Abridged version

KAWASAKI STEEL TECHNICAL REPORT

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"Environment-friendly Steel Products" and

"Environment Preservation Technology"

Development of Environment-Friendly Steel Products at Kawasaki Steel

Takashi Obara, Takako Yamashita

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The body can be viewed from the next page.

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1 Introduction

Protection of the global environment has become an extremely serious and important issue in recent years. The steel industry is responsible for approximately 10% of total energy consumption in Japan, and steel materials account for roughly 10% of the country's total physical product.[1] Thus, responding to environmental problems is an important task for the steel industry. Kawasaki Steel also gives high priority to environmental protection in its corporate activities and is making a variety of efforts to solve environment-related problems.

Kawasaki Steel's basic policy for responding to global environmental problems is shown in the conceptual diagram in **Fig. 1**.[2] The company is continuing to make efforts to reduce environmental loads and energy consumption at all stages of its business activities and is also actively contributing to the construction of a recycling society in which locally-produced waste is received and reused as a resource.

Steel has long been regarded as an excellent eco-material because of its good recyclability and low total energy cost in the production process. For this reason, increasing expectations are now placed on the role which steel products will play in realizing further reductions in environmental loads.

Hayashi et al.[3] have estimated that the energy savings achieved by using high-performance steel products are equivalent to approximately 10% of the total energy consumption of the Japanese steel industry, the equivalent of more than 5 million kℓ of heavy oil per year. These products, which make it possible to reduce the weight and/or extend the service life of products, fall under 11 categories, including high strength sheets and plates for automotive and construction applications, heat-resistant tubes for boilers, and ultra-thin gauge sheets for beverage cans. At present, the total consumption of these products is approximately 6.5 million t/y. However, the same authors estimated that an additional 4% energy saving (equivalent to 3.8 million kℓ of heavy

