Structural deformation and breakdown evaluation technology

Predictive and Evaluative Technologies Based on Structural Mechanics and Strength of Materials for Structural Failures to the Safety of Society

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Abstract

This paper explains, divided into the fields of structural mechanics and material strength, structural deformation and breakdown evaluation technology. This technology is one of the core technologies that have contributed to ensuring and enhancing the performance, quality, and safety of final products that utilize Kobe Steel's products and materials. In the field of structural mechanics, examples are introduced that encompass collision evaluation technology and structural optimization technology, aiming to balance weight reduction and collision safety in automobile body structures. Additionally, case studies are presented regarding component proposals that incorporate an environmental impact reduction perspective, with a view toward achieving a carbon-neutral society within the product's lifecycle (LCA). In the field of material strength, technology for deformation and microstructure prediction, as well as crack prediction, is introduced, utilizing heat treatment simulations that consider metallurgical factors such as phase transformation. Furthermore, case studies of efforts in the field of micromechanics, which bridge the connection between material structure design and mechanical properties, are introduced. This provides a glimpse into the potential for creating new material products with added value and the possibility of transforming manufacturing processes.

Introduction

Ensuring safety and security in community development and manufacturing is one of the KOBELCO Group's materialities. This is why Kobe Steel develops technologies to guarantee and improve the performance, quality, and safety of its products and the end products in which its materials are used. One set of core technologies related to the aforementioned materiality comprises "structural deformation and breakdown evaluation technology" based on structural mechanics and material strength. These broad categories can be described as (1) structural mechanics technologies related to the basic performance of structures and metal products and (2) material strength technologies for characteristics such as durability and safety.

In the field of structural mechanics, we have developed various structural performance evaluation technologies related to the use of lightweight materials such as aluminum plate and aluminum extrusions in architecture.[1), 2)] Civil engineering structures such as the long-span bridge[3)] in which Kobe Steel's wire rod and plate were used[4), 5)] serve as prime examples. The KOBELCO Group continually refines these performance evaluation technologies as part of the testing and research undertaken at the Kobelco Research Institute, Inc.[6)] We also innovate structural optimization techniques to support the design of lightweight automotive parts such as aluminum suspension parts.[7)]

In the field of material strength, we have developed stress and strain evaluation techniques[8)] using numerical simulation of the design fatigue life of construction machinery and other machinery products, advanced materials such as cast and forged steel, and more. Furthermore, Kobe Steel has conducted research and development into the fracture characteristics of products made from its materials. Evaluating metallurgical factors as well as fracture mechanics as it relates to brittle crack arrest behavior are two such areas of investigation.[9)] We have developed fracture behavior simulation technology that accounts for microstructure based on our research into fatigue property prediction[10)] and toughness prediction.[11)] We have cultivated many of these fundamental technologies related to strength and fracture into a unique core technology by combining a mechanical approach with metallurgy. This core technology came to fruition through Kobe Steel's machinery and engineering business division and materials business division alongside a department established to develop fundamental technologies for these business divisions.

This paper describes a group of technologies related to lightweight automotive design as examples of how our core technologies are used in the field of structural mechanics. Also described are fracture mechanics evaluation techniques as well as mechanical evaluation techniques that account for phase transformation as examples of how our core technologies are used in the field of material strength. Covered as well are Kobe Steel's developments and prospects in micromechanics, which links the fields of structural mechanics and material strength with the metallurgical behavior and microstructural design of materials.

1. Technology for predicting the performance of structural members based on material properties (field of structural mechanics)

Numerical simulation of structural deformation and load-bearing capacity in conjunction with subsequent experimental validation for safety have been used to develop predictive and evaluative technologies based on structural mechanics. These technologies have recently seen expanded use and development, primarily in technical proposals in the automotive field; this section presents several such examples.

1.1 Collision evaluation technology for vehicle parts

Vehicle manufacturers face the perpetual challenge of reconciling crashworthiness with lightweight chassis design for reduced environmental burden. Additionally, vehicle crash tests require one vehicle per test and a facility large enough to run such testing. Prerequisites to prototyping and crash testing therefore include detailed research as well as testing that reproduces the deformation experienced by each individual component during crash testing.

