UDC 629 . 12 : 69 . 057

Technical Review

Steels for Marine Transportation and Construction

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1. Introduction

The shipbuilding industry made an enormous contribution to Japan's postwar rehabilitation. Since shipbuilding is one of the major applications of steel plate, it may be said that the steel industry, especially the steel plate sector, has made remarkable progress in tandem with the shipbuilding industry. The steel industry has fully supported technological innovations in the shipbuilding industry. For example, the development of Thermo Mechanical Control Process (TMCP) steel has allowed for high-efficiency, large-heat-input, one-pass welding, while the introduction of YP40 steel (yield point (YP): 390 N/mm^2) has helped increase the strength and decrease the weight of ships and enhance the efficiency of transportation. High-strength steels manufactured using the TMCP technology described later are used for tankers and bulk carriers, and the technology to control the toughness of heat affected zones (HAZ) is applied to LPG/LNG vessels. Collectively, they have contributed to the improved competitiveness of the shipbuilding industry. The shipbuilding industry has consumed large quantities of steel plate, for which the steelmakers have mass-produced TMCP steels, which have high toughness and allow for large-heat-input welding.

In the field of building construction equipment and industrial machinery as well, the steel industry has played an important role in postwar land restoration, in the improvement and maintenance of domestic infrastructure during the period of rapid economic growth, and in the development of social foundations on a global basis in recent years. Under such social conditions, improvements in the properties of the steels used have been made with an emphasis on increasing the steels' strength and wear resistance (hardness). Looking at the strength of steel, for example, steels with ever-higher tensile strength (TS) have been developed one after another, from 590-N/mm^2 to 780-N/mm^2 steels, then further to 980-N/mm^2 and still stronger steels, making it possible to enhance the performance and increase the scale of construction equipment and industrial machinery. On the other hand, steels with superior workability and weldability have improved the manufacturing efficiency of construction equipment and industrial machinery. Concerning the production of steels, with the development of TMCP, the conventional off-line tempering process has come to be replaced by TMCP, such as the controlled rolling-direct quenching process.

The above two industry sectors have one thing in common—fierce competition with overseas competitors. Therefore, it is necessary for steelmakers not only to be cost competitive, but also to develop new products that are technologically appealing to users. In addition, in view of the brisk demand for steels in the BRIC (Brazil, Russia, India and China) and other rapidly industrializing countries, steel materials which are thicker, stronger and perform better are being developed.

In terms of higher strength and better performance of steels for shipbuilding, Nippon Steel Corporation has maintained its competitive edge with EH47 steel (YP 460 N/mm^2), high crack-arrestability steel, and corrosion-resistant steel (NSGP®-1), etc. However, with the rise of the Chinese and South Korean shipbuilding industries, the structure of the world's shipbuilding industry is changing. Therefore, it has become an important issue how the company, armed with the above technologies, will be able to expand its share in the world market in the future. In the construction equipment and industrial machinery fields, the change in industrial structure is faster than in shipbuilding. Amid the rapid growth of Chinese fabricators, certain overseas steel mills monopolistically control the Chinese market. Accordingly, it is important for the company to press ahead with technological development and catch up with them. In any case, in the fields of shipbuilding and construction equipment and industrial machinery, the ability to develop such technology that permits winning the largest market share is the most important.

In this technical review, we first describe TMCP technology and HAZ toughness control technology (i.e. HTUFF®) that are key technologies in the manufacturing of steel plates for shipbuilding, for example. We then introduce the concepts behind the performance enhancement technology applied to certain types of steel plates. The latest trends in technological development are also described at the end. In addition to Nippon Steel's activities in the fields of shipbuilding and construction equipment and industrial machinery, the activities of the company in the field of building constructions (also see Chapter 1, 1-4 for details) are briefly discussed.

2. Steel Plate Metallurgy

2.1 TMCP technology

The Thermo-mechanical Control Process (TMCP) refers to the controlled rolling process [1], the accelerated cooling process [2], or a combination of those processes (**Fig. 1**) [3]. At Nippon Steel, TMCP is called the Continuous Online Control (CLC) process [4]. Controlled rolling refers to the finish-rolling process at a temperature below the non-recrystallization temperature of austenite (γ). It permits refining

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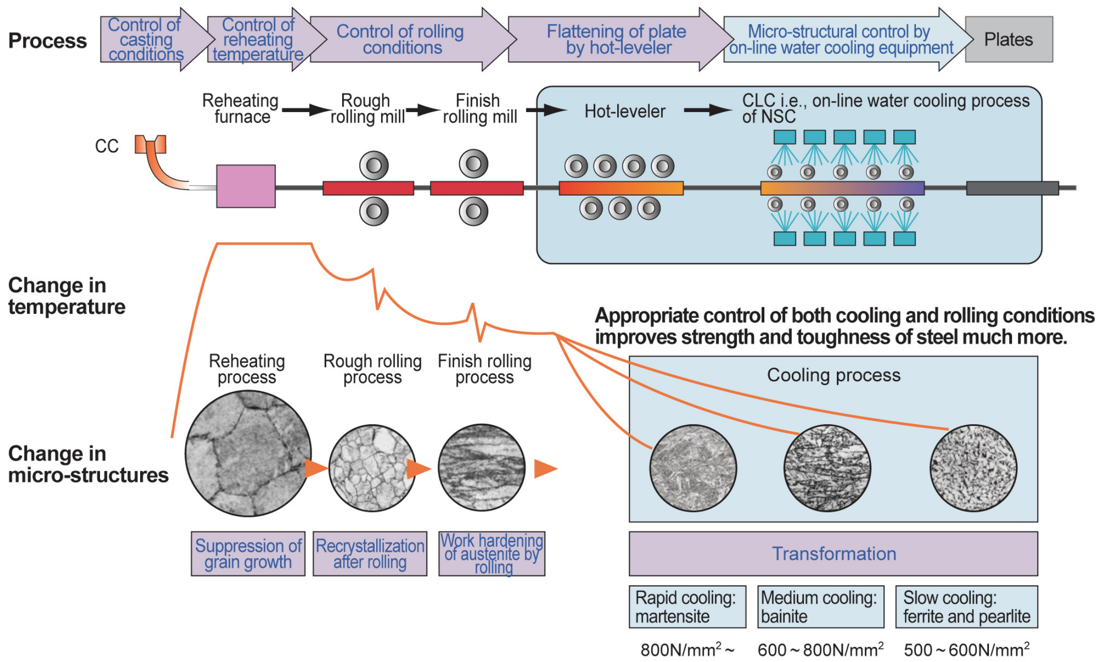


Fig. 1 Schematic illustration on TMCP and microstructural change in process

grains since γ grain boundary and intra-granular defects (grain boundary ledges, deformation bands, dislocation accumulated structures, etc.) introduced by plastic deformation become nucleation sites of γ - α transformation. Accelerated cooling causes the γ - α transformation to take place under a super-cooled condition by water-cooling from a temperature higher than the transformation onset temperature so as to increase the strength and toughness markedly by grain refining and formation of bainite or martensite.

