

This article describes this diffractive imaging technique and how it can be used to make observations of light-element materials with complex structures, with a low level of damage to the specimen.

DIFFRACTIVE IMAGING

Fig. 1 shows a schematic diagram of diffractive imaging. The microscope illuminates the specimen with a parallel beam and captures the resulting diffraction pattern by locating a detector sufficiently far from the specimen. Digital processing is used to apply an iterative phase retrieval algorithm to the diffraction pattern to retrieve the phase information lost when the diffraction pattern was recorded. An image of the specimen's structure (reconstructed pattern) is obtained by combining the recorded diffraction pattern amplitudes with the calculated phase information.

Although this method was first suggested by D. Sayre in 1952[1], it was not successfully implemented in practice until 1999 (using X-rays)[2]. This was made possible by advances in computer technology and the high intensity of third-generation synchrotron radiation. Since then, numerous examples of diffractive imaging using X-rays have been published, including the three-dimensional structures of nanoparticles[3],

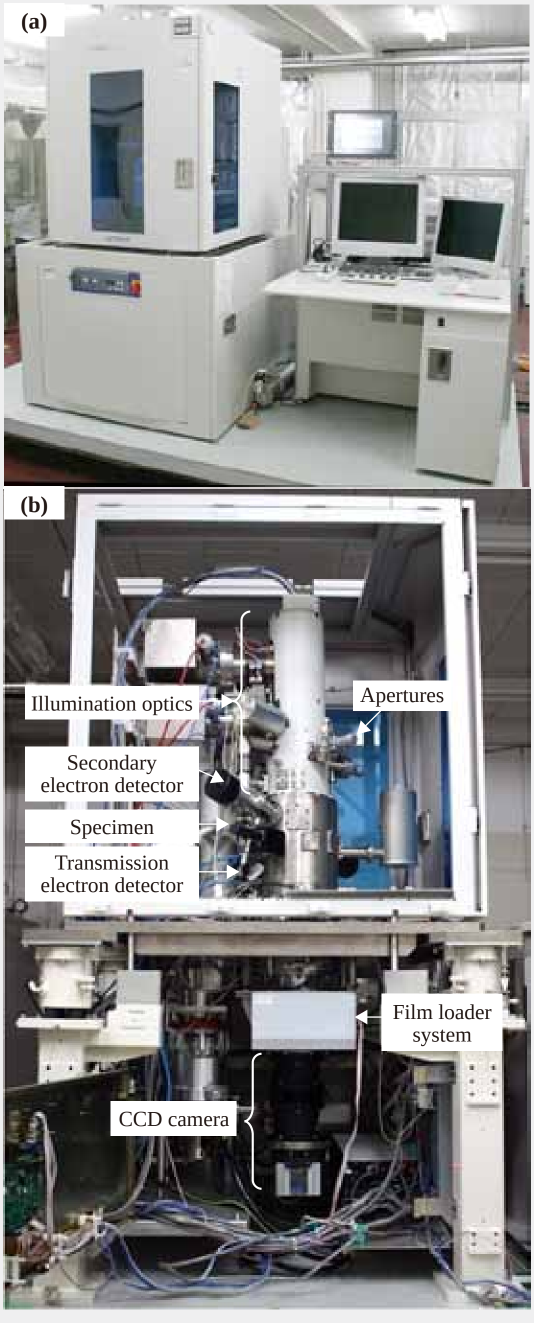
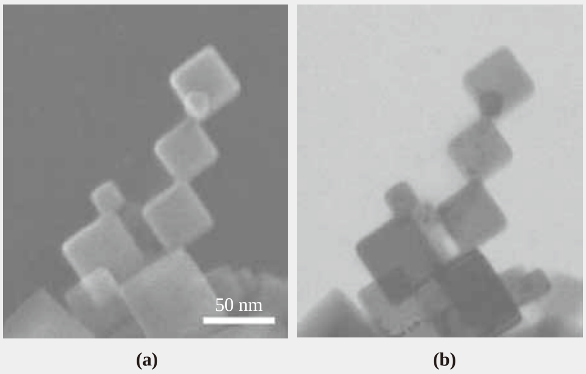


Fig. 2—Dedicated Electron Diffraction Microscope.
The photographs show the exterior (a) and interior (b) of the electron diffraction microscope. A conventional SEM was modified to record diffraction patterns by the addition of a film loader system under the SEM column (illumination optics).



STEM: scanning transmission electron microscope
BF-STEM: bright field scanning transmission electron microscope
MgO: magnesium oxide

Fig. 3—SEM Image (a) and BF-STEM Image (b) of MgO Nanoparticles.
Information about the surface morphology and inner structure of cubic nanoparticles was obtained from an SEM image and STEM image respectively.

viruses(4), chromosomes(5), and cells(6). The first successful demonstration of diffractive imaging using electrons was reported in 2002(7), and several groups have reported examples of its use since then. However, most of these have involved the analysis of material structures using high-energy 200-keV electron beams. With the aim of obtaining atomic-resolution images without causing serious damage to the specimen, Hitachi has been undertaking development work with Hokkaido University to demonstrate the use of diffractive imaging with low-energy electron beams(8).

ELECTRON DIFFRACTION MICROSCOPE

The initial proof of principle for low-energy electron diffractive imaging was conducted using a prototype microscope(8) built by modifying an instrument designed for reflection electron diffraction. Subsequently, to overcome problems with this prototype (including low resolution when used for outline observation and the fact that loading film and operating the shutter had to be performed manually), and to make the technique more practical, a dedicated low-energy electron diffraction microscope was developed(9) based on a scanning electron microscope (SEM) (see Fig. 2). The microscope uses a film loader system located under the conventional SEM column to record the diffraction pattern. It also has a charge-coupled device camera to monitor the diffraction pattern. In addition to conventional secondary electron (SE) detectors, a bright-field scanning transmission electron microscope (BF-STEM) detector is attached below the specimen (retractable). Fig. 3 shows example SE and BF-STEM images of an array of cubic magnesium oxide (MgO) nanoparticles. The SEM image shows the surface morphology and the BF-STEM image shows the inner structure of the particles. Fig. 4 shows the diffraction pattern for a single isolated MgO nanoparticle. The BF-STEM image in Fig. 4 (b) indicates that the size of the nanoparticle is about 30 nm. The diffraction pattern shown in Fig. 4 (a) includes diffraction spots for a 0.21-nm lattice spacing, while the diffraction fringes visible around each diffraction spot, shown in Fig. 4 (c), contain information about the shape of the nanoparticle. These results demonstrate that the dedicated microscope can be used to observe the outline and inner structure of a specimen as well as to perform a crystallization analysis from the diffraction pattern.

