Niobium Bearing Structural Steels
Edited by: Steven G. Jansto and Jitendra Patel
TMS (The Minerals, Metals & Materials Society), 2010

RECENT DEVELOPMENT OF NIOBIUM BEARING STRUCTURAL STEELS FOR SHIPS AND INFRASTRUCTURES IN NIPPON STEEL

Atsuhiko Yoshie[1] and Jun Sasaki[2]

[1]Nippon Steel Corporation
Technical Development Planning Division
20-1, Shintomi, Futtsu-city
Japan

[2]Nippon Steel U.S.A. Inc.,
780 Third Avenue, 34^{th} Floor
New York, N.Y. 10017
U.S.A.

Keywords: Niobium, Heavy Plate, Thermo-Mechanical Control Process (TMCP), Arrestability, Large Heat Input Weldability, Mega-Container Ship, Seismic Application, High- Rise Building, Bridge High-Performance Steel

Abstract

Since niobium gives significant metallurgical effects on restraint of grain growth, retardation of recrystallization and precipitation hardening, it has been used as the main microalloying element in thermo-mechanical control process (TMCP) of steel plates. This paper describes the effect of Nb on microstructure evolution and the new Nb bearing structural steels recently developed by Nippon Steel such as YP460MPa heavy plates with high toughness, excellent arrestability and large heat input weldability for hull structures of mega-container ships, the high strength steels for seismic application of high-rise buildings with improved toughness of heat affected zone surrounding high heat input welded joints and the high performance steels for bridge structures with high yield strength and good weldability.

Introduction

Demand for steel plates has been increasing rapidly due to an increase in the volume of physical distribution and in demand for energy and raw materials on a global scale, coupled with a trend of expanding social overhead capital in Asia and other emerging countries. On the other hand, in the fields of shipbuilding and infrastructure (construction and bridges), in particular, improving reliability, solving global environmental problems and reducing life cycle cost (LCC) are in greater demand than ever. Under such conditions, Japanese steelmakers are making efforts to increase the supply of plate products through implementation of new technologies to increase productivity, strength, fracture toughness, fatigue strength and corrosion/weathering resistance of plates, and to improve the material properties of welded joints to accept a large heat input to enhance the efficiency of plate welding.

This paper gives an outline of TMCP technologies applied in the production of steel plates for shipbuilding, construction and bridges. The examples of newly developed plates that have been put into practical applications in recent years are presented [19].

The Effect of Niobium on Microstructure Evolution

The desired microstructure of the plates is obtained by applying the strains and thermal cycles to the steel during the heating, rolling and cooling processes based on the elaborated alloy design. The technology called TMCP has significantly widened the controllable range of steel manufacturing conditions, and that has made it possible to dramatically reduce grain sizes of steel. TMCP, which combines rolling and cooling after rolling, represents an innovative new structure control process that is entirely different from the conventional heat treatment process.

Mircoalloyed elements such as niobium (Nb) and titanium (Ti) play an important role in controlling the microstructures. Even when trace amounts (in the order of 0.01 percent) of any mircoalloyed elements are added, it helps to refine the grains and increase the strength in each of the processes, from reheating to rolling to controlled cooling of plate. Here, the effects of mircoalloyed elements are explained in Figure 1 [1], taking niobium as an example. Niobium exists in steel in the form of solid solution or precipitates in combination with carbon and nitrogen. The higher the temperature rises, the more proportion of niobium exists in the form of solid solution in the steel. There is a tendency about the size of precipitates to increase at higher temperatures. Rough estimation of the size of niobium precipitates is approximately 300 nm at the temperature of reheated slabs before rolling (1,000ºC or higher), 50 nm during controlled rolling (about 800ºC), and 10 nm at the temperature (about 600ºC) of transformation during cooling after rolling. Thus, the more temperature decreases, the smaller precipitate is newly created. The precipitates that have been formed in the former processes are no use in the next process because it is too large. It is necessary, therefore, to keep niobium as a solid solution so that it can be precipitated in the required amount in the next process.

During reheating of slabs before rolling, dispersed niobium precipitates prevents the growth of austenite grains to become coarse by the pinning effect. In the subsequent rolling processes, when the rolling temperature is about 900ºC or higher, the Fe atoms rearrange themselves in a process of recrystallization. However, the niobium forms a fine precipitate using the strain energy introduced by rolling as the driving force, and its pinning effect thereby restrains the austenite grains from recrystallizing [24,25]. Therefore, it is possible to finish the rolling, with keeping many sites for ferrite transformation (ledges, deformed bands and so forth) as they are.