In the actual manufacturing process, controlled rolling and accelerated cooling are supplemented by reheating at a low temperature or addition of micro-alloying elements (MAEs) such as titanium and niobium in order to maximize the grain refining effects of controlled rolling and accelerated cooling. Controlled rolling originated as low-temperature finish rolling (rolling at low temperature in the γ recrystallization region) that started in Europe in the 1950s. It progressed remarkably in 1958 when National Steel of the United States marketed niobium bearing steel [5]. In the 1960s, the British Iron and Steel Research Association (BISRA) and Japanese researchers studied controlled rolling in earnest. Their studies bore fruit in the development of X65, which was marketed by Japanese steelmakers in 1969 [1].

After that, Nippon Steel developed the Nippon Steel Inter-Critical (NIC) [6] rolling process of low-temperature reheating at 1,000℃ or less, and controlled rolling or inter-critical (γ - α dual-phase temperature region) rolling. In addition, Nippon Steel commercialized ultra low-carbon bainite (LCB) steel [7], and also HIAREST® (steel plate whose surface has an ultrafine grain microstructure) that is manufactured by the unique thermo-mechanical process accompanied by the cooling process at the inter-pass time of rolling [8], and that has good crack arrestability. Also, Sumitomo Metal Industries introduced a special version of controlled rolling called the SHT process (characterized by a reheating and rolling process at low temperature after ordinary rolling) [9].

On the other hand, accelerated cooling (ACC) became widely used after the development of controlled rolling. R&D on ACC in Nippon Steel has a long history and at first HT60 steel (TS: 590 N/mm²) was manufactured by direct quenching (DQ) at the Hirohata Works in 1960, and crack-free HT50 steel (TS: 490 N/mm²) with an ultra-low carbon equivalent (Ceq) was manufactured by applying accelerated cooling using roller quenching (RQ) equipment in 1970.

After that, during the period 1972 to 1974, systematic research on DQ was carried out. Through two research projects for DQ and ACC, a pilot plant for online DQ and ACC was constructed at Yawata Works in 1981 and full-scale online DQ and ACC manufacturing equipment was completed as the CLC cooling equipment at the Kimitsu Works in 1983. The CLC cooling equipment was Nippon Steel's original online cooling system featuring unique equipment specifications, such as a hot leveler (HL) installed in front of the cooling unit, constraint of steel plate using rollers, and a wide range of cooling rates using water sprays. It was capable of uniform cooling in both the case of slow and rapid DQ cooling. Many of the accelerated cooling systems today incorporate some of the features of the CLC cooling equipment.

In other steel companies in Japan, Nippon Kokan K.K. installed an online ACC system (OLAC) in 1980 [10]. Then, Sumitomo Metal Industries, Kawasaki Steel and Kobe Steel put their own accelerated cooling systems into operation. Thus, TMCP technology was established as the original technology of Japan, for the first time in the world.

Today, the CLC has become indispensable technology for manufacturing steel plates such as for ships, buildings, offshore structures, pipelines, construction equipment, industrial machinery, tanks, and penstocks, etc. In particular, in the field of shipbuilding, the CLC was applied to manufacture the new HT50 soon after it was developed. Grain refinement and micro-structural change induced by the CLC application increases the strength of steel, so the new steel has tensile strength about 100 N/mm^2 higher than conventional steel manufactured by normalized or controlled rolling of the same composition, and allowing for significant reduction of the Ceq (from 0.4% to 0.3 mass%) [4]. As a result, it became possible to reduce the hardness at the weld heat affected zone and dramatically improve weldability (**Fig. 2**).

Also, the CLC cooling equipment permits changing the cooling rate over a wide range, and using a strong cooling capability, it can be applied to high strength steels, such as HT60 - HT120 (TS: 570 - 1,180 N/mm^2). Now the CLC technology, including its improved versions [11], is widely used to manufacture steel such as for ships (YP: 315 - 460 N/mm^2), bridges (SM570TMC, high-performance BHS500/700), buildings (BT-HT 325 - 690), offshore structures (YP: 355 - 550 N/mm^2), construction equipment and industrial machinery (HT80 - HT120), line-pipes (X65 - X120), tanks and penstocks (HT80 - HT100), etc. (**Fig. 3**) [3]. **Fig. 4** shows the change in strength of steels for hulls with the application of CLC. It can be seen that the application of the CLC technology has helped developing higher strength steels.

Furthermore, in order to use the benefits of TMCP to the full, it is necessary to understand quantitatively and apply optimum control of such metallurgical phenomena as grain growth, work-hardening, recovery, recrystallization, solid solution and precipitation of MAEs, and transformation which occur in the manufacturing processes, including casting, reheating, rolling, cooling and tempering, etc. It is also important to clarify the relationships between microstructures and strength, toughness and other material properties. From the above standpoint, Nippon Steel has developed "the Zaishitsu Yosoku Model" [12, 13] which is a mathematical model for predicting the metallurgical phenomena that occur in the steel manufacturing processes, final microstructures and mechanical properties.

The model consists of a process model for calculating steel temperature and working strains in the reheating, rolling and cooling processes, a microstructure model for calculating microstructural changes due to recovery, recrystallization, precipitation and transformation, and a properties model for predicting the material properties from the microstructural variables. Given the chemical composition and process conditions (i.e. reheating conditions, rolling conditions, such as rolling pass temperature and reduction, and the CLC cooling conditions, such as water flow rate and cooling time), the model calculates the changes in microstructure during the manufacturing processes and yield strength, tensile strength and Charpy toughness ($_vT_{rs}$). By using the model, it is possible to design the optimum chemical composition and rolling conditions, and also study the optimum processes. In the TMCP, designing optimum process conditions, as well as optimum chemical composition, is a crucial control factor, and therefore "the Zaishitsu Yosoku Model" is used as an important tool.