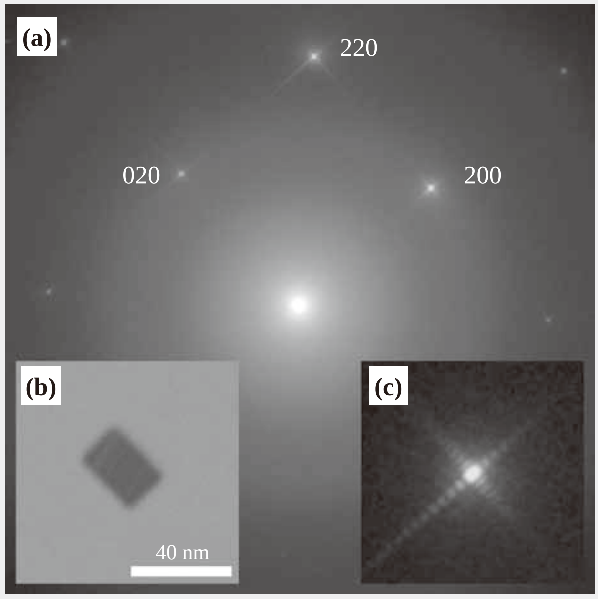


Fig. 4—Diffraction Pattern (a) and BF-STEM Image (b) of Isolated MgO Nanoparticle, and Magnified Image of 200 Diffraction Spots (c).
Fringes, which carry information about the specimen shape, can be observed around the diffraction spots.

VERIFICATION OF LOW-ENERGY ATOMIC-RESOLUTION IMAGING

Single-wall carbon nanotubes (SWCNTs) were used as specimens to verify the performance of atomic resolution imaging(10). The energy of the electron beam was set at 30 keV, which is below the knock-on voltages for SWCNTs (about 60 keV)(11) and carbon atoms at the graphene edge (about 40 keV)(11).

Fig. 1 shows the recorded diffraction pattern and reconstructed image for a SWCNT. Fig. 5 (a) shows a magnified image of the reconstructed pattern, Fig. 5 (b) shows the simulated pattern, and Fig. 5 (c) shows the atomic structure model. SWCNT is a rolled graphene sheet (a hexagonal lattice of carbon atoms). The hexagonal lattice orientations in the upper and lower layers are different, and when the arrangements of atoms in the two layers are combined, it results in the complex pattern shown in Fig. 5 (c). A comparison of these images indicates that the image reconstructed from the diffraction pattern contains information about the atomic structure of the SWCNT with a resolution of 0.12 nm. Based on the diffraction pattern, the diameter of the SWCNT was estimated to be 3.2 nm. A feature of this technique is that it was able to achieve this resolution when imaging two layers separated by more than 3 nm. This is possible because it uses a parallel beam and produces an image without use of a magnifying lens (see Fig. 1).

This work has demonstrated the ability of diffractive imaging to produce images of three-dimensional materials such as SWCNTs with atomic-scale resolution. Moreover, the bright regions indicated by the gray and white arrowheads in the reconstructed image in Fig. 5 (a) correspond respectively to single isolated carbon atoms and to overlapping atoms in the upper and lower layers, as indicated in the atomic model in Fig. 5 (c). Thus, the reconstructed image contains quantitative information sufficient to divide between a single carbon atom and two overlapping atoms. The quantitative accuracy of the image intensity has become increasingly important in recent times, with applications such as using the image intensity to identify differences in atomic number(12). The results of this work show that diffractive imaging can be used for quantitative analysis.

CONCLUSIONS

This article has described the use of a diffractive imaging technique that can make observations of light-element materials with complex structures with only a low level of damage to the specimen.

The work has demonstrated that diffractive imaging can obtain images of radiation-sensitive materials with complex three-dimensional structures, such as carbon nanotubes, with atomic-scale resolution using a low-energy electron beam that causes little damage to the specimen. In the future, Hitachi intends to utilize this technology and the dedicated microscope in the