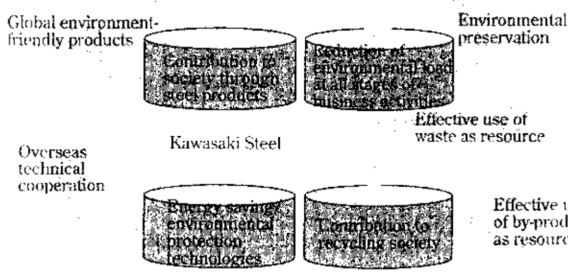

Fig. 1 Basic policy for preservation of the global environment in Kawasaki Steel

* Originally published in *Kawasaki Steel Giho*, **33**(2001)2, 59-65

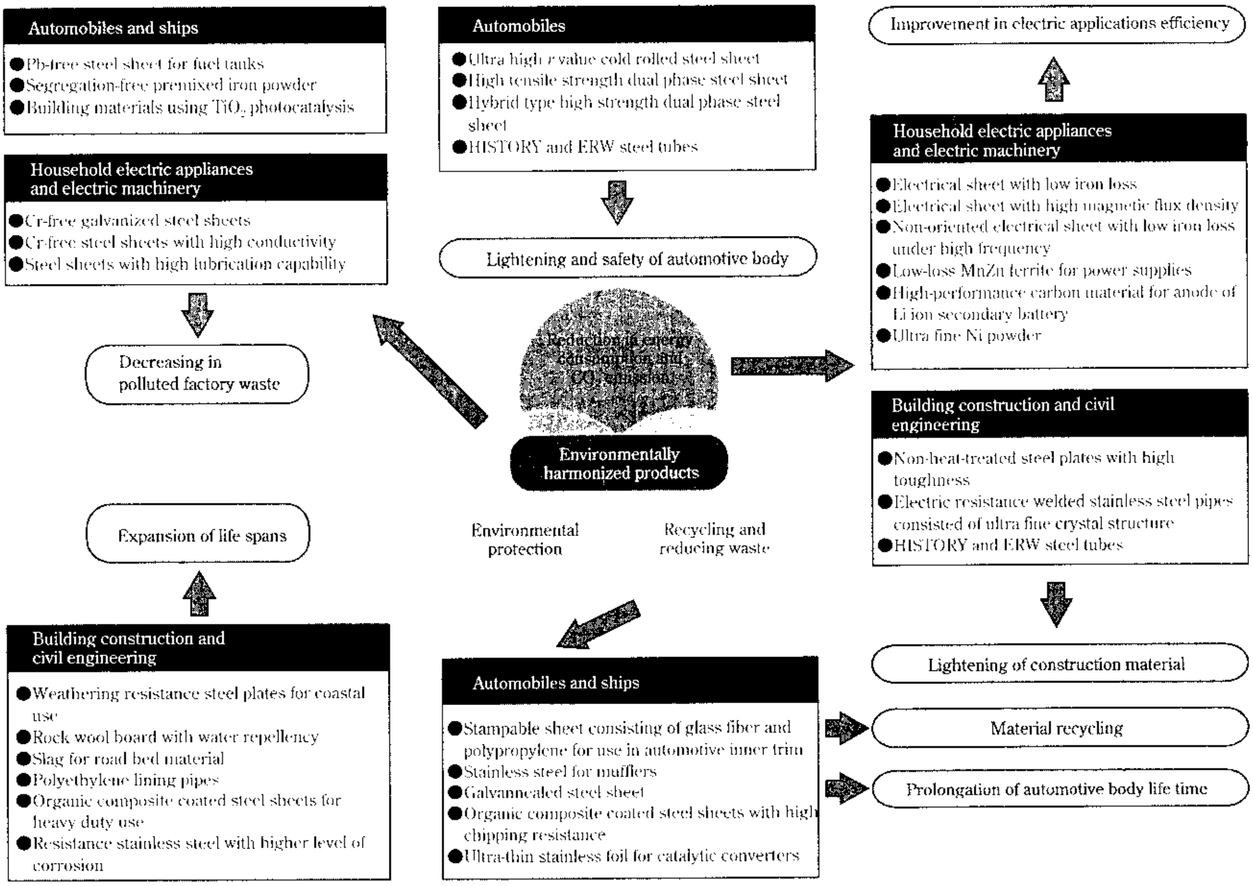

Fig. 2 Environmentally harmonized products developed recently at Kawasaki Steel

oil per year) could be realized if high-performance products were used in all possible applications, and further energy savings of 3% (3.5 million kℓ) or more are also possible if mechanical properties such as strength and toughness can be improved.[3)] Hence, the energy savings and reduction in CO_2 emissions which can be achieved by wider adoption of high-performance steels are extremely large, and it is increasingly important to promote their application from this viewpoint. In order to respond to these social needs, Kawasaki Steel has already developed and is supplying a large number of new steel products which reduce the load on the environment.

This report presents brief descriptions of typical examples of recently developed products which illustrate Kawasaki Steel's commitment to solving environmental problems. Details have been published previously and may be found in the cited literature.

2 Environment-Friendly Products Developed by Kawasaki Steel

The requirements placed on steel products as materials are (1) reduction of total cost, including consideration of service conditions, (2) improved properties, such as strength, workability, and extended service life, (3) suitability for processing, recycling, and reuse, and (4) reduction or elimination of harmful chemical substances.

Measures to ensure harmony with the environment can be roughly classified into three types: (1) energy saving and CO_2 reduction, (2) recycling and reduction of wastes, and (3) environmental protection. Energy savings may be realized in various ways, for example, by increasing the energy conversion efficiency of motors through improvements in the magnetic properties of steel materials, improving the energy efficiency of automobiles by reducing body weight, and reducing unit consumption of energy in the steel production process and in users' manufacturing processes. Improved recyclability is achieved by applying steel materials which allow easy maintenance and safe long-term use, and by producing materials that contain only alloying elements which are easily controlled in the recycling process. Examples of recently developed Kawasaki Steel products are shown in **Fig. 2** by type of environmental measure and field of application. As examples of the recognition of the above-mentioned technologies by various academic societies, new technologies and products which have received the Technical Development Prize of the Japan Society of Metal Science in the last five years are listed below.

(1) Year 2000

"Development of the concept of new steel manufacturing process (TPCP) by integration of uniform microstructure control and precipitation hardening, and development of new non-tempering high strength steel based thereon"

"Development of a carbide-hardened centrifugally-cast high speed steel roll with excellent heat crack resistance"

(2) 1999

"Development of an extra-heavy wide-flange beam with high seismic resistance using 3rd generation TMCP introducing Fine Inclusion Metallurgy"

(3) 1998

"Development of hybrid-hardened, dual phase steel sheets with excellent fatigue strength and formability for automobile wheels"

(4) 1997

"Development of cold rolled steel sheet with ultra-high r-value by warm rolling technique combined with lubrication"

"Development of nitrogen solution hardening type ultra-thin steel sheets with excellent properties for canmaking"

"Development of non-grain oriented electrical steel sheet for high efficiency motors (50RMA350)"

(5) 1996

"Development of impact-absorbing high strength automotive steel sheet"

"Development of ferritic stainless steel with corrosion resistance and high formability (River Lite SX-1)"

"Development of flexible high productivity technology for high quality, high formability ERW tubes using CBR forming mills"

As can be seen from the examples listed above, the company has devoted great energy to the development of environment-friendly steel materials. These products have earned an excellent reputation from customers and are being used in increasing amounts.

The following describes various improvements in material properties, together with element technologies which have attracted attention, in their respective fields of application.