Recently, Nippon Steel upgraded the former CLC to a second-generation CLC- μ (mu) [14] (**Fig. 5**). For the CLC- μ, Nippon Steel developed a new cooling system taking into consideration the boiling characteristic, flow of water, and the deformation behavior of steel plate so that more uniform cooling and flatter shape can be realized compared to conventional CLC. In addition, the cooling zone has been subdivided to allow for multistage cooling and the cooling rate range has been made wider than in conventional CLC. Thus, the CLC- μ is now the most advanced accelerated cooling system in the world. Employing those capabilities, Nippon Steel has developed many new products, for example, line-pipes to be used in seismic regions or areas with discontinuous permafrost which are required to have deformability in the bend-and-return process due to ground movement, and has also developed and marketed a new steel plate that has sufficient deformability even though it is stronger than the X80 steel. In addition, many new products such as steel plates for offshore structures that show exceptional weldability and weld-joint toughness even in extremely low temperature conditions of −40℃ or lower and the high-performance SBHS500 steel for bridges, have been developed and manufactured using the CLC- μ.

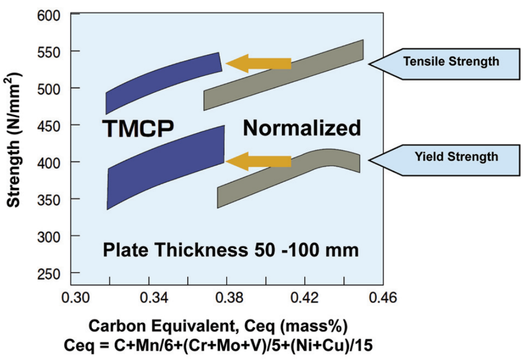


Fig. 2 Comparison of carbon equivalent (Ceq) in HT50 steels between manufactured by TMCP and normalizing process

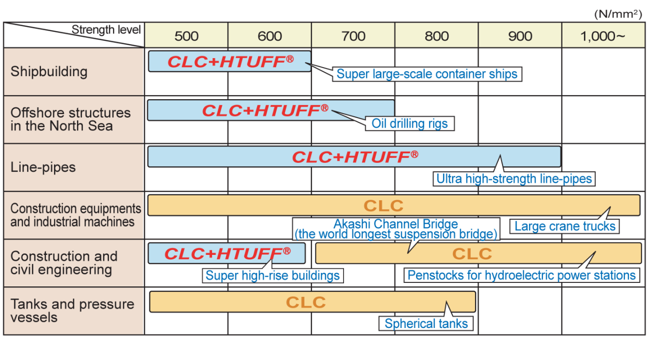


Fig. 3 Expansion of application field and strength level of the CLC and HTUFF® technology

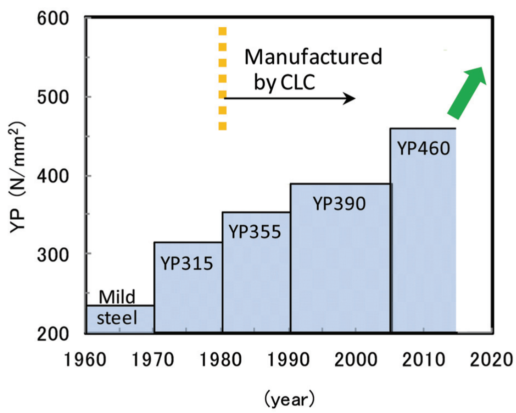


Fig. 4 Change in maximum strength of steel plates for shipbuilding in each decade

Fig. 5 Newly developed CLC-μ cooling equipment (Kimitsu Works)

2.2 HAZ toughness control technology

In most cases, steel plates are used for welded structures. Therefore, it is extremely important that steel plate should have good weldability and welded joint toughness. In particular, the technology to improve the toughness of heat-affected zones (HAZ) has been extensively studied as one of the most important technologies in the development of steel plates. As a result, a large body of knowledge has been accumulated. Of the technologies for refining the microstructure of HAZ, especially important are: the IGF (intragranular ferrite) technology that permits markedly refining the effective microstructure (effective grain size) by utilizing the IGF nucleated from intragranular nonmetallic inclusions (hereinafter simply called “inclusions”) or precipitates despite the fact that the austenite at the heating stage during welding (the prior austenite before the transformation) has become coarse, and the γ -grain refinement technology that permits effectively restraining the coarsening of γ grains by utilizing fine intragranular inclusions, etc. to pin the γ grains. Various improvements have been made to the above two technologies, as described below.

Even today, IGF technology is one of the most useful technologies for improving the HAZ toughness of steel plate. Initially, the technology was applied in practice to weld metals containing relatively large amounts of oxide particles. Then, ways of applying it to steel plates were sought. In particular, the technology attracted attention as a means of refining the microstructure of HAZ, which becomes coarse during welding, or materials that can hardly be refined by TMCP. Interlocked with the technological progress to control inclusions in the steelmaking process, the application of IGF technology to improve the HAZ toughness of steel plate began in earnest in the late 1970s. First, the application of IGF utilizing TiN was implemented [15]. Then, in the period from the late 1980s to the early 1990s, titanium oxide (TiO) steel [16], which utilized a titanium oxide, and high-performance TiN steel [17], which utilized TiN/MnS, were developed. They are both innovative high-performance steel plates developed by Nippon Steel for itself.

Concerning the mechanism of IGF transformation, as described in detail in Chapter 3, the manganese-depleted zone around inclusions is considered to play an important role. Namely, it is considered that as the result of a complicated interaction of the manganese-depleted zone and lattice coherency (interfacial energy) between inclusions/ γ matrix and inclusions/ferrite (α) interface, intragranular ferrite occurs before α transformation from the grain boundaries. In order to demonstrate the presence of a manganese-depleted zone, attempts had been made to measure manganese deficiency under a transmission electron microscope (TEM). However, because of the difficulty involved in securing a thin film from the part to be measured, etc., it was impossible to obtain measurement results with metallurgical significance. Recently, thanks to the most advanced TEM equipped with sophisticated analytical capabilities and to the progress of thin film forming technology, it has become possible to obtain highly accurate measurement results (see Chapter 3).

Next, we shall describe the γ -grain refinement technology. In recent years, high efficiency welding work using a large or super-large heat input (about 30 kJ/mm to 100 kJ/mm) has been increasing rapidly. Under that condition, there have been widespread calls for the development of a new high-performance steel plate that is capable of securing good HAZ toughness even when welded with a large heat input. For the HAZ toughness of steel plate welded with a large heat input, too, refining the γ -grain size before transformation is as important as in ensuring the base metal toughness.

