Technical Review

UDC 669 . 14 . 018 . 292 - 413

Progress of High Performance Steel Plates

Akihiko KOJIMA*
Manabu HOSHINO
Michio KANEKO
Masaaki FUJIOKA
Genichi SHIGESATO
Mutsuto TANAKA

Abstract

Nippon Steel & Sumitomo Metal Corporation has developed a variety of high performance steel plates with manufacturing process, fine particle and corrosion resistance technologies. A number of experts have organically cooperated on such developments in order to meet demands from our customers and society for higher performance steel plates.

1. Introduction

This paper describes the development of high-performance steel plates (hereinafter simply referred to as "steel plates") at Nippon Steel & Sumitomo Metal Corporation and the technological prospects of steel plates in the future, with the focus on the company's manufacturing processes, fine particle utilization technology, and corrosion prevention technology.[1–11]

2. Enhancing Steel Plate Functions by Improving Manufacturing Process

2.1 History of technology developments

The functions of steel plate base materials have been continually enhanced through sophistication of the thermo-mechanical control process (TMCP), process metallurgy, equipment technology, manufacturing technology, and quality control technology. TMCP is the combination of controlled rolling and accelerated cooling, as shown in **Fig. 1**. It is the key technology that dramatically enhances the strength, toughness, and weldability of steel plates. Described below is the progress of the technology at Nippon Steel & Sumitomo Metal.

Since the 1970s, the sophistication of controlled rolling has been pressed ahead to enhance the functions of steel plates through development of advanced new technologies such as NIC (Nippon Steel inter-critical rolling process), SHT (Sumitomo high toughness steel), and ULCB (ultralow carbon bainitic steel).

Accelerated cooling was applied for the first time in 1960 to manufacture HT60 (590-MPa-class high-tensile steel) by direct quench (DQ) at Hirohata Works. Thereafter, in 1983, a full-scale continuous on-line cooling process (CLC) was introduced at Kimitsu Works. In the same year, a dynamic accelerated cooling process (DAC) was introduced at Kashima Works. The CLC having a hot leveler before the cooling equipment was a unique cooling system featuring rolls for constraining the steel plate, sprays for intensive cooling, facilities for on-line cooling, etc. CLC-μ, which is the second-generation CLC developed recently, has significantly improved the uniform cooling and universal cooling capabilities.

Today, the most advanced accelerated cooling technology described above is applied to almost all high-performance steel plates for ships, buildings, bridges, offshore structures, line pipes, construction equipment, tanks, penstocks, etc. The latest TMCP, including DQ-tempering and DQ wherein water cooling is stopped halfway, is a technology indispensable for high-performance steel plates. Using this technology, many innovative new products have been developed. They include, for example, high-arrest steel HIAREST™ having an ultrafine-grained surface layer; ausformed bainitic steel; new LNG tank steel; highly deformable line pipe steel X80; high-tensile structural steel BT-HT; low preheat temperature steel HT80 (tensile strength (TS) 780 MPa class); steel for offshore structure, YS550 (YS: yield strength); steel for bridge, SBHS500; steel for shipbuilding, YP460 (YP: yield point); high-ductility ship steel NSafe™-Hull; and abrasion resistant steel ABREX™.

In enhancing the functions of steel plate, using a large draft in the rolling process is impractical. Therefore, to weld the porosities remaining in the slab, it was necessary to implement rolling with the high-shape factor at a high temperature. For that reason, TMCP could not always be effectively applied. However, the improvement of slab quality (i.e., reduction of porosities and segregations) by the development of the continuous casting process made it possible to apply TMCP even to heavy-gauge steel plates. For example, TMCP was employed to develop penstock steel HT100 (TS 950 MPa class) having a thickness of 100 mm. The progress of the abovementioned steelmaking process technology has led to the development of advanced new casting equipment for manufacturing extra-thick, high-quality slabs. For example, a 210-mm-thick HT80 plate for rack was

* General Manager, Head of Lab., Dr.Eng., Plate & Shape Research Lab., Steel Research Laboratories
20-1 Shintomi, Futtsu City, Chiba Pref. 293-8511