3 Overview of Development of Environment-Friendly Steel Products by Application

3.1 Automotive Steel Sheets

From the viewpoint of the environment, the most important task in the field of automotive steel products is achieving energy savings by reducing automobile body weight. In recent years, it has become possible to increase the strength of steel body members by using high strength steel sheets, while at the same time reducing body weight by applying thinner materials. As a result, the use of high strength steel sheets in auto bodies is now under study as a means of satisfying the mutually contradictory requirements of weight reduction and improved crashworthiness.

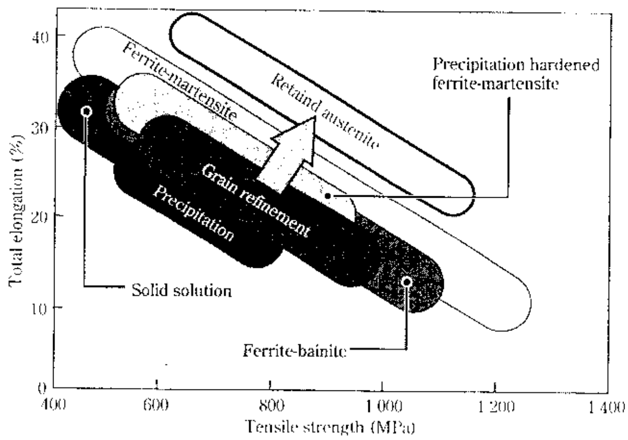

Fig. 3 Relationship between tensile strength and elongation of high strength steels

Various problems tend to occur when higher strength steels are used, such as wrinkles and material breakage during press forming and poor shape fixing due to spring-back and bowing. The hardening methods which are generally used to increase strength include solution hardening, precipitation hardening, grain refinement, phase transformation to obtain a dual phase structure (martensite/ferrite or bainite/ferrite), and work hardening. **Figure 3** shows the relationship between total elongation in the tensile test, which is a representative index of press formability, and the high strength steel sheets produced using these respective hardening mechanisms.[4] With every one of the hardening mechanisms, total elongation (El) decreases as tensile strength (TS) increases. This means that the key problem in material development is how to minimize the decrease in elongation which accompanies increased strength. As shown in the figure, the improvement in total elongation with transformation hardened sheets, that is, which dual phase materials, is superior to that of sheets produced using the other hardening mechanisms. Particularly good total elongation values were obtained by strain-induced martensite transformation from a retained austenite phase by applying high-accuracy cooling control after finishing rolling. Products manufactured by this process are mainly used in stretch-forming applications.[4]

The hole expanding property is also required in the press forming of high strength steel sheets. **Figure 4** shows schematically the relationship between tensile strength × elongation and tensile strength × hole expanding ratio (λ) with each of the hardening mechanisms mentioned above, for the case of high strength

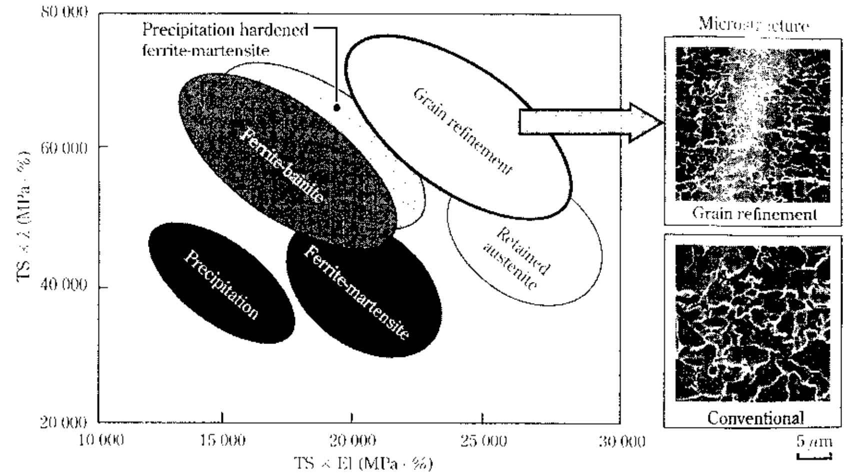

Fig. 4 Relationship between tensile strength × elongation and tensile strength × hole expanding of 590 MPa TS grade steels

steels of the 590 MPa grade. It is known that steel sheets composed of a microstructure with uniform hardness generally display good hole-expanding. For this reason, sheets with a precipitation hardened mother phase are an effective choice when hole expansion is required.[5] A resent study has shown that grain refinement improves the hole expanding property without impairing elongation.[6] This technique is therefore expected to be applied to materials which require both strength and high hole expansion. Reinforcing members must have a high capacity to absorb impact energy. Because it is thought that the capacity to absorb impact energy during high speed deformation becomes larger as the area occupied by the stress-strain curve increases, sheets with a high n-value, high tensile strength, and high work hardenability are required.