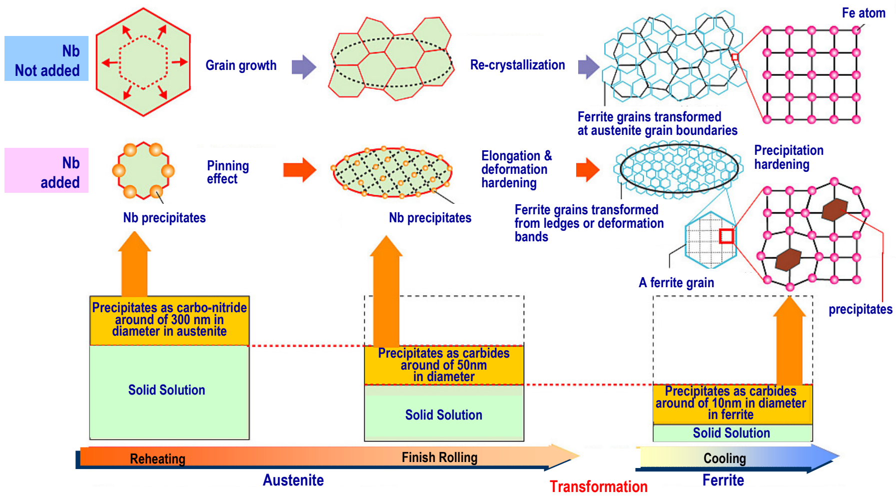


Figure 1. Niobium precipitation at each stage of TMCP and its effects on refining of ferrite grains and precipitation hardening [1].

During the transformation from austenite to ferrite during cooling after the rolling, niobium precipitates in the ferrite matrix to increase the strength by precipitation hardening. Thus, microalloyed elements are very useful even when added to steels in extremely small amounts. When only the required amount is precipitated continuously during the processes of reheating, rolling and cooling, the microalloyed element helps to refine the grains and strengthen the steel.

Nippon Steel's Original TMCP Technology "CLC"

In order to provide more tonnage of high-quality plate products for various social infrastructure projects, it has been required to positively implement continuous control of the microstructure mentioned above during the mass-production process [20-23].

In order to meet the requirements for ship plates with greater toughness and better weldability in view of the ever-increasing demand for larger ships, Nippon Steel started developing microstructural control technology based on the combination of heating and cooling processes in the 1960s. In the early 1980s, the company came up with its original TMCP technology – "CLC process." In 1984, Nippon Steel was the first company to ship 60,000 tonnes of TMCP steel for offshore structures (Oseberg Project), becoming the leading proponent of TMCP technology globally.

In order to refine the grains and obtain the required microstructure, it is necessary to employ controlled cooling technology whereby the entire steel is uniformly cooled at a predetermined cooling rate and to the certain cooling temperature. The boiling condition of cooling water always changes according to the steel surface temperature and roughness.

The way to cool down the steel also varies significantly. The basic equipment configuration has not changed to date. For example, the plate is flattened by a leveler before cooling so that the entire plate can be cooled uniformly, and the spray nozzle that allows for a wide range of control over the cooling rate is still used. Even after the first CLC equipment was put to practical use, studies to improve the cooling accuracy continued. In 2005, an improved version of cooling equipment "CLC-μ" was deployed into practical use. CLC-μ allowed uniform and flexible cooling over a very wide range of cooling rates through improvements in the conventional cooling method. It has improved the cooling accuracy over the entire temperature range. For example, the variance in temperature inside the plate after cooling has been reduced by half being compared with the original CLC. The higher sophistication of the cooling control technology mentioned above has also widened the range of control over the plate's microstructure remarkably.

The most important effect of TMCP is to permit manufacturing of plates of the same strength as conventional plates with lesser carbon equivalent (amount of alloy addition) by means of grain refinement and microstructural control. In this way, TMCP has greatly contributed to improve construction efficiency of steel structures and ensured high levels of safety and reliability, including the prevention of low temperature cracking during welding and improved weld toughness. As a result, within less than 10 years (until 1991) since CLC was commercially introduced, plates manufactured using CLC came to be widely adopted for most plate-related applications, such as ships, buildings, bridges, line pipes and pressurized vessels. To date, more than 10 million tonnes of plates have been manufactured using CLC. Figure 2 [2] shows the achieved strength level of CLC heavy plates used for each market.

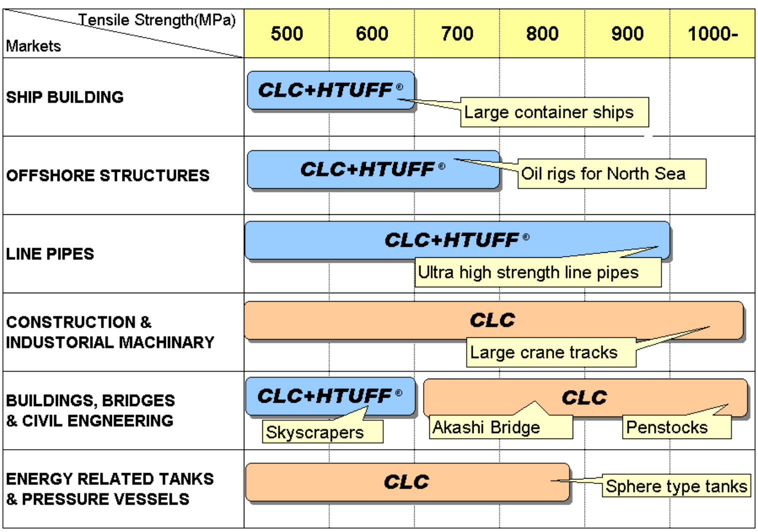


Figure 2. Strength level of TMCP and HTUFF® steel plates for each market.