Generally speaking, as the welding heat input is increased, it becomes difficult to keep the γ grains before transformation fine, especially close to the melting line, because in the HAZ, the holding time under high temperatures increases and the cooling rate becomes so low that the HAZ is exposed to high temperatures for a long time. As is well known, the pinning effect of TiN has been most widely used to refine the γ grains before transformation. However, when the welding heat input is increased significantly, it is impossible to completely restrain the growth of γ grains even with TiN. With an eye on fine particles, which are more stable than TiN under high temperatures, Nippon Steel has refined the grains of HAZ as a means of improving HAZ toughness during welding with a large or super-large heat input.

Fig. 6 shows examples of ultrafine particles (magnesium- or calcium-containing oxides or sulfides tens to hundreds of nm in size). As shown in **Fig. 7**, when those particles are finely dispersed in the HAZ, the γ grains are almost prevented from growing even under temperatures as high as 1,400℃, indicating that the particles have a strong pinning effect [18, 19]. At Nippon Steel, the technology to increase the toughness of HAZ grains using such ultrafine particles is called “HTUFF®” (pronounced H-tough): Super High HAZ Toughness Technology with Fine Microstructure imparted by Fine Particles. Recently, however, it has become more common to include IGF technology in HTUFF®.

As shown in Fig. 3, steel plates manufactured with HTUFF® are widely used for shipbuilding, offshore structures, line pipes, buildings, and civil engineering, etc. [18, 19] For example, **Fig. 8** shows the microstructure of a welded joint of a steel for large container vessels (YP: 390 N/mm^2) which allows for welding with large heat input. It has been confirmed that the welded joint has good HAZ toughness, with the austenite grains being restrained from growing even

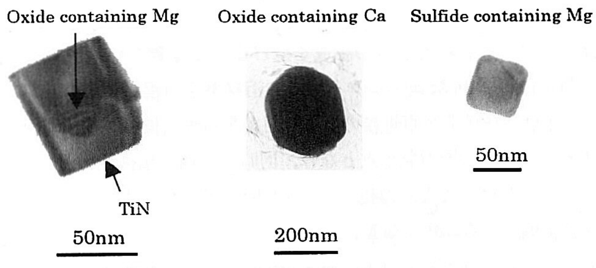


Fig. 6 Examples of ultrafine pinning particles [18, 19]

approaching the fusion line [20]. **Fig. 9** shows the progress of HAZ toughness control technology and the main steels that have been developed by applying HAZ toughness control technology.

In order to further improve HAZ toughness, it is also important to clarify the factors that govern the toughness of steel and establish a technology for predicting HAZ toughness. Nippon Steel has quantitatively identified the influences of various factors (effective grain size, brittle phase, hardness, etc.) on HAZ toughness and formulated the effects of alloying elements and welding heat hysteresis on those factors to build a model for predicting the transition temperature from the steel chemical composition and welding conditions [21].

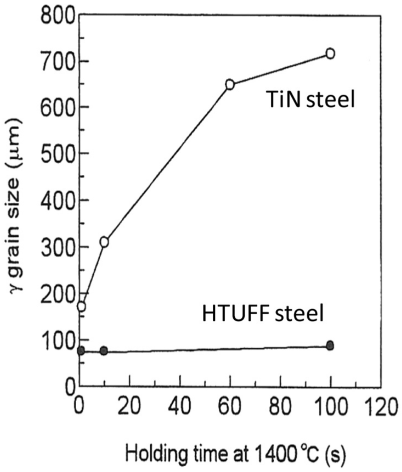


Fig. 7 Comparison of γ grain growth behavior between HTUFF and TiN steels [18, 19]

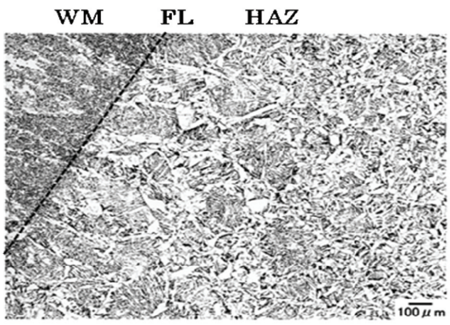


Fig. 8 Weld microstructure of YP390 N/mm² class steel for large container ships [20]

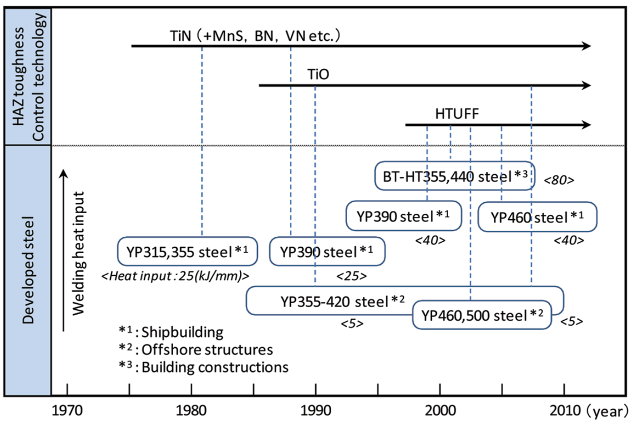


Fig. 9 Progress in HAZ toughness control technology and in developed steels

3. Activities for Shipbuilding Industry

3.1 "Thick EH47 steel plate for container vessels" having good crack arrestability

Since the turn of the 21st century, large-scale container vessels have sharply increased in number. Container vessels have a large opening through which to load and unload containers, and a thick, high-strength steel plate is used for the hatch-side coaming around the opening. **Fig. 10** shows the relationship between container vessel size and maximum thickness of steel plate used. The relationship is almost linear. For a container vessel size of 10,000 TEU, for example, a steel plate about 100 mm in thickness is required [22]. The thicker the steel plate, the lower the brittle fracture characteristic of the steel plate. Therefore, with the increase in thickness of steel plate for container vessels, there was a fear that the brittle fracture properties of steel plate would decline.

We briefly describe below the properties required of steels for shipbuilding and the circumstances that led to the development of the thick EH47 steel plate for container vessels.

In the field of Japanese shipbuilding, from the results of studies carried on until the 1980s concerning the prevention of brittle fractures, it had been concluded that: (1) Arresting a long crack would require the brittle crack arrest toughness, Kca, in the range 4,000 N/mm$^{1.5}$ to 6,000 N/mm$^{1.5}$ and (2) Any crack propagating along the welded joint would deviate to the base metal during propagation and eventually be arrested as long as the joint has a sufficient toughness, regardless of the welding heat input [23]. Thus, it was considered that by preventing the brittle fracture of welds and using high-toughness steel for important members to secure sufficient crack arrestability, it would be possible to achieve "double integrity" and prevent the hull from serious damage even if a brittle fracture could occur.