Thus, it is essential to expand the application of high strength steel sheets in order to reduce auto body weight. However, as a precondition for wider use of high strength sheets, if is necessary to secure the properties required in parts by controlling the microstructure on the basis of metallurgical theory, for example, by phase transformation and by making practical use of grain refinement technologies. Moreover, a technology which employs a combination of microstructure control and grain refinement is also needed. Among recent trends, Kawasaki Steel is positively applying computer simulation techniques to the analysis of formed parts, beginning with analysis of the high speed deformation characteristics of automotive structural parts by the finite element method (FEM), and to the analysis of press formability.[7]

3.2 Stainless Steel

The engine accounts for a large part of the total weight of an automobile. Because the engine and exhaust gas are heated to extremely high temperatures,

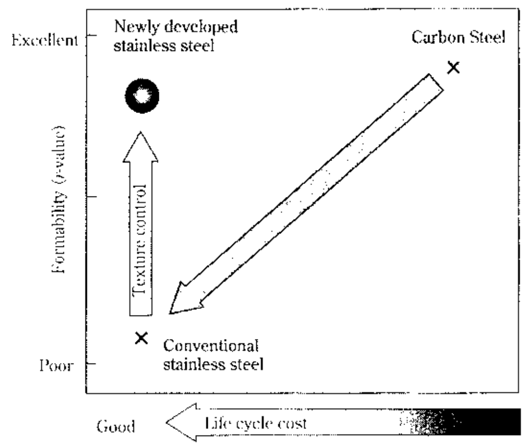

Fig. 5 Relationship between life cycle cost and r-value of carbon

sintered parts with good thermal fatigue resistance have often been used in engine-related parts. It has long been known that stainless steel generally possesses good thermal fatigue resistance. However, stainless steel has poor formability due to its high content of alloying elements, and as a result, its use has been limited to large pressure vessels and other applications in which formability is not essential. To extend product life, as shown in **Fig. 5**, the use of stainless steel should be expanded because it offers high corrosion resistance and excellent life cycle cost performance.

These facts suggest that the range of applications of stainless steel can be expanded by improving formability while continuing to pursue higher corrosion resistance. Kawasaki Steel therefore developed a high heat-resistance stainless steel with a good r-value by texture control. This new product has been applied to the exhaust manifold, making it possible to reduce the thickness of this part and thereby provide a low heat capacity simul-

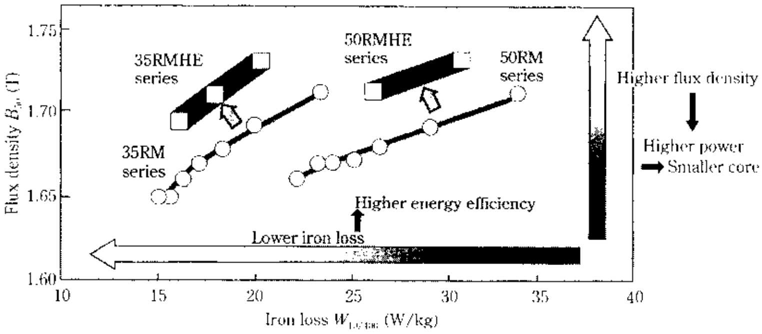

Fig. 6 Iron loss at 1.0 T, 400 Hz and flux density at 5 000 A/m of RM and RMHE series

taneously with weight reduction.[8)]

Kawasaki Steel can also supply material for exhaust manifolds in the form of ERW tubes. The company has developed and put into practical use a CBR (chance free bulge roll) forming mill which makes it possible to obtain high secondary workability by reducing additional forming strain during pipemaking and secure the weld quality necessary to withstand severe secondary working. In addition, this process reduces manufacturing costs by eliminating the need for heat treatment after pipemaking.[9)] The company has also developed a product called the HISTORY (high speed tube welding and optimum reducing technology) tube to meet the need for tubes with high strength combined with excellent workability.[10)] The microstructure of this product is refined by applying large rolling strain in the warm rolling region, which results in a remarkable improvement in ductility. As can be seen from these new technologies, Kawasaki Steel is developing materials with higher formability, and at the same time, is also actively working to improve the properties of steel sheets by process improvement.

As another example, stainless steels for mufflers must provide not only formability and weldability, but also excellent corrosion resistance in order to resist perforation corrosion by the highly corrosive condensate exhaust gas, containing NH_4^+ and Cl^-. Kawasaki Steel worked to elucidate the mechanism of corrosion by the exhaust gas condensate and clarified the mechanism which promotes corrosion.[11)] At the same time, it also found that Cr and Mo are effective in preventing perforation corrosion, and a high corrosion-resistance muffler material was developed by adding Mo to 18% Cr steel.[12)] The use of this material has reduced perforation corrosion in mufflers and helped to prevent noise and exhaust gas leaks due to perforation, as well as to extend auto body life.

The concepts used in the development of the stainless steels described above are also being applied in a similar manner to the development of stainless steels for construction materials and linepipes. Specifically, the company is conducting research and development with an emphasis on extending building life by improving corrosion resistance to meet the requirements of the service environment, while simultaneously improving formability.