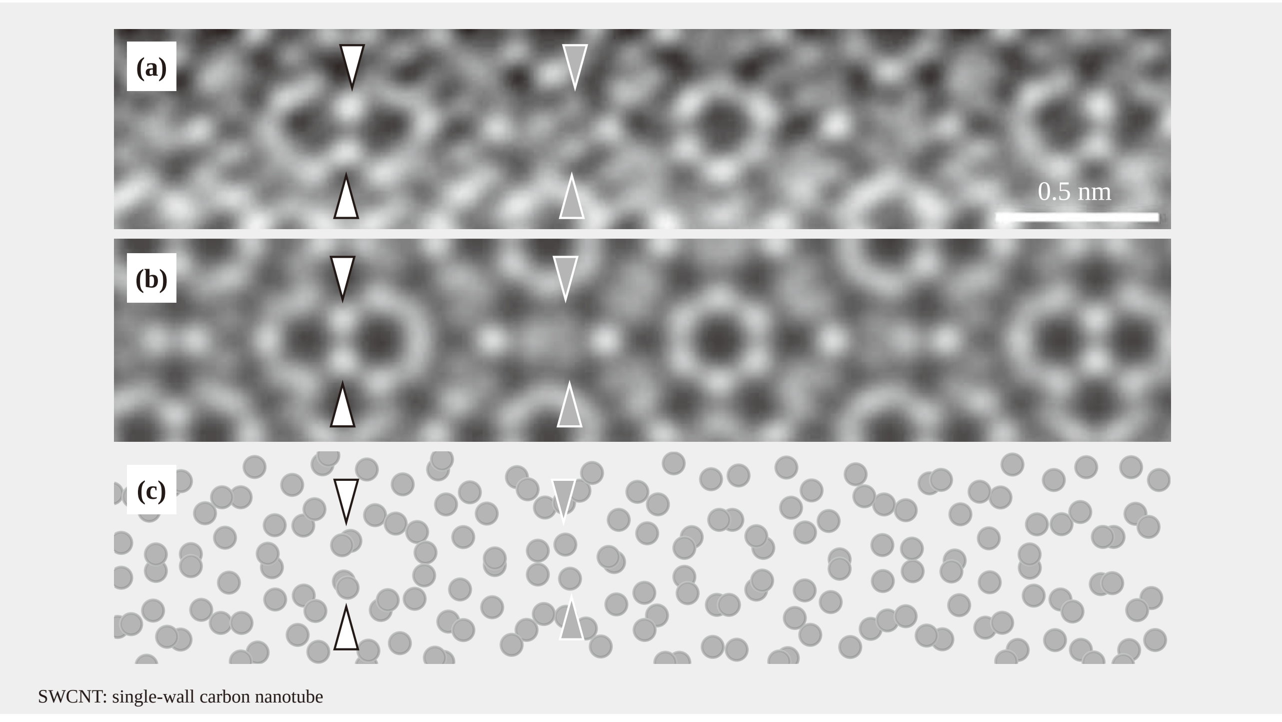


Fig. 5—Reconstructed Pattern of SWCNT Obtained Using 30-keV Electron Beam (a), Simulated Pattern (b), and Model of SWCNT Atomic Arrangement (c).
The resolution of the reconstructed pattern (a) is sufficient to resolve two atoms with a spacing of 0.12 nm (indicated by the gray arrowheads). In the figures (a)–(c), the white arrowheads indicate two overlapping carbon atoms and the gray arrowheads indicate single isolated carbon atoms.

development of new materials and devices that use light-element materials.

This work was conducted in collaboration with Professor Gohara's group at Hokkaido University. The SWCNTs were synthesized by Professor Shinohara's group at Nagoya University. Part of this work was supported by the Japan Science and Technology Agency.

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Production Control System to Visualize Future Effects by Production Trouble

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OVERVIEW: When unexpected problems or accidents occur at the production and logistics sites that have spread throughout the world in conjunction with the globalization of business, it is essential that the supply chain be able to minimize the effects of such events in ways that are as flexible and resilient as possible. Using a statistical model of unexpected component shipment delays and manufacturing equipment failures, Hitachi has developed a production control system that predicts future variations in production volumes resulting from such incidents with high accuracy. This system uses prediction to select appropriate loss recovery strategies and is able to minimize production volume dips and delivery delays. Using this system, Hitachi intends to extend its application to applicable processes, and to develop it for sale by a production control consulting business.

INTRODUCTION

IN recent years, along with the globalization of business, the supply chains of various manufacturers' production sites have expanded worldwide. However, there have been times when these supply chains have been disrupted by unexpected events, such as during the natural disasters that occurred around the world in 2011, including the Great East Japan Earthquake and flooding in the Kingdom of Thailand. These and other events have resulted in service disruptions to a steadily increasing number of customers. Thus, there is a clear need for production control methods that can minimize the influence of such problems while also providing flexible and resilient support to supply chains.

In conventional production control, the estimated number of available components and production volumes are set for each production process. When unexpected problems occur in an upstream process, such as an unexpected component shortage or manufacturing equipment failure, these can affect downstream processes as well. They cause shortages in component deliveries and place excessive demands on manufacturing capacity in downstream processes, thus delaying progress and ultimately causing delivery delays. In response, Hitachi has developed a production control system, based on a statistical model, that is capable of making highly accurate predictions of the future production volume variations resulting from the flow-on effects to downstream processes of problems in an upstream process. This article describes the production control, which uses a statistical model for the highly accurate control of the variations that occur in production volume after an unexpected problem.

STATISTICAL-MODEL-BASED PRODUCTION CONTROL

Fig. 1 shows a diagram of the statistical-model-based production control developed in this project. The first task is to gather, in realtime, actual data for each component from the manufacturing shop floor, such as when it completes each process. Next, the statistical model is applied to this collected data to

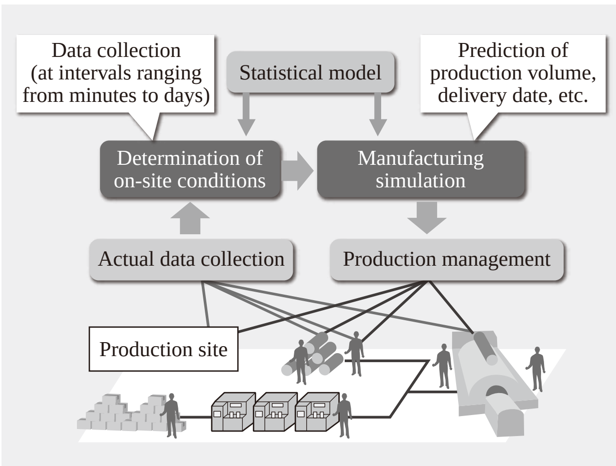

Fig. 1—Statistical-model-based Production Control.
The future production volume is predicted by a manufacturing simulation that uses a production model generated from actual data by a statistical model.

generate input data for a manufacturing simulation. This provides a model of the current production situation. The manufacturing simulation is then run using the generated model to predict future production volumes and delivery times.

If the predictions indicate that upstream problems will propagate to downstream processes, potentially reducing production volumes, delaying deliveries, or causing other issues, the system triggers an investigation of loss recovery strategies. Manufacturing simulations are then performed to examine each loss recovery strategy and assess its effectiveness. The strategy found to be the most effective is adopted to resolve the problem.

This production control scheme involves two tasks: modeling and visualization. "Modeling" means that a high-precision production model is generated from the gathered actual data. "Visualization" means providing a visual representation of the conditions that result as the effects of problems in upstream processes propagate to downstream processes. A variability modeling technique was then developed to aid in creating production models, and a technique for predicting how problems propagate was developed to aid in visualizing the influence that problems have on downstream processes.