The susceptibility of steel to a brittle fracture initiation has been evaluated by a deep-notch test of center-notched type. It has been reported that the Kc value of deep notch correlates with the Charpy impact value required by the rules and regulations for the classification of ships and hence, it is considered possible to prevent brittle fracture initiations by securing the above Charpy impact values.

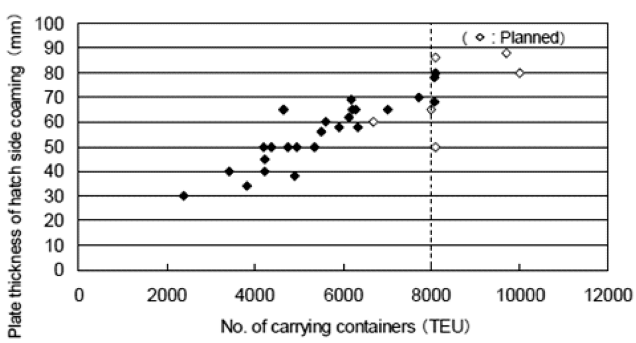


Fig. 10 Relation between container ship size and maximum thickness of plates

On the other hand, knowledge about crack arrestability mentioned above was obtained through experiments with steel plates 40 mm or less in thickness. For thicker steel plates, a decline in brittle fracture characteristic due to the increase in thickness was anticipated. In view of the recent increase in thickness of steel plates for container vessels, therefore, the fracture performance of those thick steel plates became a matter of serious concern.

Accordingly, Nippon Steel and Mitsubishi Heavy Industries, Ltd. jointly carried out crack-arrest tests on steel plates 50 to 70 mm thick using large-scale tensile testing equipment having a maximum loading capacity of 8,000 tons (80 MN). As a result, it was confirmed and publicized that brittle cracks in welded joints of thick steel plate did not deviate from the base metal and brittle cracks in steel plates 50 mm or more in thickness could not always be arrested even when they had a high Charpy impact value [24].

The above test results greatly shocked the shipbuilding industry as they suggested that the scenario of brittle crack arrest that had been assumed in conventional ship design would not hold true with thick steel plates. On the other hand, as a solution for ensuring the safety of large container vessels by improving the crack arrestability of thick steel plates, Nippon Steel, Mitsubishi Heavy Industries, Ltd. and Nippon Kaiji Kyokai co-developed the EH47 steel with good crack arrestability and offering high fracture toughness of welds. In order to improve the brittle fracture initiation characteristic of welded joints, the HTUFF® technology described above was applied to refine the microstructure of HAZ in welding with a large heat input. In addition, in order to improve the crack arrestability, the chemical composition and TMCP conditions (heating temperature, CR temperature, reduction ratio, cooling rate, etc.) were optimized to refine the microstructure of the base metal [25]. Even at −10℃, which is the lowest working temperature of the EH47 steel, brittle cracks induced under working stress in the YP460 steel can be arrested within a short distance. The EH47 steel was employed for the first time for a container vessel for Mitsui O.S.K. Lines, Ltd. built by Mitsubishi Heavy Industries, Ltd. It attracted much attention as steel which enhanced safety through improved crack propagation characteristics and crack arrestability and for reducing the steel weight by strengthening the steel.

3.2 "NSGP®-1, highly corrosion-resistant steel for crude oil tankers

In the 1990s, as illustrated in **Fig. 11**, pits having a maximum depth of 10 mm were observed on the bottom plates of crude oil tankers for some unknown cause. In the worst case, the number of pits per tank substantially exceeded a thousand. Since there was much concern about ocean contamination by oil spills, the burden on inspection and repair crews for crude oil tankers sharply increased, calling for appropriate measures to prevent pits in oil tankers the world over.

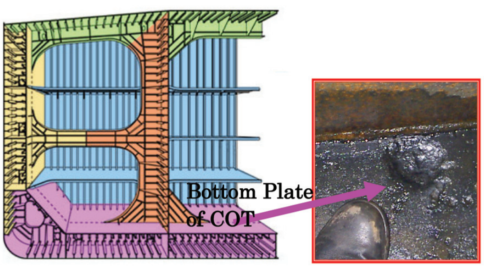


Fig. 11 Typical pits observed on bottom plate of cargo oil tank

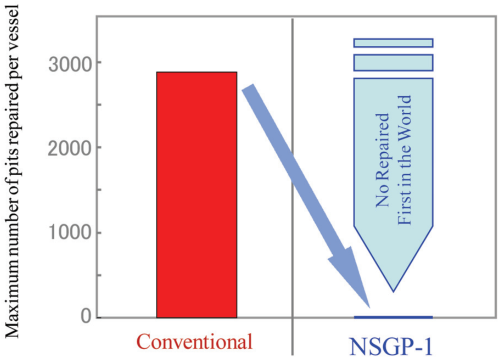


Fig. 12 Onboard evaluation results of NSGP-1 and conventional steels

Certain EU countries submitted a draft international convention on the enforcement of painting to prevent pitting corrosion to the International Maritime Organization (IMO). Even so, there was still strong concern about the occurrence of corrosion if the painted surface were exposed from any reason. That situation has given rise to a new problem—an increase in the use of paints and volatile organic compounds (VOCs).

In 2002, Nippon Steel and NYK Line launched joint R&D on using steel to prevent pitting corrosion since they considered that it would not only reduce the risk of ocean contamination, but also contribute much to the reduction of VOC emissions.

As a result, Nippon Steel was able to clarify the pitting process, develop a test method for reproducing the inside of pitting and define the quantitative correspondence between the test result and the rate of pitting corrosion with an actual vessel. Then, with clear targets for corrosion prevention—eliminating the risk of oil spills, minimizing the burden of maintenance, reducing the emission of VOCs, and implementing economical corrosion prevention, the company developed the world's first highly corrosion-resistant steel for bottom plates of crude oil tank, NSGP®-1 (Nippon Steel Green Protect-1) [26]. After confirming the effect of the newly developed steel when applied to a very large crude oil tanker (**Fig. 12**) [27], the company marketed the steel in 2007. So far, NSGP®-1 has been used for nine very large crude oil tankers. At the 87th IMO Maritime Safety Committee Meeting held in 2010, a revised convention providing for measures to prevent corrosion of the cargo tanks of crude oil tankers was adopted. At the same time, certain corrosion-resistant steels, including NSGP®-1, together with painting, were acknowledged to be effective corrosion-prevention technologies. The company's test method and criteria for corrosion evaluation have been included in the IMO rules, contributing much to improved safety of vessels.