3.3 Electrical Steel Sheets

Electrical sheets are functional materials which are frequently used as iron cores in power supply and conversion systems in equipment such as generators, motors, and transformers. Increasing the efficiency of this equipment helps significantly to reduce power consumption, and in turn, to prevent global warming and other problems. From the viewpoint of equipment performance, electrical sheets must possess two properties, namely, high magnetic flux density and low iron loss. These are also environmental requirement.

First, in the field of non-grain oriented electrical sheets, there is currently strong interest in improving motor efficiency. As shown in **Fig. 6**, the use of electrical sheets with high magnetic flux density in the motor core increases motor power, making it possible to reduce the size of the core. At the same time, low iron loss improves energy conversion efficiency, and thus reduces energy consumption in the system as a whole. From early on, Kawasaki Steel has been developing electrical steel products with low iron loss and high magnetic flux density, but recently, the company has also developed the "RMA Series" of products, which provide both properties simultaneously, and the "RMHE Series," which offers low iron loss in combination with high magnetic permeability.[13)] The company has also developed non-grain oriented electrical sheets with low iron loss in the high frequency region.[14)]

Grain oriented electrical sheets are used mainly as material for the iron cores of power conversion transformers in power transmission systems. Although the energy efficiency of such transformers is now extremely high, at approximately 98%, even a small improvement in efficiency can yield meaningful energy savings, considering the present large volume of power consumption. In recognition of this fact, Kawasaki Steel is attempting to achieve further reductions in iron loss.

Figure 7 summarizes the development of grain oriented electrical sheets at Kawasaki Steel. High grade grain-oriented electrical sheets (HGO) have obtained

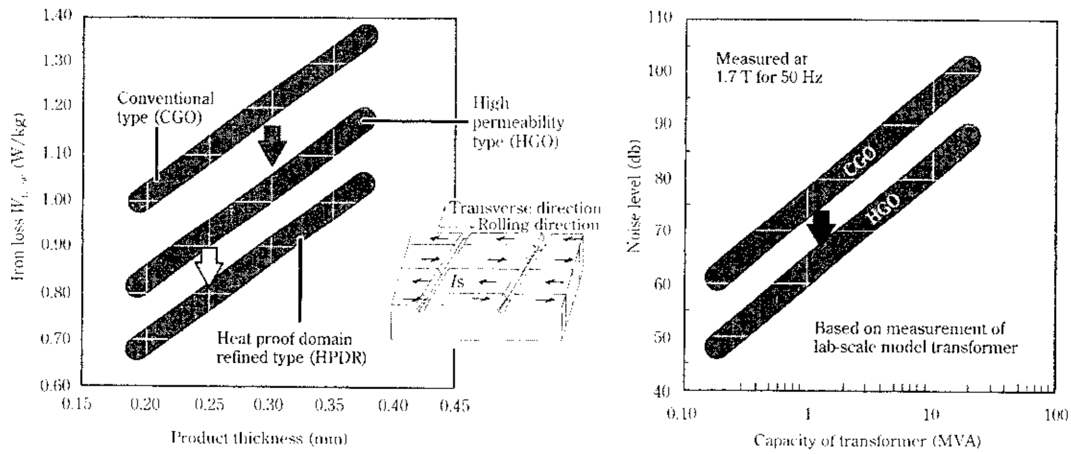

Fig. 7 Grain-oriented electrical steel saves energy by improving iron loss of transformers

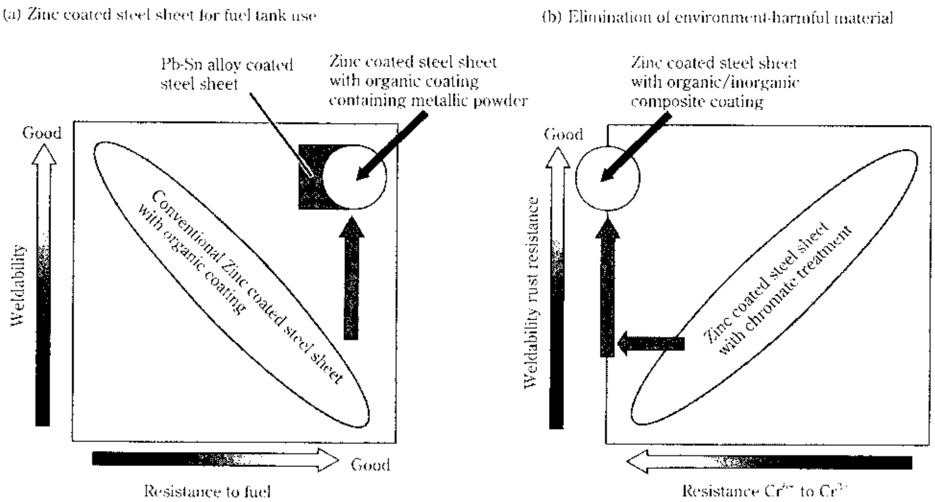

Fig. 8 Relationship between weldability and resistance to fuel (a), and white rust resistance and reducing chromium oxide (b) of zinc coated steel sheets