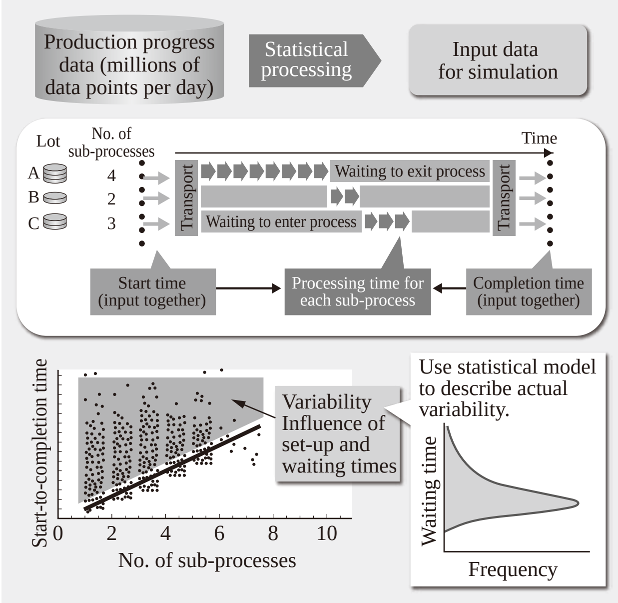

Fig. 2—Variability Modeling Technique.
A statistical model was used to describe the distribution of the variability of actual results in the form of an equation, and the equation was then used as the input to a simulation.

Variability Modeling Technique

This section uses an example of a mass-produced product to describe the issues associated with the generation of input data for a manufacturing simulation from the collected actual data (see Fig. 2). For a mass-produced product with a production volume that exceeds several million units annually, the volume of actual data collected from the plant will total several million data points each day. Using hypothetical lots A, B, and C, consider an example in which lot A is handled in four sub-processes, lot B, in two sub-processes, and lot C, in three sub-processes. Data on the start and completion times for the overall process are collected separately for lots A, B, and C. However, the period between the start and completion times also includes the time needed for transportation between processing equipment, the time spent waiting for loading into a new sub-process, and the time needed for removal from each process. In other words, collecting only the start and completion times fails to provide any information about the times required for each sub-process.

A variability modeling technique based on statistical work was developed to address this issue. This technique considers the number of sub-processes included in each lot and the time required from start to completion. The graph at the bottom-left of Fig. 2 shows a scatter plot with the number of sub-processes on the horizontal axis and the start-to-completion times on the vertical axis. Each point represents an actual product. The slope of the line visible along the bottom border of the scatter plot is related to the processing time for a single sub-process. Meanwhile, the variabilities in the upper portion of the scatter plot are influenced by set-up and waiting times. These variabilities can be expressed with the statistical model shown at the bottom-right of the figure.

Propagation Prediction Technique

Next, a manufacturing simulation is created based on the variability modeling technique and incorporating information such as machine times and production volumes (see Fig. 1). This simulation is used to predict the influence that unexpected problems in upstream supply chain processes have on downstream processes.

Essentially, an unexpected problem in an upstream process will always cause some variations in the production volume downstream, and while some of these variations in the supply chain will be damped, others will be amplified, ultimately resulting in delivery delays. Therefore, in order to examine ways of responding to problems, it is essential to be able to visualize just how variations arising in upstream processes will propagate to downstream processes.

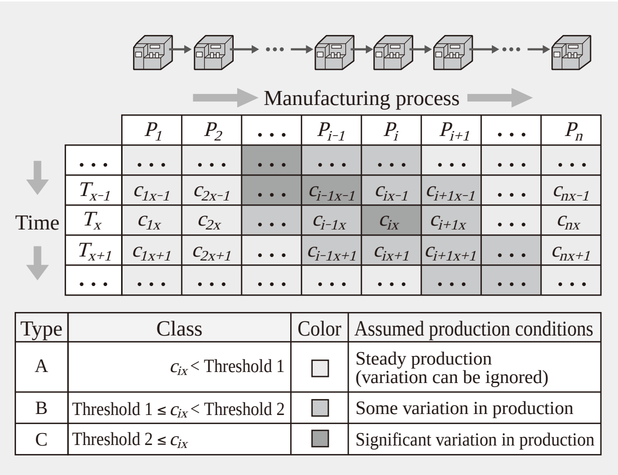

Fig. 3—Propagation Prediction Technique.
A map is used to provide a visual representation of how variations in the productivity index propagate.

In response, Hitachi has developed a propagation prediction technique for intuitively visualizing how variations occurring in upstream processes propagate to downstream processes (see Fig. 3). In this approach, the coefficient of variation (CV), which quantifies the variability, is extended and replaced by a new index called the “visualization coefficient”[(1)]. The visualization coefficient is defined as the value of the variance to the productivity index during the current process, divided by the moving average. As shown in the figure, the propagation prediction technique employs a map to help users visualize the propagation of variations from upstream to downstream. In this map, the horizontal axis represents production processes while the vertical axis represents time. Each square represents the state of progress in a process at a given time. The visualization coefficient associated with the productivity index for each square is calculated from the prediction data, which are generated using actual data and the manufacturing simulation.

Calculated visualization coefficient values that are less than or equal to threshold 1 indicate that production will be steady, with negligible variations, while values between thresholds 1 and 2 indicate that some production variation will occur. Values greater than or equal to threshold 2 indicate that variations will be ongoing. These are shown with different colors. Thus, by visualizing production variations at each process, this method can be used to visualize variations at any time and in any production process, and can show the extent of their propagation to downstream processes with the passage of time[(2), (3)].

APPLICATION EXAMPLE

Production Control of Mass-produced Goods

The production control based on the statistical model described above was implemented at a Hitachi facility and the results were observed. This section describes how the system handled problems in this test[(4)] (see Fig. 4). The horizontal axis of Fig. 4 represents the production schedule, and the vertical axis represents the cumulative production volume.