Progress of Steel Plates Applied in Shipbuilding

Changes in conditions surrounding ships

In terms of the major changes in the conditions surrounding ship buildings, the growing awareness of the importance of ensuring the safety and protecting the environment on a global basis have been acknowledged. From the standpoint of securing the safety of ships and protecting the environment, various activities to enhance the safety of ships have been carried out in view of a number of serious accidents in the past. All those accidents were caused directly or indirectly by brittle fracture, fatigue failure or corrosion of steel plates in the vessels. Establishing international rules for preventing similar accidents and enhancing the safety and reliability of ships has been being discussed under the leadership of the International Maritime Organization (IMO). Another major change is the increase in volume of physical distribution around the world as a result of the ongoing globalization. With the progress of globalization, the transportation of raw materials, fuels, and other commodities, is also expected to expand. As a result, the demand for various types of vessels, such as oil tankers, LNG ships, bulk carriers, container ships, automobile carriers, LPG ships, and chemical tankers has increased.

In view of the global trends mentioned above, the requirements from ship owners, shipbuilders and organizations that make rules and regulations to the steelmakers are summarized to the following four points.

1) Improving the reliability of resistance to brittle fracture for protecting the environment and ensuring the safety of ships.
2) Increasing the size and decreasing the weight of ships for increasing the efficiency of transportation and reducing fuel consumption.
3) Improving the corrosion resistance and anti-fatigue properties of ships for reducing the life cycle cost.
4) Increasing the productivity of shipbuilding.

Improvement of brittle crack propagation arrestability of thick, high-strength steel plates

The main reason for increasing the number of large-scale ships' construction, in recent years, is the higher efficiency of transportation. Those large-scale ships require thick, high-strength steel plates capable of withstanding very large loads. In the case of container ships, as shown in Figure 3 [3], mega-container ships carrying 8,000 to 10,000 or more containers have now been constructed. As shown in Figure 4 [4], when a high-strength steel plate whose yield point (YP) is 40 kgf/mm^2 is used for a large container ship carrying 8,000 containers, the plate thickness must be more than 70 mm.

On the other hand, a welding method which permits applying a large heat input per pass has come to be widely used so that the productivity in shipbuilding does not decline even when thicker plate is used. Therefore, high HAZ (Heat Affected Zone) toughness steel which can be welded with a large heat input has also been developed by employing the optimum combination of chemical composition and TMCP conditions.

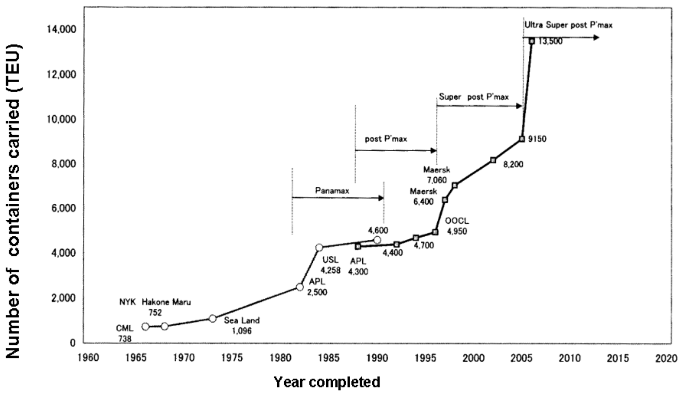


Figure 3. Changes in maximum capacity of full container ships (TEU) around the world [3].

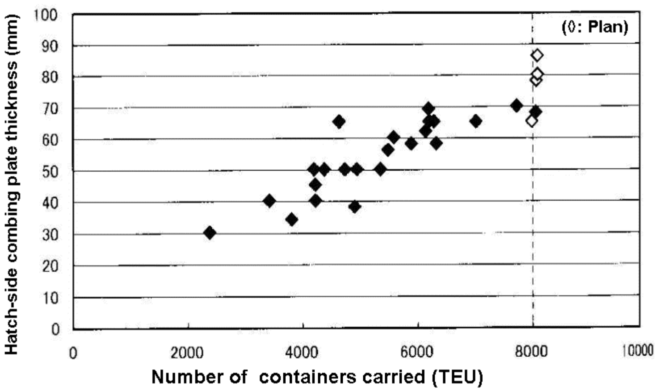


Figure 4. Changes in thickness of plate used for hatch-side combing with increase in container ship size [4].