low iron loss by reducing in eddy current loss through a decrease in steel sheet thickness and by reducing hysteresis loss through high alignment of crystal orientation. The company also developed HPDR to reduce eddy current loss by domain refinement, using a technique for forming numerous grooves on the sheet surface.[15] By dramatically reducing iron loss, this product makes it possible to reduce exciting current and noise level in transformers. HGO is a high grade grain oriented electrical sheet which achieves high magnetic flux density simultaneously with low iron loss, and reduces the cost of measures to prevent transformer noise.[16,17]

3.4 Coated Steel Sheets

Coating technologies such as hot dip galvanizing and organic coating are not only used to extend the life of steel products, but are also widely employed to impart special functions, such as elimination of the need for oil coating in the press forming process and elimination of the painting and cleaning processes. In manufacturing coated sheets in recent years, Kawasaki Steel has made an effort to reduce the load on the environment by using materials which do not contain harmful substances and are easily recycled.

For example, as shown in **Fig. 8** (a), excellent resistance to fuel corrosion is required in fuel tank materials. A thick organic coating is generally necessary in order to improve corrosion resistance, but weldability decreases as the film thickness is increased. The company therefore developed a product which simultaneously satisfies the mutually contradictory requirements of corrosion resistance and weldability. Weldability is secured in this new product without reducing the film thickness by employing a technique for dispersing metallic powder in the organic coating.[18] Because the product replaces terne sheets (Pb-Sn plated steel sheet), which are the conventional material for auto fuel tanks, it also helps to reduce harmful substances when autos

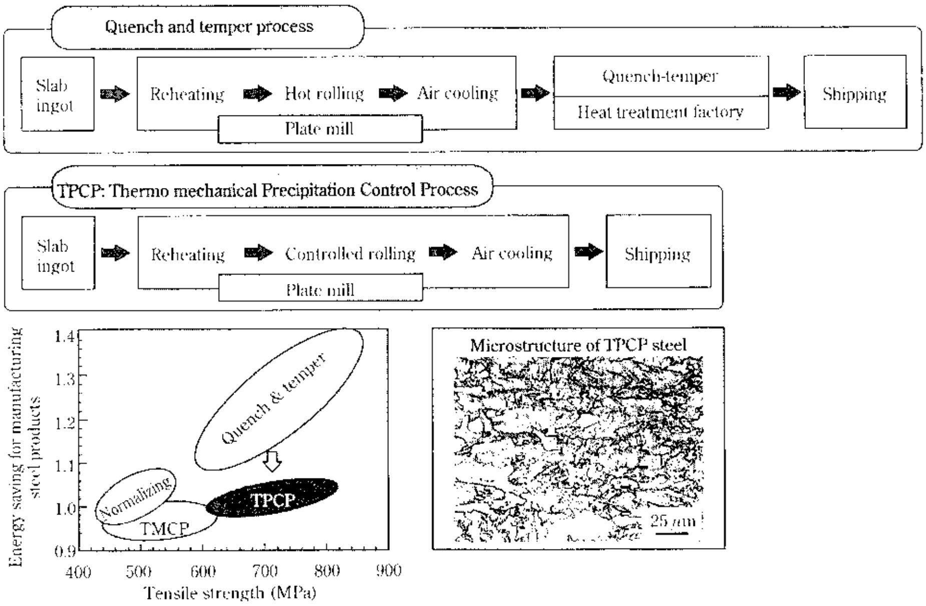

Fig. 9 Outline of TPCP and quench and temper process, and the typical properties. The required energy have been calculated on the basis of the NRIM's database for evaluation of LCA and normalized by the value for the normalizing process.

are scrapped.

Similarly, although organic coatings are also used to improve the corrosion resistance (resistance to white rust) of zinc galvanized steel sheets for household electrical appliances, it had been necessary to increase the coating thickness in order to guarantee corrosion resistance. However, the use of heavier coatings reduced electrical conductivity, which is essential for good weldability. To avoid this reduction in the conductivity of coated materials, the company developed a new coating in which an inorganic rust-preventive agent is mixed with an organic resin that possesses excellent corrosion resistance. This film composition makes it possible to maintain the same level of corrosion resistance as in conventional materials with heavy organic coatings, even when the coating thickness is decreased and thus ensures good weldability simultaneously with corrosion resistance.