In this example, a piece of manufacturing equipment failed on the fourth day. The production volume through to the end of the month was then predicted using the manufacturing simulation based on the input data generated with the variability modeling technique. The results indicated that cumulative production would be 60% lower than the monthly goal.

The propagation of variations resulting from manufacturing equipment failures was visualized with the propagation prediction technique, and countermeasures were investigated (see Fig. 5). The horizontal axis represents production processes from the input of components through to product shipment, while the vertical axis represents time. The gray horizontal line in the figure represents the present time. The region above the horizontal line visualizes the actual result, while the region below visualizes the propagation of production variations, as predicted by the manufacturing simulation using current production conditions as initial values. The figure shows how manufacturing equipment failures occurring in upstream processes cause variations in production volumes, which then propagate to

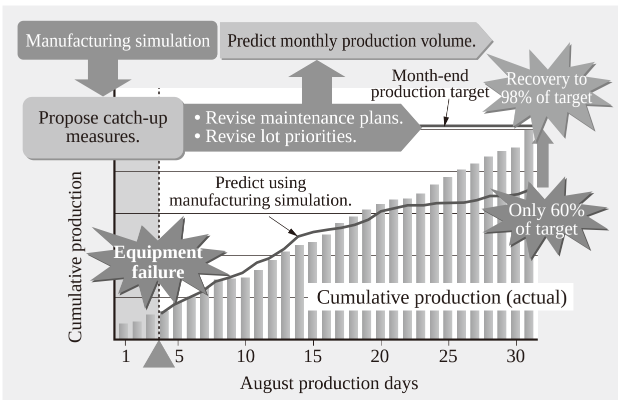

Fig. 4—Example of Response to Problems Using Developed Production Control.
Measures such as changes to manufacturing equipment maintenance schedules and lot priorities are made in order to catch up with the target for month-end production.

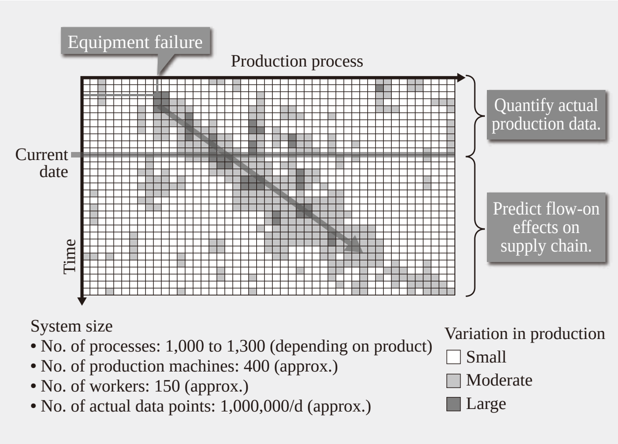

Fig. 5—Example Application of Propagation Prediction to Mass-produced Goods.
The technique predicts the flow-on effects (variations in production volume) after a manufacturing equipment failure occurs.

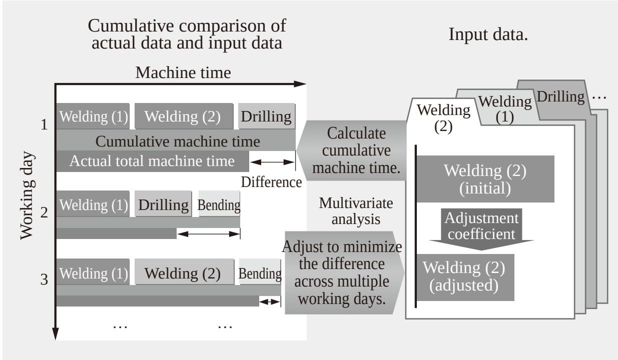

Fig. 6—Machine Time Estimation Using Total Machine Time.
The estimated machine time was adjusted to minimize the difference between the cumulative machine time for tasks performed on working days and the actual total machine time.

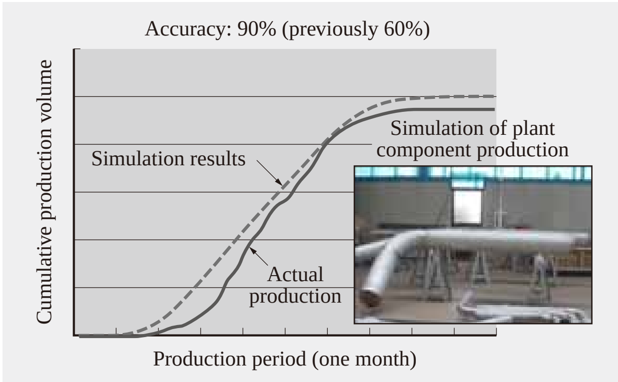

Fig. 7—Production Volume Prediction for Manufacturing Plant Components.
When compared against actual production, the machine times estimated using multivariate analysis had a simulation accuracy of 90%.

downstream processes over time. Based on this figure, we could predict that delivery delays would occur in the light gray and gray regions, which were affected by the variations.

The prediction was then used as a basis for drawing up countermeasures, including revisions to manufacturing equipment operation times and front-loading the production of products with little flexibility in their delivery dates. A new manufacturing simulation that took these changes into account was then generated and run to produce revised predictions for cumulative production by the end of the month. The simulation results indicated that the countermeasures would restore production to 98% of the monthly goal (see Fig. 4).

Production Control of Non-mass-produced Goods

With the addition of multivariate analysis, which can be used to generate production models on the basis of design data and other characteristics, this statistical model-based production control is also applicable to non-mass-produced goods produced in volumes of between one and several tens of thousands, such as components for manufacturing plant. Multivariate analysis is a procedure used in statistical theory for analyzing the correlations within a group of variables using data related to the variables. In the context of this study, multivariate analysis can be employed to estimate the machine time for each component and task (see Fig. 6) by modeling the relation between the gathered machine times and design data, such as the component size after a task or the number of processes.

When applied to manufacturing plant components, the method was able to predict production volume one month ahead with an accuracy of 90% (see Fig. 7).