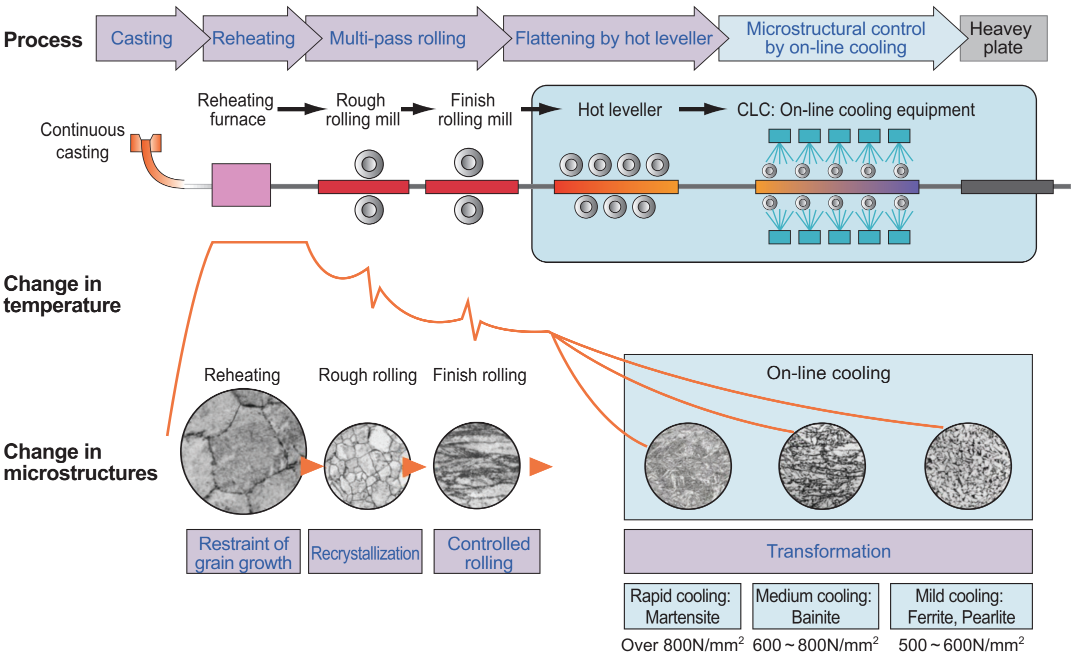

Fig. 1 Schematic illustration of TMCP and microstructural changes

developed.

2.2 Technological outlook

TMCP has greatly helped develop high-performance steel plates since it increases the strength and toughness of steel through grain refinement and transformation hardening and simultaneously improves the weldability of steel through the reduction of the carbon equivalent. This technology that was first applied to HT50 (TS 490 MPa class) has come to be applied even to high strength steels exceeding HT100 and low temperature steels (for −196°C). The properties required of steel plates in recent years are not simple. Demands for high levels of strength, toughness, ductility, thickness, etc., which are contradictory to one another, have become stronger than ever before. Under that condition, implementation of a more extensive and more sophisticated microstructure control is needed. To that end, it is important to fully understand and control the process of formation of microstructures, including bainite and martensite.

In TMCP, Ti, Nb, B, etc., which markedly change the microstructures of steel even when added in small amounts, have been utilized. Therefore, examining the condition of presence of those micro-alloyed elements and controlling them precisely is important. In recent years, it has become possible to quantitatively analyze the amount of segregation of B in austenite (γ) grain boundaries by employing the most advanced electron microscopy. In addition, thanks to the progress of computational science, including first-principles calculation, the phenomenon of intergranular segregation has come to be better understood. In the future, it is necessary to implement an atomic-level control of the micro-alloyed elements in TMCP based on analysis and calculation.

From the perspective of sophisticating the microstructure control of steel, a material prediction model that expresses the correlation of steel composition, TMCP conditions, microstructures, and materials was developed primarily for HT50. The model has been used for the enhancement of steel plate functions. In the future, it is necessary to develop the model into a powerful tool for increasing the efficiency of technology development by improving the accuracy and widening the scope of application of the model considering bainite and martensite as well.

In the development of YP460 for ships employing TMCP, an 8 000-ton tensile tester was employed to evaluate the brittle fracture arrestability of steel with the aim of standardizing the classification of ships, as well as developing new steels. In the future, from the perspective of securing a rational balance between the reliability and economics of welded structures, a study based on fracture mechanics, like the one mentioned above, will become increasingly important.