One essential requirement for corrosion resistance in galvanized steel sheets for household appliances is good adhesion between the sheet and the organic film. Adhesion had generally been secured by chromate treatment, which included the use of hexavalent chromium (Cr^{6+}), a substance that increases the load on the environment. Furthermore, it was necessary to increase the Cr^{6+}/Cr^{3+} ratio of the chromate coating in order to obtain satisfactory corrosion resistance, as can be seen in Fig. 8 (b), which is a schematic illustration of the relationship between the chromate coating weight and corrosion resistance. Because the newly developed organic film described above possesses good adhesion without chromating, the need for chromate treatment is eliminated, providing a fundamental solution to this problem. Thus, it is now possible to supply sheets which have good weldability for use in household electrical appliances and are free of substances that place loads on the environment.[19]

3.5 Plates, Long Products, Wire Rod Material, and Bars

Welded structures, which are a main application of steel plates, have become increasingly sophisticated in order to meet stricter safety, environmental, and cost requirements. In recent years, efforts have been made to realize total cost reductions and reduce environmental loads by applying the following three concepts to the development of plates: (1) Increasing strength without sacrificing weldability, (2) reducing the work load by eliminating assembly processes and reducing (pre-heating) in welding, and (3) reducing maintenance costs by extending the life of structures.

An outstanding example in this field is extra-low carbon bainitic steel, which was developed to solve the problem of reduced weldability that generally accompanies high strength. The product is based on a new control concept which provides a uniform microstructure using the thermo-mechanical precipitation control process (TPCP). An extra-low carbon content of approximately 0.02 mass% or less is adopted, and the microstructure is controlled by rolling to a single phase of granular bainitic ferrite, which has comparatively high strength, resulting in a product with strength equivalent to that of existing materials.

An outline of the TPCP process is shown in **Fig. 9** in comparison with the manufacturing process for conventional quenched and tempered materials. As can be

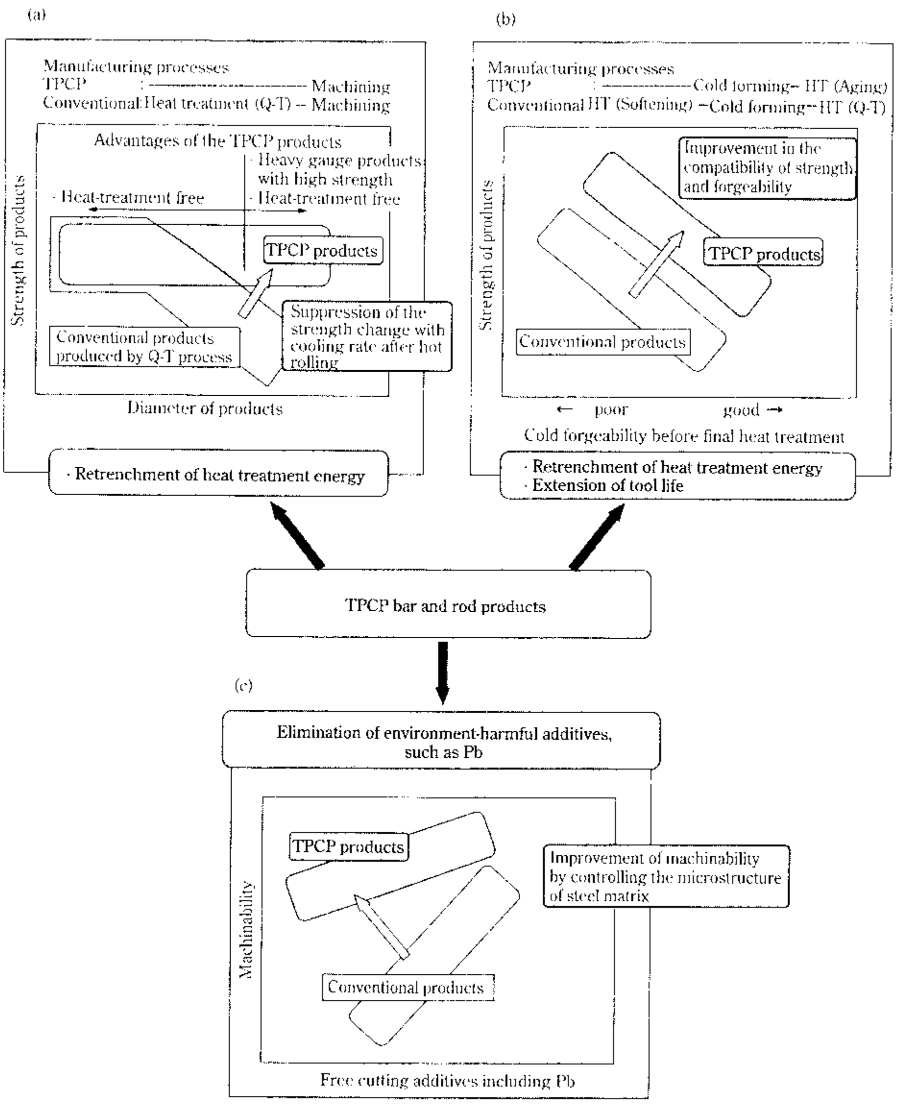

Fig. 10 Effects of TPCP at bars and wire rod steels

understood from the figure, TPCP contributes to energy saving by making it possible to omit the processes of quenching and tempering. The elimination of these processes also reduces manufacturing costs. Moreover, because it is possible to secure a uniform single phase of bainitic ferrite by TPCP regardless of the plate thickness, the process enables 100% preheat-free welding.[20]