Refining the base metal structure by TMCP and improving the HAZ toughness that have been described so far are both techniques that could prevent brittle fractures. On the other hand, it has been pointed out that with the increase in size of ships, the ability to arrest brittle cracks might become a problem, especially with container ships. From the standpoint of preventing not only the initiation of brittle fractures, but also the propagation of brittle cracks and thereby making doubly sure of safety, it is desirable that the steel plate should have sufficient ability to arrest brittle cracks. Since most of brittle cracks originate in weld zones, it is important to arrest the propagation of cracks along welded joints. In the past, a large-scale arrest test of welded joints using ship plates of up to 40 mm in thickness was carried out by the SR147 subcommittee of the Shipbuilding

Research Association [5]. In the discussions on the test results, it was suggested that the brittle cracks propagating along the welded joints would turn toward the base metal under the influence of the residual stress of welding and some other factors, then eventually stop there [5]. Since test results of ship plates exceeding 40 mm in thickness were unavailable, however, a similar large-scale arrest test was carried out with thicker plates [6]. The test piece shape is shown in Figure 5. The test was carried out using an 8,000-ton tensile test apparatus with a pin-to-pin distance of 7.2 m. The test results are shown in Figure 6. Unlike the case with thinner plates, the cracks in the thicker plates propagated straight along the welded joints and did not stop halfway. In case of a test using a plate which was not welded, the cracks did not stop halfway either. Thus, it was found that even with steels which meet the Charpy impact values of ordinary ship E grade, it would be difficult to stop long cracks halfway. These results suggest the necessity of reviewing the performance required for the steel plates used for mega-container ships and their method of construction, including the design. They also suggest the importance of the ability of the steel plates to arrest brittle cracks. Arrest Design Study Committee was

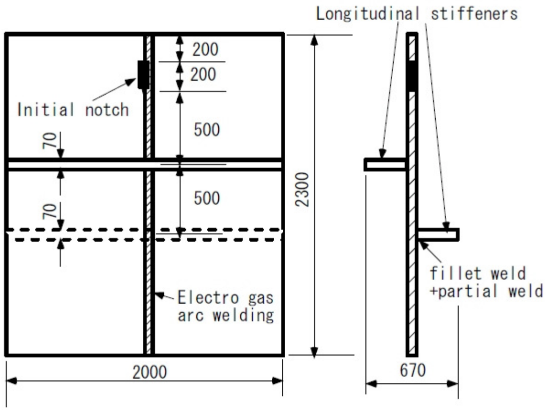


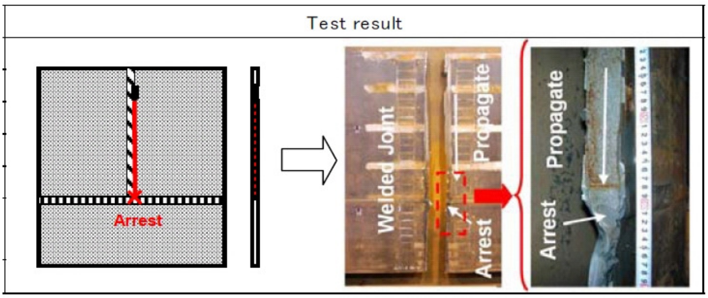
Figure 5. Dimensions of specimen [6].

established within Nippon Kaiji Kyokai (NK) in 2007 and a joint study on this project have been started by universities, the classification society, shipbuilders and steelmakers. It is expected that the joint study will lead to the establishment of an arrest test method and clarification of the arrest phenomenon leading to improvements in the safety and reliability of ships.

Figure 6. Appearance of the specimen [6].

As a ship plate with excellent ability to arrest brittle cracks, HIAREST® steel plate, which has the fine grain size at surface layer, approximately 2 μm, was developed [7]. The K_{ca} of this steel at –10ºC is greater than 10,000 $N/mm^{1.5}$ when the thickness is 25 mm. However, it is only manufactured using a particular process and the maximum plate thickness is limited up to 50 mm. For mega-container ships, therefore, it is required to develop a higher-strength steel which can be made into a thicker plate and which has sufficient ability to arrest brittle cracks. To meet that requirement, EH47 steel for shipbuilding whose YP is as high as 460 N/mm^2 and which has excellent ability to arrest brittle cracks has been put into practical use as shown in Figure 7 [8]. This steel is manufactured by applying the TMCP to refine the structure of the base metal and the HAZ structure control technology to secure a high HAZ toughness which allows for welding with large heat input in one pass even when the plate thickness is more than 50 mm. EH47 steel plate was co-developed by a shipbuilder and Nippon Steel and have been applied to the upper deck and the hatch-side combing of a mega-container ship as shown in Figure 8 [4]. Since the high-strength steel permits reducing the thickness of the plates used, it should enhance the ability to arrest brittle cracks. In addition, since it permits welding the plate in one pass, the possibility of welding defects has been reduced. EH47 plate and its welding method [9], which have been developed bearing in mind their application to mega-container ships, can be a total solution for three major problems: 1) improving the reliability of fracture toughness by preventing the occurrence of brittle fractures and improving the ability of the base metal to arrest the propagation of brittle cracks; 2) improved transportation efficiency and fuel efficiency by increasing the size and strength (reducing plate thickness) of ships; and 3) improved productivity in shipbuilding by applying welding with a large heat input.