3.3 Fatigue solution for shipbuilding

In order to prolong the life of many welded steel structures, it is important to improve the anti-fatigue technologies. To that end, there are demands for: (1) technology to prevent the occurrence of fatigue cracks, and (2) technology to restrain the extension of fatigue cracks. In particular, ships are required to have an enough anti-fatigue performance during their service life and periodical inspections specified in various rules and regulations under repeated loads with consideration given to the severe meteorological conditions of the open seas. In order to apply the effects of the above measures in (1) and (2), responding rationally to fatigue design of ships, it is necessary to accurately predict the fatigue life with consideration given even to the stress amplitude and residual stress at the area at which a fatigue crack will reach, which vary according to the weather and cargo loading conditions. Therefore, in dealing with the problem of fatigue in a ship or any other welded steel structure, the "total solution for fatigue" that embraces the above technologies (1) and (2), and technology for estimating fatigue life, (3), is extremely important. The total solution for fatigue is described in detail in Chapter 3, 3-5 "Approaches for Fundamental Principles 2: Total Solution for Fatigue of Steel."

3.4 Welding technology in the shipbuilding industry

Looking at the progress of welding technology in the field of shipbuilding, improvements have been made to the efficiency of welding and new welding techniques adapted to the increase in strength and toughness of welded joints have been developed. First, in response to the increase in thickness of steel plates accompanying the increase in scale of container vessels, joint research by Nippon Steel, Nippon Steel & Sumikin Welding and Mitsubishi Heavy Industries led to the development of the "two-electrode VEGA®" (Vibratory Electro-Gas Arc Welding) method that allows for high-efficiency, one-pass welding [28]. This welding method is schematically shown in **Fig. 13**. It is an improved version of the conventional single-electrode VEGA® welding method. Provided with two electrodes, the new welding method has widened the applicable plate thickness range and increased the welding speed. In developing the two-electrode welding method, studies were made to optimize: (1) polarities of two electrodes, (2) distance between two electrodes, (3) flux composition of welding material and (4) oscillating conditions of two electrodes, so as to restrain the occurrence of arc interference and slag spattering. Those development efforts have enabled application of the new welding method even to steel plates exceeding 65 mm in thickness while maintaining good welding performance and stable penetration. As a vertical welding technology that effectively cuts down on welding time and eliminates welding defects, the two-electrode VEGA welding method has been applied since 2001 to the building of container vessels at Mitsubishi Heavy Industries. During development of the EH47 steel, which has good crack arrestability and high fracture toughness of welds as described earlier, Nippon Steel developed a new welding material that permits applying a large heat input for welding. This was the flux-cored wire (FCW) EG-47T with high toughness in the YP 460-N/mm^2 class. The mechanical properties of EH47 steel welded joints prepared by applying the two-electrode VEGA® welding method with the above welding material have fully met the requirements of the Rules and Regulations for the Classification of Ships [29].

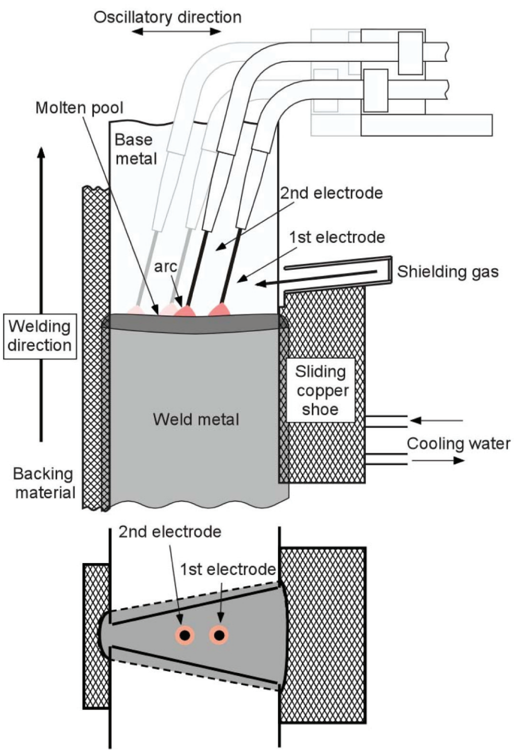


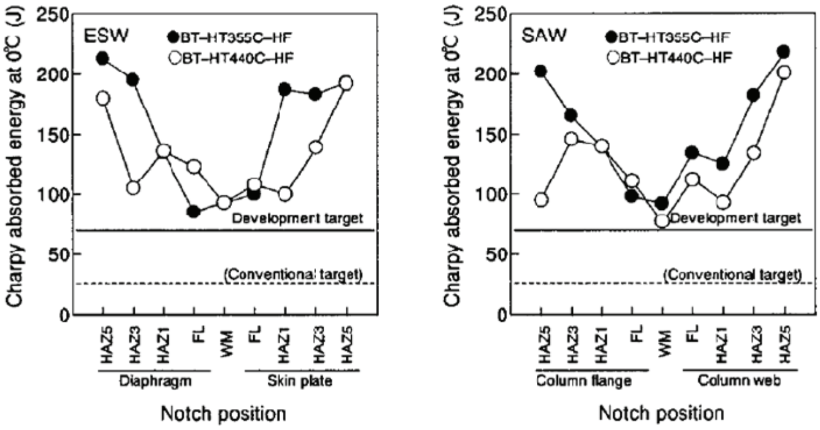
Fig. 13 Schematic illustration of two-electrode VEGA®

In the construction of tankers, on the other hand, it has become necessary to further enhance the efficiency of the steel plate joining process in view of the movement to legislate for double constructions (double hull, double bottom), etc. As an efficient welding method to join large steel plates in shipbuilding, FCuB (flux copper backing) one-sided submerged arc welding had long been applied at many shipyards. In order to meet the growing demand for higher efficiency, Nippon Steel, Nippon Steel & Sumikin Welding and Ariake Shipyard, Universal Shipbuilding Corporation developed a four-electrode high-speed one-sided welding method (NH-HISAW method) through joint research carried out to obtain a welding speed twice or more that of the FCuB one-sided welding method [30]. In the newly developed welding method, while the backing flux sprinkled over the backing copper plate is pushed against the back of a large steel plate with compressed air, submerged arc welding is performed from the surface to form back beads with the first and second electrodes, and surface beads simultaneously with the third and fourth electrodes. For example, a 16-mm-thick steel plate can be welded at a speed of 1.5 m/min. The new welding method has already been put to practical use on the block assembly lines of several shipyards.