CONCLUSIONS

This article has described a highly accurate statistical-model-based production control system capable of predicting variations in the future production volumes of production processes when unexpected problems occur, such as component shipment shortages or manufacturing equipment failures. The system is currently used for production control of manufacturing plant components at a Hitachi facility, and the intention is to extend its use to more processes in the future. Hitachi also plans to introduce a production control consulting service for external customers based on this technology.

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IT Resource Management Technology for Reducing Operating Costs of Large Cloud Data Centers

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OVERVIEW: Growing use of the cloud is making data centers larger and more complex. This is increasing operating costs and placing a greater burden on the administrators charged with managing data center operations. In response, Hitachi is taking steps to deal with the three key challenges faced by administrators: the difficulty of centralized management of increasingly large data centers, the growing workload being placed on individual administrators due to the specialized nature of advanced management skills, and the increasing amount of time spent on coordinating administrators of different layer. To overcome these challenges, Hitachi has implemented management repository technology that allows centralized administration of large-scale IT resources, root cause analysis technology that formalizes the advanced know-how of administrators in the form of structured knowledge, and virtual server and storage administration coordination technology that automates storage configuration and reduces the workload associated with coordinating different administrators.

INTRODUCTION

THE quantity of digital data has grown explosively in recent years as mobile devices such as smartphones and tablet personal computers (PCs) have proliferated. The total quantity of digital data in the world is forecast to reach 73 Zbyte (Z: 10^{21}) by 2020, of which it is estimated 44.4% will be stored in the cloud[1]. This is approximately 10 times larger than the quantity in 2012. The emergence of the cloud is also driving a shift away from ownership and toward sharing of information technology (IT) resources, with the aim of cutting costs by consolidating these resources in data centers rather than having them dispersed as they have been in the past.

Recognizing this growth in use of the cloud, Hitachi supplies a wide range of products extending from the servers, storage, and other IT resources used at data centers through to Hitachi cloud computing solutions.

This article identifies three challenges faced by administrators seeking to cut the operating costs of data centers, which are becoming larger due to growing use of the cloud, and describes IT resource management techniques for overcoming them.

CHALLENGES FOR IT RESOURCE MANAGEMENT

While data centers are getting larger, the number of administrators available to manage them remains roughly constant. This has created a need to reduce the workload imposed on administrators so as to cut operating costs.

In response, Hitachi has identified three key challenges faced by the administrators of these increasingly large data centers (see Fig. 1).

The first challenge is that the centralized management of IT resources has become difficult. The growing size of data centers has led to an explosion in the quantity of IT resources that need to be managed, making it difficult to continue with the centralized management practices used in the past to deal with configuration, performance, and other administrative information. By impeding a clear understanding of the overall situation at large data centers, this makes timely administration impossible.

The second challenge is the specialized nature of advanced management skills. In addition to data centers becoming larger, advances in virtualization technology for servers and storage are making system configurations more complex. Even more so than in the past, this demands that administrators acquire advanced know-how and extensive experience. In many cases, however, companies are unable to obtain enough administrators with adequate experience. This is placing a growing workload on individual administrators with specific advanced management skills, making it difficult to get many tasks completed quickly.

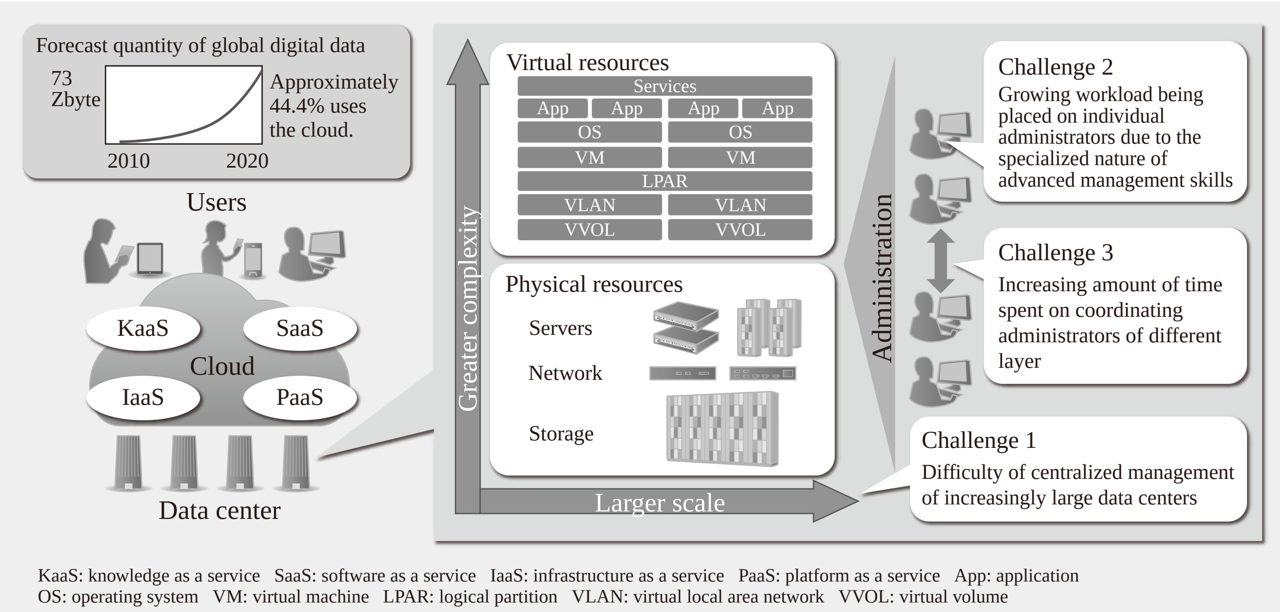


Fig. 1—Challenges for Administration of Large Cloud Data Centers.
As use of large cloud data centers grows, new challenges are arising in their administration due to the growing scale and complexity of both physical and virtual resources.

The third challenge is the increasing amount of time spent on coordinating administrators of different layer. As data centers become larger, administrators' working practices are becoming increasingly compartmentalized based on factors such as the type of resources being administered or the services provided. This creates situations where the work of a number of administrators with different roles must be coordinated. Not only does this human involvement slow the time taken for work to be completed, it is also sometimes a cause of faults as their differing responsibilities result in administrators' know-how becoming more specialized, impeding the exchange of information between them.