3. Enhancement of Steel Plate Functions by Progress of Grain Refinement Technology

3.1 History of technology developments

Since steel plates are used in welded structures, the properties of weld zones are as important as those of the base steel. In particular, the toughness of heat affected zone (HAZ) is one of the most important considerations when enhancing the functions of steel plate. Various techniques to improve the HAZ toughness of steel have been developed to meet diverse requirements of welded structures—higher structural reliability and resistance in harsh operating conditions, better welding efficiency, lighter weight, and larger size. The technology development at Nippon Steel & Sumitomo Metal is described below.

The most important problem in improving the HAZ toughness of steel is how to refine the HAZ microstructure after phase transformation in the coarse grain region near the fusion line that is heated to 1 400°C or higher. Keeping this problem in mind, techniques to refine the HAZ microstructure, as shown in **Fig. 2**, have been developed. The point in those techniques is to utilize thermally-stable fine particles either as pinning particles for restraining the growth of γ grains or as nuclei for ferrite transformation within γ grains in the thermal history of HAZ. The ferrite formed by the latter method is called intragranular ferrite (IGF).

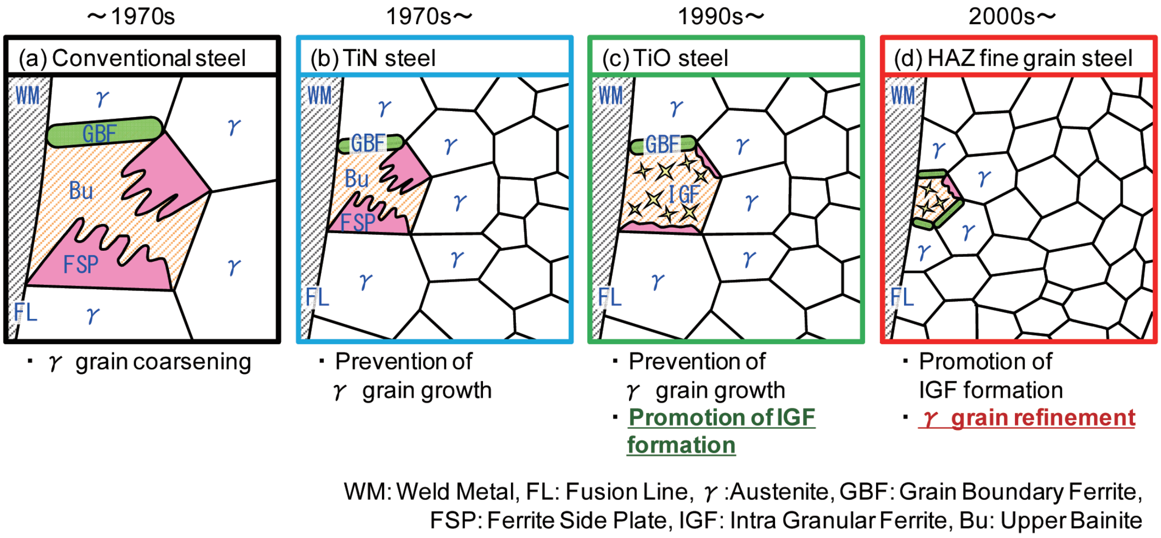

Fig. 2 Progress of HAZ toughening technology HTUFF in Nippon Steel & Sumitomo Metal

As shown in Fig. 2, TiN steel was developed in the 1970s. TiN steel utilizes TiN particles tens of nm in size mainly for pinning the growth of γ grains. In the development of TiN steel, it was found that TiN particles were also effective as nuclei for IGF transformation. Today, TiN steel has become widespread as a standard technology. In the 1990s, the concept of oxide metallurgy was proposed, which led to the development of TiO steel that uses Ti oxide particles several μm in size dispersed in the steel by means of Ti deoxidation without Al addition as the nucleus for IGF transformation. In the 2000s, HAZ fine grain steel was developed on the basis of advanced oxide metallurgy. This is a technology whereby the growth of γ grains adjacent to the fusion line is strongly restrained by dispersing in the steel Mg- or Ca-containing oxides or sulfides tens to hundreds of nm in size.