4. Activities for the Building Construction Industry

In the wake of the Great Hanshin-Awaji Earthquake of 1995, studies on the fracture performance of architectural structures were promoted, the qualities of steel structures were reevaluated, and attempts to rationalize the fabrication works were promoted [31]. As a result, higher fracture toughness came to be required of the welds of steel frames. For example, the welds of steel frames of certain high-rise buildings were required to have a Charpy absorbed energy as high as 70 J at 0℃ [32]. In addition, with the increase in number and scale of multipurpose buildings and the increase in demand for large-span column-less spaces, the need for higher strength, heavier cross-section steel plates and more efficient welding in the fabrication of steel frames became greater [31, 33]. In Japan, the commonest feature of structures in high-rise buildings is the four-sided box column [32]. Examples of high-efficiency welding that can be applied to these include electroslag welding (ESW) for diaphragm welds and multi-electrode submerged arc welding (SAW). With these welding methods, the heat input reaches as high as 50 kJ/mm to 100 kJ/mm.

If conventional steel plates for building constructions were welded with such a large heat input, there was a fear that the microstructure of HAZ should become markedly coarse, causing HAZ toughness to decline. Therefore, a new steel plate for architectural steel frames offering a high HAZ toughness even when welded with a large heat input was called for. In order to meet the need, Nippon Steel successfully developed a high HAZ toughness steel for building constructions by applying HTUFF® as described earlier [33-36]. **Fig. 14** presents examples of joint toughness of four-sided thick-plate box



(a) Column diaphragm joint (ESW)
Heat input : BT-HT355C-HF 81.4kJ/mm
BT-HT440C-HF 100.4kJ/mm

(b) Column corner joint (SAW)
Heat input : BT-HT355C-HF 41.0kJ/mm
BT-HT440C-HF 50.3kJ/mm

Fig. 14 Welded joint toughness of box columns [33)]

columns (BT-HT355C and BT-HT440C) welded with a large heat input, in terms of the average Charpy absorbed energy at 0℃. It can be seen that the joints have a high toughness exceeding 70 J [33)].

In developing a new steel to be used in the form of steel plates of varying thickness and in developing a new welding technique to be applied to a new steel, it is important to know not only the holding time in the austenite region during welding with a high heat input, as in ESW, but also the cooling behavior during welding as represented by the cooling time from 800℃ to 500℃, which significantly influences the transformation mechanism from austenite to ferrite. In addition, in order to put a new welding technique to practical use, it is necessary to propose welding conditions necessary to obtain the desired penetration shape. Therefore, Nippon Steel developed a technique to estimate penetration shape and temperature hysteresis as part of the application technology and confirmed that the estimation results agreed well with the measurement results [37)].

Although we do not go into details here, in the field of building constructions, fire-resistant steels and low yield point steels, etc. have been developed and applied widely to enhance the safety of buildings and improve the efficiency of construction and aesthetic appeal of buildings as described in Chapter 1-4 "Steels, Steel Products, and Steel Structures Sustaining Growth of Society (Infrastructure Field)."

5. Activities for Construction Equipment and Industrial Machinery Industry

In recent years, owing to brisk activities in the development of industrial foundations in the newly industrialized economies (NIEs), the production of construction equipment and industrial machinery, including hydraulic shovels, tractor shovels, cranes, etc., has been increasing. The market for construction equipment that was some 400,000 units a decade ago has exceeded 700,000 units thanks to steady growth in the United States and European markets and the rapid expansion of the Chinese market. Of these, China's domestic production alone accounts for about 100,000 units [38)].

Steel plates used for construction equipment and industrial machinery must have high strength to allow for the increase in scale and the decrease in weight of equipment and good wear resistance to minimize the amount of equipment wear caused by ores, earth, etc. In addition to those basic performances, it is important that the steel plates have high toughness to enable the equipment to be used in increasingly severe working environments and good workability to facilitate cutting, bending, welding, etc. in the equipment manufacturing process.

In the future, the manufacturers of construction equipment/ industrial machinery will have to face such global environmental problems as coping with the tightening of exhaust emission regulations, improving the recyclability of their products and putting oil-alternative fuels to practical use [38)]. At present, the performance requirements of steels for those activities are not very clear.

In this section, therefore, we outline high-tensile steels used for construction equipment/industrial machinery, with the focus on enhancement of their strength and wear resistance.

5.1 High-strength steels

More and more large-sized cranes have come to be used to enhance the efficiency of construction work. On the other hand, in order to reduce the weight of cranes, the steels used for cranes, especially for the booms and outriggers, are required to have high strength.

In order to meet the above requirement, Nippon Steel has so far developed and manufactured high-strength steels (e.g., WEL-TEN® 780 and WEL-TEN® 950) having a tensile strength of 780 to 1,180 N/mm^2 [39)]. Those high-strength steels not only have the prescribed tensile strength but also guarantee the low-temperature toughness appropriate to specific working environments. Recently, in the field of construction equipment/industrial machinery, the yield strength-based design is becoming standard instead of the conventional tensile strength-based design. Therefore, the company has developed a new steel (YP: 960 N/mm^2) that guarantees a high yield strength suitable for yield strength-based design.

Those high-strength steels had long been manufactured by the reheat-quench-temper (RQ-T) process after rolling. With the development of TMCP technology in the 1980s, however, the direct quench-temper (DQ-T) process that omits reheating has been widely used. With the DQ-T process, by delicately controlling the steel composition, rolling conditions and water-cooling conditions, it is possible to manufacture a high-strength steel having a better strength-toughness balance than one manufactured by the RQ-T process. In particular, with the CR-DQ-T process that takes advantage of non-recrystallization rolling, steels that are still superior in strength and toughness have been obtained by carefully controlling the hardenability of the steel.

In any of these processes, high strength and high toughness of the steel are secured by optimum control of the carbon equivalent, the concentrations of Cr, Mo, B and other alloying elements that influence the hardenability index, and the heating, rolling, cooling and heat treatment processes, and at the same time, the weldability and workability (shearability, bendability, etc.) are improved by keeping a low value of weld cracking parameter Pcm ($Pcm = C + Si/30 + Mn/20 + Cu/20 + Ni/60 + Cr/20 + Mo/15 + V/10 + 5B$). Looking at bendability, for example, the steel plate can be worked on to a bending radius of 1.5 times to twice the plate thickness. In the future, Nippon Steel intends to develop new steels having higher tensile strength for cranes equipped with enhanced functions.