Kobe Steel has been working on the evaluation of full-vehicle-body crashworthiness using in-house crash test facilities[12), 13)] and on the improvement of full-vehicle crash simulation accuracy.[14)] These endeavors have led to our extensive expertise regarding the crash behavior of the entire vehicle and to the development of test methods for individual components. **Fig. 1** shows the full-vehicle crash analysis of a side impact and the crash simulation of an individual component (side sill). Devising a way to assign boundary conditions when cutting out parts has enabled the evaluation of prototype parts, supporting rapid, precise research into lightweight structures.

Increasing material strength can both reduce vehicle weight and improve crashworthiness. However, metal materials generally exhibit an inverse relationship between strength and ductility, making it important to predict the likelihood of fracture during a collision. Within the field of material strength, described in Section 2, Kobe Steel is analyzing mechanical properties highly correlated with fracture during collision[15)] and developing numerical simulation technology for accurate prediction of fracture phenomena.[16)]

1.2 Development and design of lightweight automotive components

Kobe Steel presents steel and aluminum materials - the main metals used for vehicle bodies - on equal footing to optimally meet customers' needs when presenting solutions. We also use optimization analysis and the expertise of our design engineers when navigating manufacturing constraints to design lightweight parts fit for purpose.

Fig. 2 shows an example of lightweight designs based on performance predictions from parametric optimization for a bumper made of roll-formed high-strength steel plate and an aluminum extruded bumper, comparing their weight and flexural strength. The left graph in Fig. 2 reveals that for a cross-section with small external dimensions, the high-strength steel plate and aluminum extrusion have no substantial weight difference, making the former advantageous from a cost perspective. Conversely, given a cross-section with large

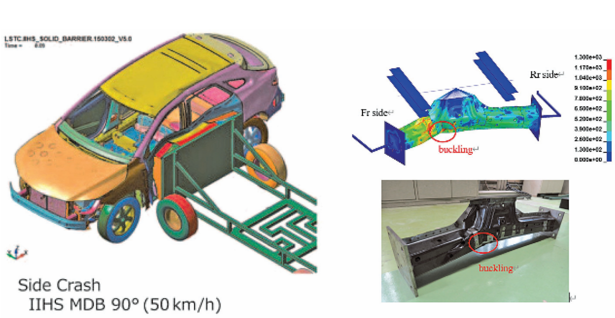


Fig. 1 Full-vehicle crash simulation and example of component collision evaluation

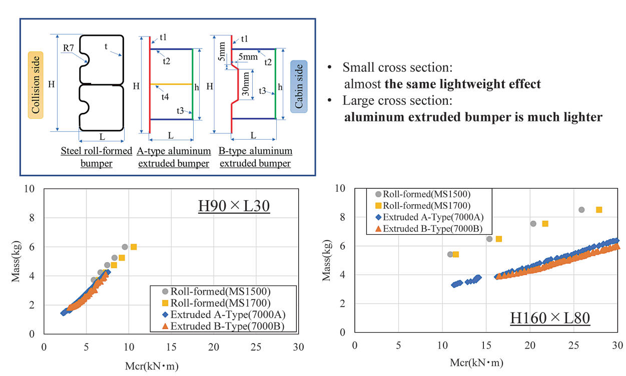


Fig. 2 Comparison of roll-formed steel bumpers and aluminum extrusion bumpers with different external dimensions

external dimensions (Fig. 2, right graph), the weight reduction of an aluminum extrusion is significant. Therefore, high-strength steel plate and aluminum extrusions are each advantageous in different ranges of cross-sections.[17)]

Fig. 3 shows an LCA (life cycle assessment) of doors with a lightweight design. We designed front doors in three different materials - steel, aluminum, and a steel/aluminum composite[18)] - and compared their weight and life-cycle GHG (greenhouse gas) emissions.[19)]

The graph shows that steel has the lowest GHG emissions from manufacturing, while aluminum has the highest. However, life-cycle GHG emissions are lower for aluminum and the composite than for steel. Rankings also vary with mileage. In the future, parts development will need to account for (1) the degree of weight reduction, (2) the cost of weight reduction, and (3) LCA (life-cycle GHG emissions).