Test condition	
Specimen No.	4
Steel grade	YP47
Kca value	Over 5900 $N/mm^{1.5}$
Thickness	50mm
Test temperature	-10℃
Applied stress	Design stress for hull girder strength
Result	Arrest



Y.Yamaguchi et al.(2006)

Figure 7. Test Result of a large-scale arrest test of developed steel plate [8].

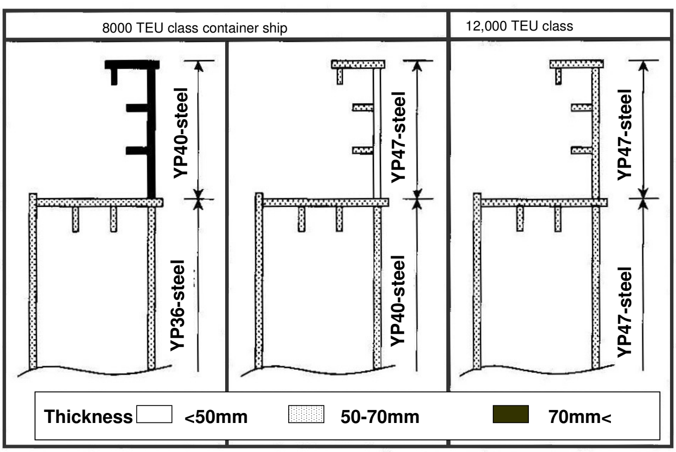


Figure 8. Examples of hull structures in mega-container ships [4].

Progress of Structural Applications of Steel Plates

Development of stronger, higher-performance steels

In Japan, steel frame structures are designed in accordance with a seismic design method which takes into consideration possible damage caused by earthquakes. Namely, when a significant earthquake occurs, the steel frame is intentionally subjected to plastic deformation so as to absorb the seismic energy and prevent the entire structure from collapsing. This seismic design method was put into effect in 1981. As a result, securing sufficient deformation performance in steel frames became an important design consideration, and extra strength and plastic deformation performance after yielding were required of the steels used [8]. In view of those requirements, a Japanese standard (JIS G 3136) for rolled steels exclusive for building construction was established in 1994. Those steels are so-called SN steels. The important properties of these specifications are that the variance of yield point or proof stress is restrained (upper and lower limits provided) so that the plastic deformation occurs as designed during a significant earthquake, that an upper limit in the yield ratio is provided so that the steel retains sufficient strength even after it yields, and that steels having performance in the thickness direction are provided. Figure 9 shows examples of the application of SN steels [10].

By applying the TMCP described earlier, structural steels which meet the SN steel specifications and which afford superior performance have been put to practical use. The TMCP 490-N/mm^2 steel is manufactured with a lower carbon equivalent than conventional steel and hence offers excellent weldability and HAZ toughness. This TMCP steel plate was used for the first time in the Hitachi System Plaza Shin-Kawasaki Building that was completed in 1989. Since then, thick TMCP steel plates have been used in many high-rise buildings.

In terms of a higher-strength steel, the high-performance 590-N/mm^2 steel (SA440) has been put to practical use. [11]. When 490-N/mm^2 steel is used in super high-rise buildings, plate thickness may be as large as about 100 mm. In this case, the difficulty in fabrication, or welding of the steel plates, can become a problem. In the case of SA440, the range between the upper and lower limits of the yield point is controlled within 100 N/mm^2 and the yield ratio is controlled within 80% by applying a special successive triple heat treatment: quenching-quenching from intercritical temperature region-and tempering. SA440 is a steel with good seismic properties, high toughness and excellent weldability. This steel has made it possible not only to decrease the cost of construction through reduction of the steel frame weight, but also to improve the reliability of construction (welded joints, etc.) by avoiding the use of excessively thick plates. SA440 was employed for a number of high rise buildings serving as landmarks, such as the Minato Mirai 21 Landmark Tower completed in 1993 and Roppongi Hills Mori Tower completed in 2003. The low-P_{cm} type SA440 that features a smaller amount of added alloy and reduced weld crack sensitivity, both made possible by carefully controlling the manufacturing conditions, has also been developed and put to practical use [12]. The P_{cm} of this steel is less than 0.22 (0.28 for SA440). As long as the plate thickness is within

100 mm, this steel does not require preheating for CO_2 gas-shielded arc welding and submerged arc welding. This steel was used in Nagoya Midland Square, which was completed in 2006.

The 780-N/mm^2 steel has also been put to practical use [13]. This 780-N/mm^2 steel has a yield ratio of less than 85% and improved weldability. So far, this new steel has been used for some of the columns, large beams, seismic walls, etc. of Kokura Station Building, although it has not been widely used yet. However, as described later, there is the possibility that even stronger structural steels will be demanded in the future.