REPOSITORY TECHNOLOGY FOR MANAGEMENT OF LARGE-SCALE IT RESOURCES

This section describes the use of repository technology for management of large-scale IT resources as a way of dealing with the first challenge.

As data centers become larger and more complex, this is increasing the quantities and types of IT resources being managed, and also the amount of data handled by the management software that administrators use in their daily work. This has led to problems such as insufficient memory or slow execution for the management software that has been used in the past for centralized management, making this approach to administration increasingly impractical. The main cause of this lies in the databases (DBs) used for storing and searching of configuration information for IT resources. Typically, management software stores configuration information acquired from a particular managed IT resource in a corresponding table in the DB (so that server configuration information is stored in a server table and storage configuration information is stored in a storage table, for example). However, as the quantity of data being handled by management software grows, this increases the number of tables that must be dealt with for a single operation, such as displaying a report screen that gives an overview of the entire data center. It is this that results in the DB running out of memory or being slow to execute.

A common solution to this problem is to index the DB. However, as the quantity of data and number of tables increases, the number of indexes that need to be specified also rises, and this causes its own problems with the execution time required to generate the indexes and with the quantity of data they contain. An estimate based on the quantity of IT resources at a large data center puts the size of the required indexes at more than 100 Gbyte. In response, Hitachi has developed repository technology for the management of large-scale IT resources that minimizes memory use and supports fast searching (see Fig. 2). This technology analyzes the main use cases applicable to data center administration to identify which data is actually needed, then generates consolidated tables

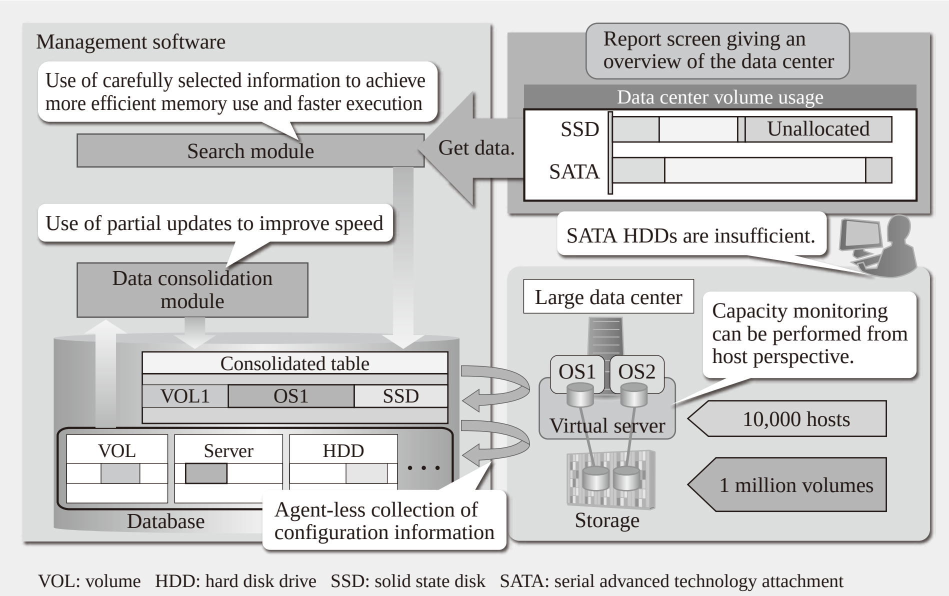


Fig. 2—Platform for Management of Configuration Information Used in Administration of Large-scale IT Resources.
The way data is stored is consolidated based on administrator use cases. Report screens able to provide an overview of the entire data center are made possible by fast search performance.

based on the results. By only defining indexes for these consolidated tables, the repository technology for the management of large-scale IT resources is able to combine efficient use of memory with fast operation. Using this technology, Hitachi has implemented an IT resource management repository with world-class scalability (approximately 40 times that of the previous Hitachi system).

ROOT CAUSE ANALYSIS TECHNOLOGY

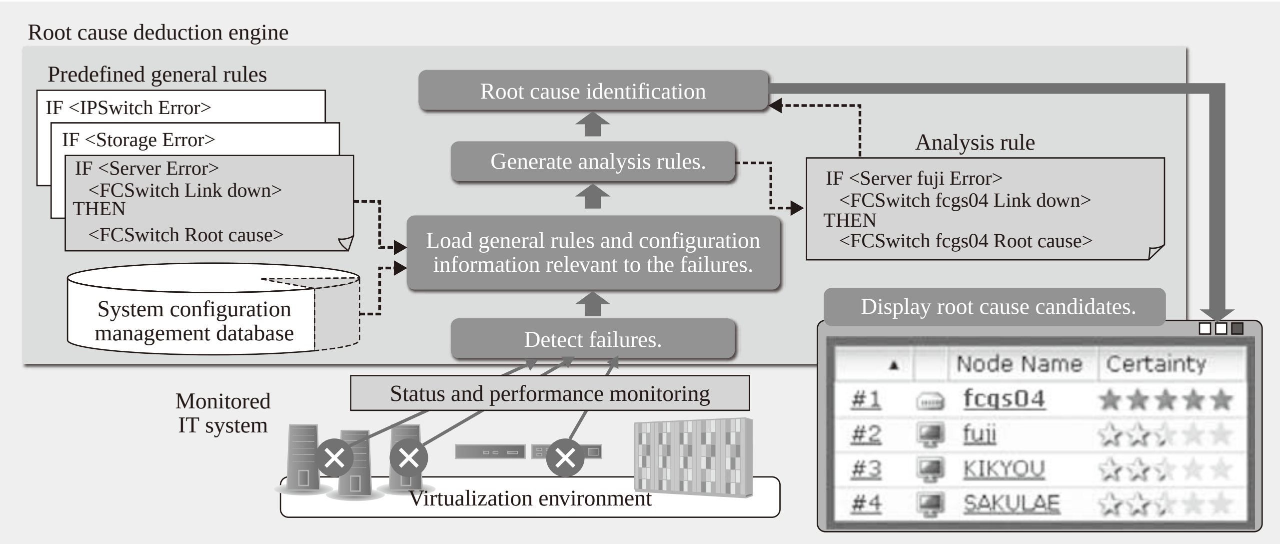
This section describes the use of root cause analysis technology as a way of dealing with the second challenge.