2. Strength and fracture prediction technology that accounts for metallurgical factors (field of material strength)

Kobe Steel's core technology for prediction and evaluation of durability and fracture in metal products and structures will result in enhanced safety and productivity. Numerical simulation based on elastic-plastic fracture mechanics can predict strength and deformation. However, successive changes in physical properties and phase transformations caused by heat treatment and processing during manufacturing must be considered. Kobe Steel has enhanced its predictive and evaluative technologies by accounting for metallurgical factors such as carburization, segregation, and phase transformation. We also use fracture mechanics to design robust products, predict the progression of fatigue cracking, and evaluate the permissibility of cracks that do not affect the product. Kobe Steel's technical fortitude also includes materials engineering, such as in the form of metallographic structure control, as a core technology. We capitalize on this strength when developing technologies by combining fracture mechanics with materials engineering. This section introduces examples of our unique strength and fracture prediction technologies that account for phase transformation, including technologies to prevent deformation and quench cracks during quenching and to prevent brittle fracture in the slab after continuous casting.

2.1 Quenching deformation and microstructure prediction technology accounting for phase transformation

Heat treatment is part of the manufacturing process of Kobe Steel's products (crankshafts, large compressor gears, etc.) and materials (end products: automotive gears, shaft materials, bolts, etc.). Reducing the deformation and residual stress inherent to heat treatment improves product quality. Doing so requires an understanding of the effects of the cooling process and part geometry. However, the phenomena that occur during quenching are extremely complex, with the microstructure (phase transformation), stress/strain (dynamics), and temperature (heat transfer) all influencing each other. This led us to develop a heat treatment simulation program that combines these factors. We use this program to propose solutions to customers and to solve challenges related to our products.

Fig. 4 shows a use case of carburized automotive gears[20)] in which the martensite volume fraction was predicted by combining carburization simulation[21)] with heat treatment simulation. The carburized surface has a high carbon concentration and low martensitic transformation temperature. As such, the carburized surface transforms and expands after the interior, creating compressive residual stress in the surface. Therefore, scrutinizing the

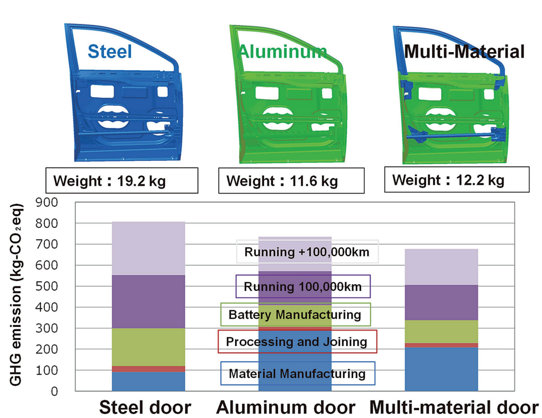


Fig. 3 Design and LCA of lightweight doors

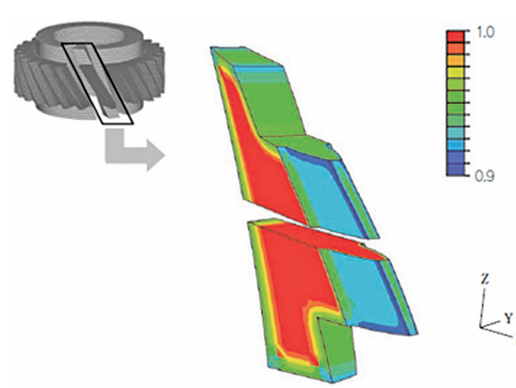


Fig. 4 Calculated martensite volume fraction of carburized gear

progressive deformation and transformation that occur during cooling reveals the mechanisms behind the thermal stress and deformation caused by thermal contraction and volumetric expansion associated with transformation. This scrutiny in turn enables specification of the material properties, cooling processes, and part geometries that control these phenomena.

The aforementioned theory assumes homogeneous materials. However, segregation in large ingots causes non-uniform material properties and quench cracks.[22)]

We are now considering how this technology can be used to identify root causes of cracking to determine effective countermeasures. This involves accounting for the effects of upstream processes on the microstructure and evaluating localized stress caused by segregation.