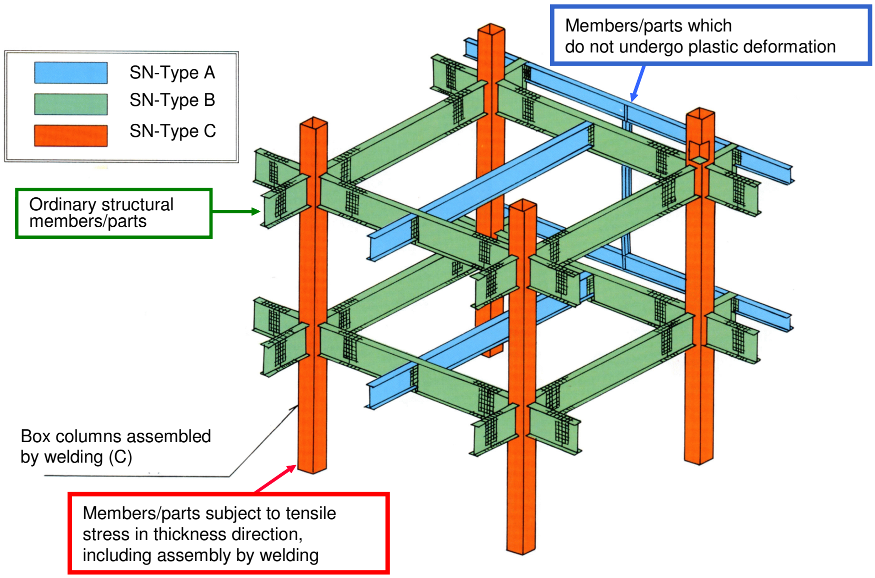


Figure 9. Points of application of SN steel [10].

<u>Improvement of a seismic performance using steels with extra-low yield points</u>

What has been described so far is based on the supposition that in a big earthquake the steel structure bearing the seismic force undergoes plastic deformation to absorb the seismic energy. On the other hand, the idea that certain structural members (damping devices) incorporated into the structure would effectively absorb the seismic energy is becoming widespread. As damping devices, viscous materials (e.g., oil dampers), visco-elastic materials (e.g., lead), and steels are used. In steel damping devices, steel with an extra-low yield point, which, in an earthquake, undergoes plastic deformation ahead of other structural members, is used. For steel dampers, Buckling Restrained Brace (BRB) using hysteresis energy absorption has been put to practical use. The yield point (YP) of extra-low YP steels is either 100 N/mm^2 (LY100) or 225 N/mm^2 (LY225), and the range of variance is extremely narrow (40 N/mm^2). Those steels have a large deformation capacity, with the total elongation being 40% to 50% or more. An example of application of the damping technology employing extra-low YP steels is shown in Figure 10 [14].

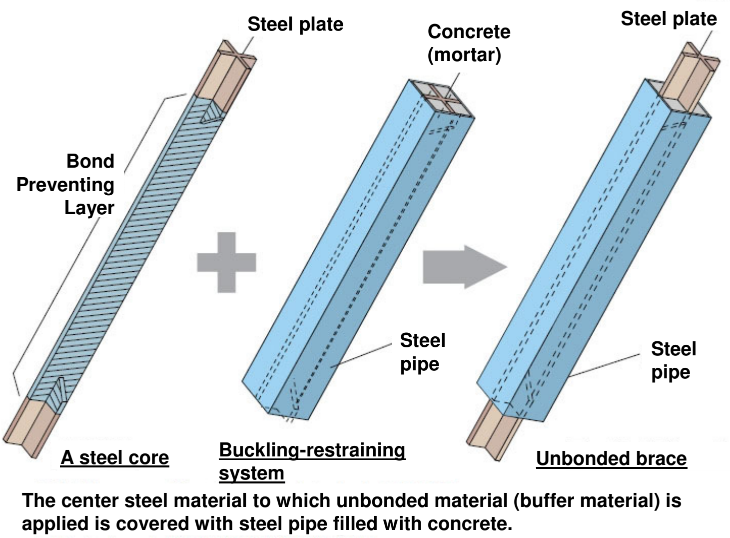


Figure 10. Structure of unbonded brace [14].

Development of system structure for new construction employing innovative new structural materials

The "Development of System Structure for New Construction Employing Innovative New Structural Materials" project was started in 2004 [15]. It is an inter-ministerial project of the Cabinet Office and the other Ministries of Japan. The objective of this project is to develop a new construction system employing innovative new materials in order to create sustainable cities/buildings incorporating a resource-recycling system. Specifically, in order to ensure that the buildings maintain an elastic construction even during a sizable earthquake, high-strength steels which maintain their elasticity are used for the main structural members and high energy-absorption steels which easily undergo plastic deformation to absorb the seismic energy are used for the sub-structural members. In particular, the project aims to rationally create damage-control construction procedures through the combination of high-strength steels and high-performance devices as shown in Figure 11 [10]. The tasks involved in the project are classified into the development of structural members such as ultra-strong fasteners and the development of joint technologies such as bolt-jointed construction which completely eliminates the need for welding and an innovative new and completely non-welded construction for sophisticated structural members. Materials to be used for these structural members are high-strength steels that are compatible with economic rationality. At present, TMCP 800-N/mm^2 steel (YP650-N/mm^2 steel) is being developed. The application of 1000-N/mm^2 steel (YP880-

N/mm^2 steel) in the next step has been also being discussed. As ultra-strong fasteners, assembling basic section members using 20T-class ultra-strong fasteners using bearing joints is being discussed. The above inter-ministerial project represents a change in the traditional concept of earthquake-resisting construction, namely "Prevent the collapse of the entire building by allowing the seismic energy to be absorbed by plastic deformation of the beams" to a concept to "Keep the main structural members from plastic deformation in order to ensure the asset value of the building and permit reuse even after a major earthquake."