In addition to the above steels, several steels utilizing the IGF technology were developed. They include, for example, B-added steel using BN, TiN–MnS steel using TiN and MnS in combination, and Ti–B steel combining TiN with $Fe_{23}(CB)_6$, $Fe_3(CB)$, or BN. The above techniques to improve HAZ toughness by utilizing fine particles are collectively called High HAZ Toughness Technology with Fine Microstructure Imparted by Fine Particles (HTUFF™).

The application of HTUFF has made it possible for the company to develop and supply many advanced new steel products for various uses ahead of other steelmakers at home and abroad. They include large-heat-input welding steel for shipbuilding, construction, wind power generation, etc.; high-strength, low-temperature joint CTOD (crack tip opening displacement) guaranteed steel for offshore structure; and steel for line pipe in cold regions. The company's world-renowned steelmaking technology has supported mass production of the abovementioned sophisticated steels.

3.2 Technological outlook

The mechanism of HTUFF has been largely elucidated thanks to the progress of analytical techniques. In the IGF transformation, for example, the Mn-depleted zone around the Ti oxide plays an important role. This has been proved by the use of a focused ion beam system and a field-emission transmission electron microscope in combination. In the future, it is important to deepen the understanding of the HTUFF mechanism by employing the advanced analytical technology and further enhance the functions of HTUFF-based steels.

As the basic technology for improving the toughness of HAZ, clarifying the factors governing toughness and establishing a method for predicting toughness is important. In 1980s, the factors that govern CTOD were clarified using a method based on microscopic fracture mechanics. In recent years, for welding with a large heat input, the effects of alloying elements and thermal history on the factors governing HAZ toughness have been formulated and several models for predicting HAZ toughness have been developed. Basic studies like these have to be pressed ahead in the future.

To place high HAZ toughness steels into practical use, the development of suitable welding materials is indispensible. Nippon Steel & Sumikin Welding Co, Ltd., a member company of the Nippon Steel & Sumitomo Metal Group, has developed various new welding materials suitable for high HAZ toughness steels and has proposed specific welding materials for specific steel plates. From the perspective of promoting the practical use of high HAZ toughness steels, too, the above organization for development of welding materials is significant and should be further reinforced in the future.

4. Enhancement of Steel Plate Functions by Progress of Anti-corrosion Technology

4.1 History of technology developments

A low alloy corrosion resistant steel contains a small proportion of alloying elements added to improve its resistance to corrosion. For example, a bridge made of corrosion resistant steel has a service life of 100 years. Thus, corrosion resistant steel is a material that is highly durable and that helps save resources, and therefore, it plays an important role in the development of sustainable society. The development of corrosion resistant steels at Nippon Steel & Sumitomo Metal is described below.

Unlike the case of stainless steel whose corrosion resistance is attributable to a passive film formed on its surface, the corrosion resistance of a low alloy steel is attributable to a protective rust layer, precipitated film, etc. formed on the surface by the alloying element through the interaction with the corrosive environment. It is, therefore, important to investigate the effect of the alloying element on the interface reaction between the environment and the steel surface, and thereby clarify the mechanisms of corrosion and corrosion pre-