2.2 Prediction and prevention of cracking in continuous casting slabs

Kobe Steel's various steel products, such as wire rod, steel sheet, and steel plate, are made by rolling slabs and blooms produced by continuous casting. Adding alloying elements to increase the strength of steel increases the likelihood of brittle fracture during cooling after casting.[23)] This reduces the production yield. Controlling thermal stress in the slab during cooling, traditionally achieved by cooling the slab slowly, helps prevent cracking.[24)] However, measuring thermal stress to determine internal residual stress is extremely labor intensive. Qualitative measures must also be taken because the cooling process alters material properties (toughness). Heat transfer analysis using the finite element method alone is inadequate for quantitative prediction of thermal stress in slabs; heat generation and expansion due to phase transformation during slab cooling must be accounted for. Kobe Steel has developed relevant core technologies in materials engineering, including heat transfer and solidification analysis software[25)] and technologies that predict phase transformation during continuous cooling.[26)] These innovations have made it possible to quantify slab stress via numerical simulation. Our technology first charts temperature development throughout continuous casting. It then analyzes heat transfer within the cooling slabs that have passed through the casting machine and been cut and stacked. These data are combined with a transformation prediction model to account for phase transformation behavior and calculate stress within the slab. This enables quantitative management of the thermal stresses involved in

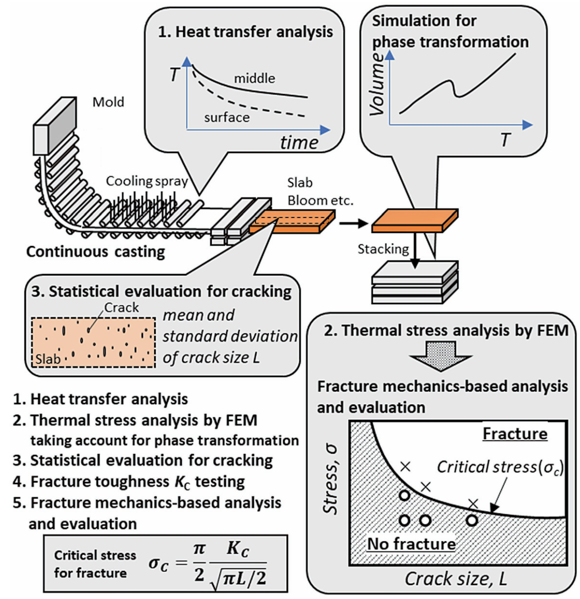


Fig. 5 Fracture mechanics-based prediction of brittle fracture of slab accounting for thermal stress and phase transformation

brittle fracture.

An additional point to consider is that brittle fracture originates from miniscule cracks inside the slab. Specifically, they originate from solidification cracks at the solid-liquid interface, which are not true cracks, but rather areas of segregation from molten steel from the liquid phase. As such, we developed fracture mechanics analysis technology to statistically analyze the frequency of occurrence of internal cracks and evaluate the risk of brittle fracture based on crack size.[27)] This technology (**Fig. 5**) uses fracture mechanics to ascertain the relationship between the critical stress σ_C (determined by a numerical simulation program that accounts for phase transformation), crack size L, and fracture toughness K_C of the slab. We validated this formula against experimental results. Our technology therefore enables definition of the requisite conditions, such as cooling rate, for precluding brittle fracture. As such, it can prevent brittle fracture originating from cracks in the slab as well as pitting from hot rolling.[27)] It has led to the improved productivity of Kobe Steel's products and established safe, logic-guided manufacturing process management.

3. Material modeling technology that accounts for the microstructure of materials (field of micromechanics)

A material's macroscopic mechanical properties are governed by its microscopic metallographic structure. Moreover, microscopic defects cause cracks that in turn lead to macroscopic fracture phenomena. Therefore, material modeling technology must account for microstructure to overcome increasingly complex engineering demands, meet varied material needs, and solve significant challenges. This is why Kobe Steel has been refining crystal plasticity analysis methods that account for the non-uniformity of material deformation and multi-scale analysis methods that connect the micro and macro scales. This section introduces examples and future prospects of each application.