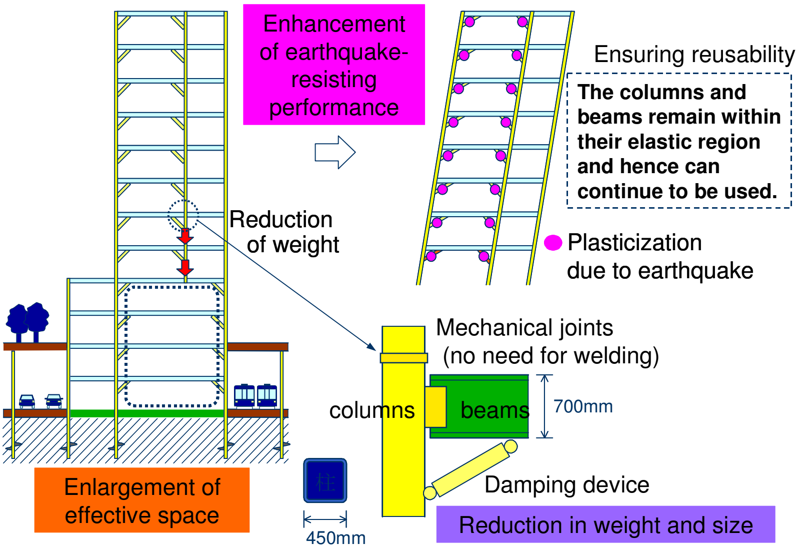


Figure 11. New construction system using high-strength steels [10].

Improved toughness of welded joints obtained by welding with large heat input

In addition to the development of higher-strength steels and improved earthquake-resisting performance, improving the toughness of welded joints is a major objective. In the wake of the Hanshin-Awaji Earthquake of 1995, the toughness required for steel frame structures began to be studied in earnest. Japanese steelmakers have developed new steel plates to improve the HAZ toughness for a large heat input welding [16]. The approach to this problem differs between steelmakers. Basically, however, they focus on refining the microstructure of the weld zone that becomes course with the increase in heat input by refining and dispersing the nitride, oxide and sulfide particles. At the same time, efforts have been made to reduce impurities and a hard structure resulting from low-temperature transformation (martensite–austenite constituent: MA). Figure 12 shows examples of changes in technology to improve HAZ toughness in Nippon Steel [16]. The technology whereby the coarsening of prior austenite grains in the HAZ is restrained by

TiN pinning was established in the 1970s. After that, in view of the continual increase in welding heat input, a technology whereby an oxide of Ti which is stable at high temperature is used as the nucleus for transformation within the prior austenite grains was developed in the early 1990s. By the transformation of ferrite (intragranular ferrite: IGF) to be formed from coarse grains of prior austenite, it has ultimately become possible to refine the microstructure. The Ti oxides tend to create a Mn-depleted zone. As a result, the temperature at which the transformation starts at the boundary of Ti oxide rises, causing ferrite to transform preferentially.

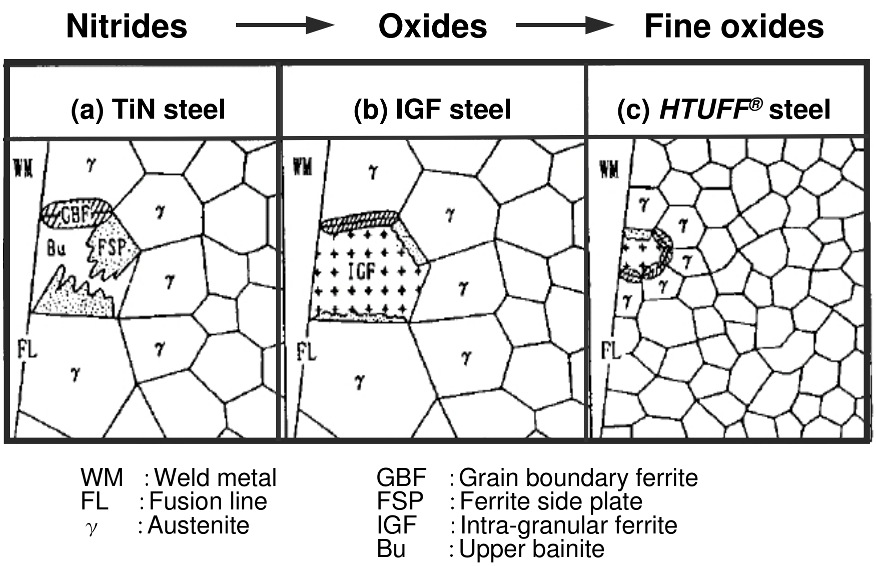


Figure 12. Examples of development in technology for improving HAZ toughness [16].