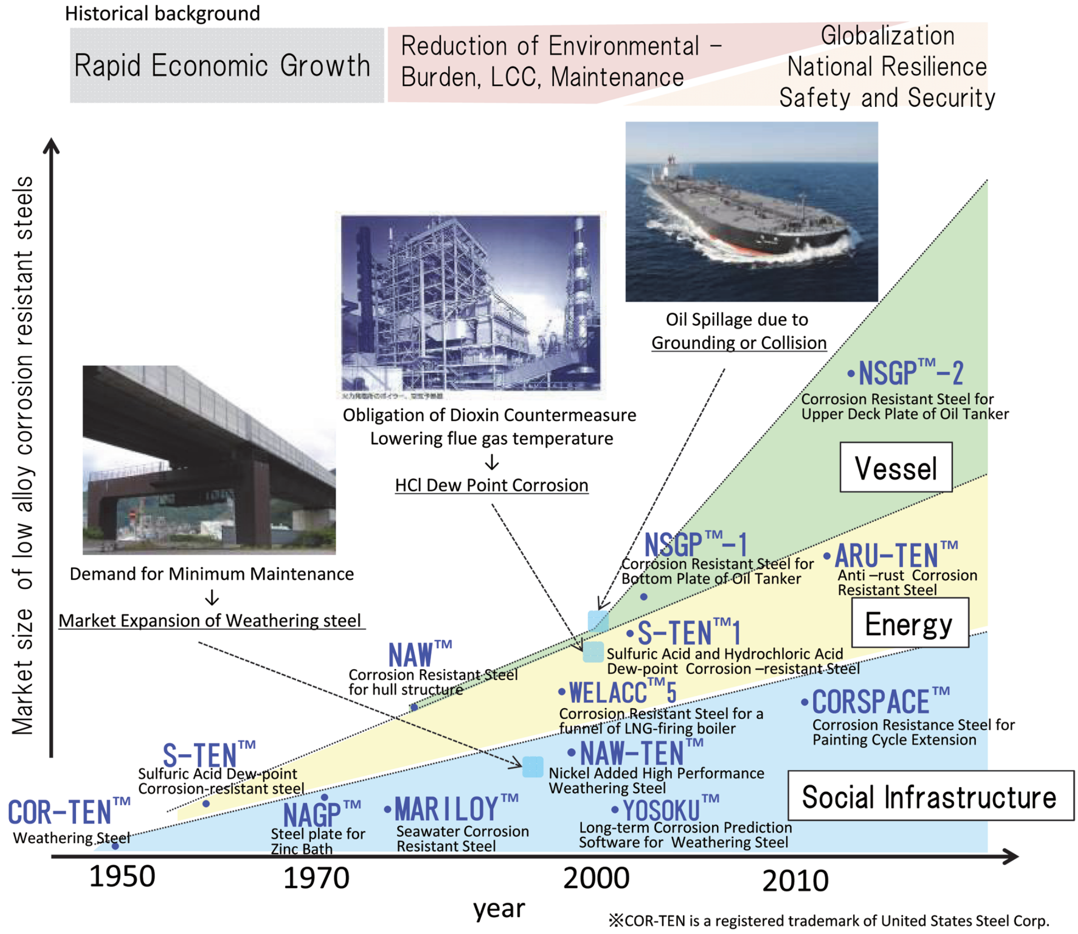

Fig. 3 Progress of corrosion resistant steel plates in Nippon Steel & Sumitomo Metal

vention. Positive attempts have been made to clarify those mechanisms and develop new steel materials by employing various advanced analytical techniques, such as the in-situ observation of corroded surfaces applying synchrotron radiation. The development of corrosion-resistant steels at Nippon Steel and Sumitomo Metal is shown in **Fig. 3**.

The weathering steel containing a small proportion of an alloying element (Cu, Cr, etc.) forms a highly protective rust layer (protective rust) on the surface while it is exposed to the atmospheric environments and thereby lowers the corrosion rate significantly. In a region where there are so many particles of airborne salt that the ordinary weathering steel is not very effective, it is necessary to restrain the phenomenon whereby chloride ions penetrate the rust layer on the steel, causing the pH value at the steel surface to decrease. Nickel-added high performance weathering steels having superior corrosion resistance were developed by controlling the rust layer ion-exchange function by Ni addition and thereby allowing Na ions in sea salt to pass through selectively. Eventually, the anti-corrosion mechanism was clarified by the development of advanced analytical technology that made the in-situ observation of corrosion in a wet corrosive environment possible. In addition, techniques to estimate the life of weathering steels, evaluate the protective rust quantitatively, repair corroded steel plates, etc. were developed to minimize the life cycle cost of weatherproof steel bridges.

Steel materials used in the flue-gas systems are corroded by the condensation of acidic substances (SO_x, HCl, etc.) contained in the hot exhaust gas from boiler plants. In the wake of environmental regulations on exhaust gas, S-TEN 1 having excellent resistance not only to sulfuric acid dew-point corrosion but also to hydrochloric acid dew-point corrosion was developed.

In the field of vessels, from the viewpoint of preventing ocean pollutions caused by wrecked crude oil tankers, the use of double-hull tankers was made obligatory in 1992. In addition, with the aim of preventing crude oil spillage, corrosion prevention measures for oil tanks were investigated. As a result, the unpainted corrosion-resistant steel Japan proposed in 2013 was formally adopted as an alternative steel material for oil tank (by an international convention). Nippon Steel & Sumitomo Metal also developed NSGP™-1 (corrosion resistant steel for bottom plate of oil tanker) and NSGP™-2 (corrosion resistant steel for upper deck plate of oil tanker).