Special steels which are used as steel bars and wire rod material are manufactured into final products by customers through a complex process of secondary working which includes forging, machining, and heat treatment. In order to reduce the load on the environment, it is essential to consider not only the steel manufacturing process, but also these secondary processes. The main secondary processes which are applied to steel bars and wire rod materials are annealing, working, quenching, and tempering. Omission of the heat treatment steps from this process is an effective means of saving energy. Kawasaki Steel has developed various non-tempering steels, which make it possible to omit the quenching and tempering process and are therefore useful in saving energy and reducing manufacturing costs in the customer's production process.

Figure 10 presents an outline of the applications of TPCP in the field of steel bars and wire rod material, together with the advantages of TPCP products. The energy savings which are realized by the omission of quenching and tempering are shown in Fig. 10 (a), and those realized by the omission of annealing are shown (b). Fig. 10 (c) is an example of Kawasaki Steel's efforts to eliminate the use of elements such as Pb, which is added to conventional steels for machine structural use in order to improve machinability, but is harmful to the human body. The figure shows the concept of a graphite steel for machine structural use which was developed as a substitute for Pb-added steel. In this product, graphite is finely dispersed in the steel matrix by optimizing the chemical composition and hot rolling conditions.

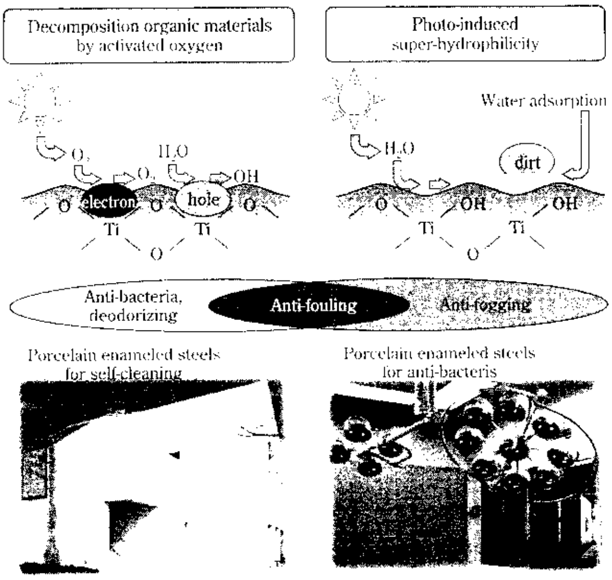

Fig. 11 Building materials using TiO_2 photocatalysis

As illustrated by these examples, TPCP makes it possible to achieve energy savings in the steel manufacturing process while also eliminating harmful substances from products.[21)]

3.6 Other Environment-Friendly Products

This section presents examples of the development of environment-friendly materials in fields other than the company's main product lines. R & D work which has drawn attention in recent years includes research on the removal of NO_x and SO_x from air, water treatment, and the decomposition of chemical substances by applying the photocatalytic function of TiO_2. These technologies, which are now being studied for practical use, are based on the fact that pollutants can be decomposed by the active oxygen generated by TiO_2 when exposed to sunlight, and the photo-induced super-hydrophilicity of this substance also gives it an anti-fouling property. Kawasaki Steel began working with photocatalyst technologies at an early stage in their development and has already developed civil engineering materials such as guardrails and sound damping walls, as well as interior and exterior construction materials. In addition to purifying auto exhaust gas and factory smoke, these materials make it possible to wash dust, oil, and mold from structures when exposed to ordinary rain, and thus have a maintenance-free function in combination with air purification.[22)]

Figure 11 shows the principles of air purification, the anti-bacterial and sterilizing functions, and the anti-fouling property of the TiO_2 photocatalyst, together with examples of the use of enameled materials containing this photocatalyst in the interior and exterior of buildings. Because the advantages of this technology are not limited to reducing environmental loads, but also include "cleaning" the environment, their application should be expanded to non-steel products.

4 Conclusion

This report has presented representative examples of newly developed steel sheets and other products with properties or chemical compositions which reduce loads on the environment. Because steel has an overwhelming advantage over other materials in terms of quantity, price, strength, and recyclability, among other characteristics, further expansion of the possibilities and future potential of steel is expected. In responding to social needs, Kawasaki Steel will continue to develop product lines which maximize the possibilities of steel and actively contribute to reducing loads on the environment.

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