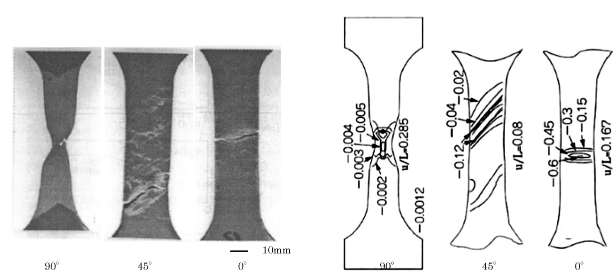
3.1 Application of crystal plasticity analysis in forming

Mechanical analysis based on crystal plasticity theory can account for the anisotropy of crystalline structures. It can also quantitatively relate macroscopic and microscopic structural changes in terms of mechanical properties with definite physical implications. We are advancing the constitutive laws of crystal plasticity to accommodate various load paths.[28] Our objectives in doing so are to develop lightweight formed materials that satisfy increasingly stringent specifications and to improve forming conditions.

Tensile testing of single-crystal silicon steel sheet serves as a prime example.[29), 30)] **Fig. 6** compares the experimental and calculated deformation resulting from tensile testing at different angles α between the tensile axis and the crystallographic orientation. The results strongly indicate the following: local deformation in the transverse direction at α = 90°, local deformation in the thickness direction at α = 0°, and shear bands at α = 45°. We are using this technology to evaluate the effects of texture formation on a surface pattern called ridging, which occurs in 6000-series aluminum sheet for automotive panels after forming. This endeavor will clarify the mechanisms behind deformation, which will improve surface appearance quality.[31]

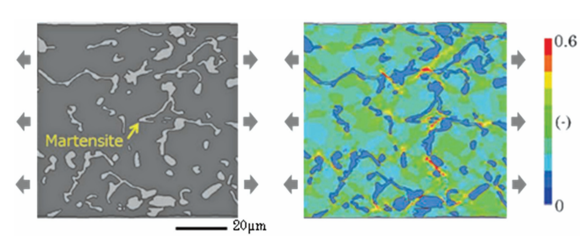
3.2 Multiscale analysis accounting for material microstructure

Multiscale analysis calculates the mechanical properties of each microstructure to predict macroscopic mechanical properties and analyze microscopic mechanical phenomena. Kobe Steel has developed a method to quantitatively model microscopic metallographic structures and has created a proprietary FEM program based on homogenization in elastic-plastic theory. Described next is the application of multiscale analysis to dual-phase steel (hereinafter, DP steel), a common high-tensile strength steel, to evaluate the mechanical behavior of the microstructure.[32] DP steels have a composite microstructure containing ferrite and martensite phases; our simulation is based on the tensile test results of each phase. **Fig. 7**(b) shows the equivalent distribution of plastic strain at 20% elongation. Plastic strain is concentrated in the ferrite phase near dense areas of the hard martensite phase. There is also a small percentage of plastic strain in the martensite phase, suggesting that this phase, which fractures when subjected to extremely low strain in single-phase materials, has high deformability in DP steel. Our method enables analysis of the mechanical properties of each phase, interactions caused by parameters of each phase such as dispersion states and microstructure-level shapes and sizes, and the resultant macroscopic mechanical properties. This enables prediction of the microstructure required for the desired macroscopic mechanical properties. We will use this information in conjunction with our metallographic structure control technology in our future materials development ventures. Furthermore, this technology makes it possible to analyze microscopic matrix damage, including initial flaws, and the deformation and fracture behavior of inclusions during forming. We are researching how to use this technology to improve the internal quality of materials.



(a) Tensile specimen after test (b) Calculated result (Distribution of thickness strain)

Fig. 6 Localized strain in tensile test specimen of silicon steel sheet



(a) Deformation of microstructure (b) Distribution of equivalent strain

Fig. 7 Deformation state of microstructure (at 20% elongation)

Conclusions

This paper describes one of Kobe Steel's core technologies, structural deformation and breakdown evaluation technology, which is divided into the fields of structural mechanics and material strength. Example applications of each fundamental technology were presented. Described as well is our progress in the field of micromechanics, which connects the microscopic realm of metallurgy with the macroscopic realm of dynamics. Core technologies in micromechanics relate strongly to other core technologies, such as nanoscale analysis and evaluation techniques as well as materials integration.[33] Developing these technologies into cross-sectional predictive and evaluative technologies that connect the nano scale to the macro scale will lead new material concepts for structural materials. We plan to expand these technologies to process simulations that also connect with the manufacturing process, which will further improve quality and productivity. We will continue fostering a safe and secure society by developing and producing materials with increased added value.

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