The tendency toward gigantism is found not only in cranes but also in power shovels, bulldozers and concrete pumps. For concrete pumps, high-strength steels with a tensile strength of 780 N/mm^2 or 950 N/mm^2 have come to be used.

Nippon Steel has also developed new welding materials adapted for those high-strength steels and offers welding solutions to its customers. As the welding materials for the high-strength steel having a tensile strength of 950 N/mm^2, the company has created a covered arc electrode (L-100EL), submerged arc welding material (NB-270H × Y-100) and gas metal arc welding wire (YM-100A). High strength and low-temperature toughness are secured in weld metal.

For field welding, a welding material that enables efficient all-position welding is required. To meet the requirement, Nippon Steel has developed an all-position flux-cored wire (SF-80A)[40] for high-strength steel of YP 690-N/mm^2 class. With ordinary flux-cored wire, the concentration of diffusible hydrogen in the weld metal becomes high. Therefore, when it is applied to a high-strength steel plate, the steel plate needs to be preheated to a high temperature so as to prevent low-temperature cracking. Thus, it was formerly difficult to apply a flux-cored wire to high-strength steels. Nippon Steel & Sumikin Welding Co., Ltd., a member company of the Nippon Steel Group, has the technology ("seamless flux-cored wire") whereby the outer covering of a wire filled with flux in the flux-cored wire manufacturing process is subjected to high frequency electric resistance welding to enclose the flux completely. With this technology, it is possible to decrease the amount of moisture (hydrogen source) of flux in the wire by high temperature dehydrogenation treatment at the time of wire production and the hydrogen content of the weld metal can be reduced, making it possible to reduce the burden of preheating when flux-cored wire is applied to high-strength steel.

5.2 Abrasion-resistant steels

In addition to high strength, abrasion resistance is an important property required of steels for construction equipment. Improving the abrasion resistance of the buckets of hydraulic shovels, tractor shovels, and the rear bodies of dump trucks, etc. is important. Since the abrasion resistance of steel plate has a strong correlation with its surface hardness, abrasion-resistant steels with a hard surface are used for construction equipment.

As abrasion-resistant steels for construction equipment, Nippon Steel manufactures WEL-HARD® 400, which has an average Brinell hardness of 400, and WEL-HARD® 500 (average Brinell hardness: 500)[41]. Since abrasion-resistant steels are especially hard, it is also important to give consideration to their impact toughness, delayed cracking resistance and weldability. Both the WEL-HARD® 400 and 500 abrasion-resistant steels afford good weldability as well. For example, in fillet welding of a 25 mm thick steel plate, preheating is unnecessary.

Considering that the parts of construction equipment that make contact with rock and sand become heated by friction, the company has also developed abrasion-resistant steels with high-temperature hardness.

5.3 Others

In order to allow for laser cutting of thin, high-strength steel sheets, Nippon Steel has developed low-C, high-Al steel sheets that restrain the occurrence of blowholes more effectively than ordinary steel sheets[42].

In addition, taking advantage of the progress of magnetism application technology in recent years, the company has come up with electrical steel plates and magnetism shielding materials through optimum control of the amounts of Si and Al additions, grain size and manufacturing conditions[43].

6. New Directions and Outlook for the Future

6.1 Developing thicker and stronger steel plates

In the field of shipbuilding, the application of CLC to YP 355 steel has made it possible to reduce the Ceq markedly, thereby promoting the use of high-strength steels that can be welded with a high heat input without preheating. The development of high-strength steels for shipbuilding by application of such a TMCP led to the establishment of technology for welding with a high input and became a business model of joint technological development by a shipbuilding company and a steelmaker in Japan. Since then, many container ships have been constructed for economic developments such as in Asian countries and transportation efficiency improvement. For container ships, which have a large openings for loading and unloading containers, 70- to 100-mm thick, high-strength steel plates, such as YP 390 or YP 460, have come to be used to ensure the required hull strength.

It is considered that the use of still stronger, thicker steel plates will increase in the future. In the field of building construction, due to the increase in the number of tall and massive buildings, the applications of plates, which have higher strength and larger thickness, have been expanded. Under those circumstances, Nippon Steel has developed and commercialized SN 400, 490, BT-HT 325, 355, 385, 440 and 630 and high yield strength BT-HT 400, 500 and 690 exclusively for column members. In the field of construction equipment and industrial machinery, reflecting the brisk Chinese market, the demand for high strength steels for cranes has increased. In particular, the entry into the market of Chinese and South Korean steel mills has promoted the use of HT 780 for general purposes. Today, even HT 950 and higher strength steels have come to be used.

Due to the entry of new and growing steel companies such as from China and South Korea to the market, there is pressure for Nippon Steel's steel products to demonstrate some technological advantages (e.g., thicker, tougher, more corrosion resistant, better weldability with larger heat input and better deformation characteristics). It is required that the steel development model whereby Nippon Steel can share its superior technologies with its customers (i.e. the business model established in the field of shipbuilding, for example) should be deployable on a global basis. However, competition with late-coming steel mills will prompt further productivity improvements and cost reduction. Accordingly, it is considered necessary for the company to revolutionize its manufacturing processes by evolving its integrated process metallurgy still further.

6.2 Further improving HAZ toughness in welding with high heat input

For shipbuilding, in which welding with a high heat input is widely applied, it has become increasingly difficult to secure the required weld toughness with the increase in thickness and strength of base metals used. In the future, further increasing the welding heat input and lowering the guaranteed temperature will be required. In order to enhance HAZ toughness under that condition, it is necessary to make the HAZ toughness control technology described earlier much more sophisticated. To that end, Nippon Steel has been seeking inclusions with a superior ability to form IGF and which have a strong pinning effect. In order to refine the above technology efficiently, it is important to press ahead with studies not only on practical matters, such as inclusion and welding control technology, but also on basic science, such as the mechanisms of intragranular transformation and γ pinning.

Improving HAZ toughness also requires that attention be paid to such brittle phases as M-A (high carbon martensite-austenite constituent), degenerated-pearlite and cementite. The inclusions and precipitates mentioned earlier also become brittle phases when they grow markedly. Besides, at extremely low temperatures, it is possible for brittle phases which are so small that they pose no problem at ordinary temperatures to cause fractures in the HAZ. Therefore, a future task is to systematize and clarify the influences of various brittle phases on HAZ toughness, as well as reduce such brittle phases.

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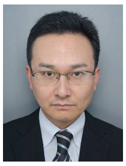
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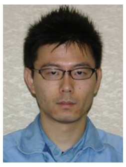
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