4.2 Technological outlook

In recent years, from the perspective of materializing a recycling-based society and protecting the global environment, there is growing demand for new steel products having higher durability and consuming less alloying elements. As new corrosion-resistant steel plates with new surface treatment or coating, ARU-TEN™, and CORSPACE™ (corrosion-resistant steel for painting cycle extension) have been developed. To press ahead with the development of such new steel products that meet the needs of the times, it is necessary to systematize the huge volume of extensive knowledge that

Table 1 Award records of high performance steel plates of Nippon Steel & Sumitomo Metal in recent years

Year	Award names	Achievements
2000	Ichimura Award	Weathering steel for use in coastal regions
2002	Ichimura Award	Development of high performance 60 kgf/mm^2 high tensile strength steel plate with strikingly improved welding capabilities
2004	Ichimura Award	Super high HAZ toughness technology with fine microstructure imparted by fine particles (HTUFF)
2007	Ichimura Award	Sulfuric acid and hydrochloric acid dew-point corrosion resistant steel (New S-TEN 1)
2008	Okochi Award	YP 47 kgf/mm^2 class higher strength steel plate and new hull structure design for large container ships (jointly with Mitsubishi Heavy Industries)
2009	Ichimura Award	Development of steel plate for improving the fatigue strength in welded joints
2011	Ichimura Award	Corrosion resistant steel for cargo oil tank (NSGP-1)
2012	National Commendation for Invention	Development of the functional steel plate with high enhancement to fatigue life for welded structures
2013	Nikkei Excellent Products & Services Awards	7% nickel steel for LNG tank

has been accumulated so far. In addition, it is important to further enhance the performance of corrosion resistant steel plates by deepening the understanding of the mechanisms of corrosion and anti-corrosion, while paying attention to the phenomenon of corrosion and the working of alloying elements.

5. Conclusion

At Nippon Steel & Sumitomo Metal, to fully meet the demands for high-performance steel plates from our society and customers, the researchers and engineers in diverse fields—plate making, refining, solidification, rolling, cooling, welding, fracture, structure, analysis, mathematic, etc.—have been engaged in the development of new technologies with the cooperation of the operating, manufacturing, and sales personnel. The results of their efforts have been highly rated, as can be seen from examples of the awards the company has received (**Table 1**). We intend to continue making a concerted effort to meet any new challenges from the society and customers with our advanced steel plate technology.

References

1) Uemori, R. et al.: Shinnittetsu Giho. (391), 37 (2011)
2) Uemori, R. et al.: Shinnittetsu Giho. (391), 67 (2011)
3) Iwasaki, M. et al.: Shinnittetsu Giho. (391), 88 (2011)
4) Ogawa, S. et al.: Shinnittetsu Giho. (391), 94 (2011)
5) Takahashi, M. et al.: Shinnittetsu Giho. (391), 127 (2011)
6) Hayashi, S. et al.: Shinnittetsu Giho. (391), 137 (2011)
7) Yamamura, K. et al.: Shinnittetsu Giho. (391), 143 (2011)
8) Kaneko, M. et al.: Shinnittetsu Giho. (391), 162 (2011)
9) Kimura, M. et al.: Shinnittetsu Giho. (391), 165 (2011)
10) Someya, R. et al.: Sumitomo Metal. 50 (1), 22 (1998)
11) Hosokawa, T. et al.: Sumitomo Metal. 49 (2), 103 (1997)

Akihiko KOJIMA
General Manager, Head of Lab., Dr.Eng.
Plate & Shape Research Lab.
Steel Research Laboratories
20-1 Shintomi, Futtsu City, Chiba Pref. 293-8511

Masaaki FUJIOKA
Chief Researcher
Plate & Shape Research Lab.
Steel Research Laboratories

Manabu HOSHINO
Chief Researcher
Plate & Shape Research Lab.
Steel Research Laboratories

Genichi SHIGESATO
Chief Researcher, Ph.D
Plate & Shape Research Lab.
Steel Research Laboratories

Michio KANEKO
Chief Researcher, Dr.Eng.
Plate & Shape Research Lab.
Steel Research Laboratories

Mutsuto TANAKA
Senior Manager, Head of Dept.
Plate Products Technical Service & Solution Dept.
Plate Technology Div.
Plate Unit