Larger and more complex data centers require administrators with more advanced know-how and more extensive experience than in the past. However, companies are often unable to assign enough administrators with adequate experience. Among the different types of administration work, this creates particular difficulties for fault recovery work, which demands a rapid response. To reduce the recovery time, shortening the time between detecting the failures and identifying the root cause is very important. Accordingly, Hitachi has developed root cause analysis (RCA) technology for identifying the cause when a failure occurs.

RCA defines general rules for the patterns of where failures occur and the corresponding root cause. When failures are detected, the general rules are retrieved by looking for matches with the incoming failure events. Using the configuration information for any general rules found by this retrieving, analysis rules that specify the exact relationship between the failure events and the equipment affected are generated and the root cause identified. The technology also calculates a certainty of the root cause based on the rate of failure events actually received from among those failure events contained in the analysis rules that could have been expected to be received when the failure occurred. Together with the certainty factor, the root cause is then reported to the administrator as a candidate for the cause of the problem.

Typically, when a fault occurs on a large system, it only affects a subset of equipment. Accordingly, the generating of analysis rules is only performed for equipment that could potentially be affected by the fault (determined from information on connections between devices). Also, generation of analysis rules is performed on-demand for specific equipment by using the limited general rules associated with received events, including only those rules that are required for analyzing the root cause. This allows root cause analysis to be performed quickly (see Fig. 3).

The connection relationships between equipment at large data centers are complex, and a fault occurring at such a data center often results in a very large number of failure events being detected. This makes it very difficult to determine which failure events are related and which failure events to consider when indicating the root cause. To deal with this, Hitachi investigated in advance how failure events occur under the customer's system to generate the general rules that can then be used as the basis for the analysis of failure events when an actual fault occurs. This shortens the time taken from fault detection until the root cause is identified. The technology also analyzes faults on



IT: information technology

Fig. 3—Procedure for Root Cause Analysis.
This system performs rapid root cause analysis for large cloud data centers by loading the configuration information for the devices that connect to the devices which the failure events are detected, and then analyzing by using analysis rules generated from general rules and this information.

servers, storages, and network equipment. Identifying the root cause becomes even more difficult in cases when a fault on one of these devices affects other types of device. Hitachi's technology can analyze the cause of failure events occurring rapidly, even if the site does not have a separate administrator dedicated to each type of device.

In this way, the cost of operating large cloud data centers can be cut by minimizing the workload associated with responding to faults.

COORDINATION TECHNOLOGY FOR VIRTUAL SERVER AND STORAGE MANAGEMENT

This section describes the use of coordination technology for virtual server and storage management as a way of dealing with the third challenge.

In the cloud, it is necessary to be able to allocate IT resources rapidly when users require them. However, as the administration of large data centers is split between administrators of different layer, some companies adopt practices whereby an in-house workflow must be followed to coordinate this work between the different administrators. In the case of services that take an infrastructure-as-a-service (IaaS) approach to the provision of virtual servers, for example, the administrators responsible for virtual servers and storage respectively need to work together on a system configuration in order to provide both the virtual servers for the system and the storage used to hold its data. This involvement of people in the process makes it difficult to achieve the prompt service expected from the cloud.

In response, Hitachi has developed technology for coordinating administration that eliminates the need for communication between these administrators, and

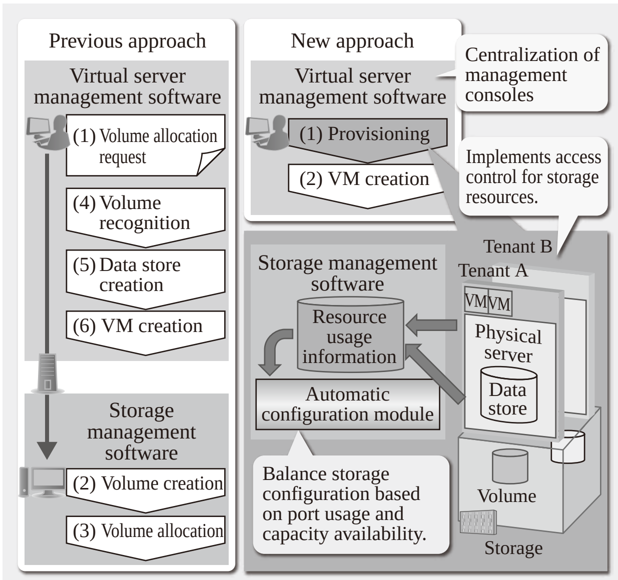


Fig. 4—Storage Administration Technology for Use by Virtual Server Administrators.
The system includes an automatic configuration module for storage that allows even virtual server administrators who lack expertise in storage to perform tasks that in the past would have required the virtual server administrator and storage administrator to work together.

allows the administrator responsible for virtual servers to allocate the virtual server and storage IT resources on his or her own (see Fig. 4). Rather than simply consolidating the administration functions for virtual servers and storage, this technology uses an automatic configuration module to set resource parameters automatically based on a dynamic assessment of storage usage. This means that even a virtual server administrator who lacks storage expertise can configure a system's storage. This shortens the time taken to perform the administration task to a few minutes, instead of the several hours or more required for communication between administrators.

CONCLUSIONS

This article has described Hitachi's repository technology for management of large-scale IT resources, root cause analysis technology, and coordination technology for virtual server and storage management, and how these technologies relate to three specific challenges facing the administration of large cloud data centers.

A common feature of all three technologies is that they reduce the administration workload. Reducing the work associated with tasks frequently performed by administrators is important for reducing the cost of operating increasingly large and complex data centers. Hitachi has plans to reduce these workloads even further in the future. The technologies described in this article have been released as part of the Hitachi Command Suite and Hitachi IT Operations management software.

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