Structural steels are welded with a larger heat input than other types of steel. There are cases in which the heat input approaches 100 kJ. As long as it is able to guarantee the absorbed energy of 27 J (at 0ºC) as the HAZ toughness in a Charpy impact test, it can easily be achieved by using an oxide of Ti. However, when the absorbed energy of 70 J (at 0ºC) needs to be guaranteed, it is not always possible to secure the required HAZ toughness when using Ti oxides. Therefore, a new type of steel for welding with large heat input (HTUFF® steel) has been developed and put to practical use. This new steel utilizes oxides/sulfides which are stable even at high temperatures as shown in Figure 13 [16] and which can be dispersed in fine particles to obtain a significant pinning effect. Generally speaking, there is a correlation between the prior austenite grain size and the Charpy absorbed energy of HAZ. The smaller the prior austenite grain, the higher the absorbed energy that can be obtained. By using the newly developed steel, it has become possible to obtain 70 J or higher absorbed energy even when the heat input is 100 kJ/mm. Since the steel was put to practical use in 1999, it has been adopted not only for buildings, but also for ships, bridges, offshore structures, and line pipes, etc. So far, more than 300,000 tonnes have been shipped.

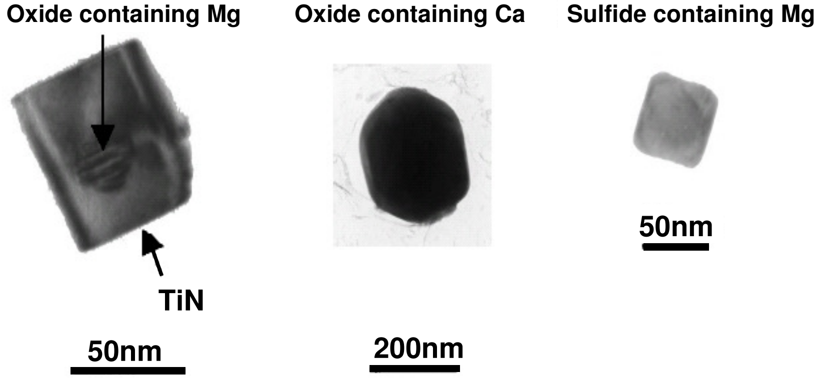


Figure 13. Examples of pinning particles of HTUFF® steel [16].

Progress in Steel Plates Applied to Bridges

The major achievements in the field of steel bridges in the past decade are the development and practical use of stronger, high-performance steel, the development of corrosion-resisting steel, and the establishment of methods for their application. The high-performance steel for bridges is called BHS (bridge high-performance steel) in Japan. Developed to help construct economical, high-quality steel bridges, BHS is a rolled steel plates for welded structures whose yield point is 500 N/mm^2 or 700 N/mm^2 [17]. BHS was proposed at a committee of the industrial-academic society installed within the Creative Project Research Unit of Tokyo Institute of Technology in 1994. In line with that proposal, specifications for bridge high-performance steels (BHS 500, 500W and 700W) were established in 2004 as product specifications of the Japan Iron and Steel Federation (JISF). The weld crack sensitivity (P_{cm}) of BHS is set exceptionally low—0.20 or less for BHS 500/500W, and 0.30 or less (thickness 50 mm or under) and 0.32 or less (thickness over 50 mm) for BHS 700W.

Many bridges in Japan are small- or medium-sized ones whose span is several tens of meters. The yield strength that minimizes the steel weight is 400 N/mm^2 for a span length of 50 meters and 500 N/mm^2 for a span length of 70 meters. On the other hand, for truss bridges which permit making the most effective use of the tensile strength of steels, it is advantageous to use a high-strength steel, such as a 780-N/mm^2 class steel. BHS 700 was developed on the assumption that it would be applied to truss bridges [18]. As shown in Figure 14 [17], the yield strength of BHS 500 is 40 to 80 N/mm^2 higher than that of conventional SM570 steel, and the yield strength of BHS 700 is 15 to 35 N/mm^2 higher than that of conventional HT 780. Thus, with BHS, it is possible to cut the cost of construction of a bridge through reduction of the steel weight and to simplify the construction of joints through reduction of the steel plate thickness. In addition, since BHS has better weldability and workability than conventional steels, it is possible to reduce or omit the preheating for welding thanks to the low P_{cm} achieved by TMCP. In specific terms, BHS 500 and BHS 500W do not require any preheating, while BHS 700W only requires preheating to 50ºC or less. Concerning the toughness of any structural bridge member which is subjected to bending work, absorbed energy of 100 J or more before cold working is required so that even after the toughness declines due to the cold working, absorbed energy of 27 J or more (at –5ºC) can be secured in a Charpy impact test. This requirement is based on the assumption that the bending radius is at least seven times the plate thickness.

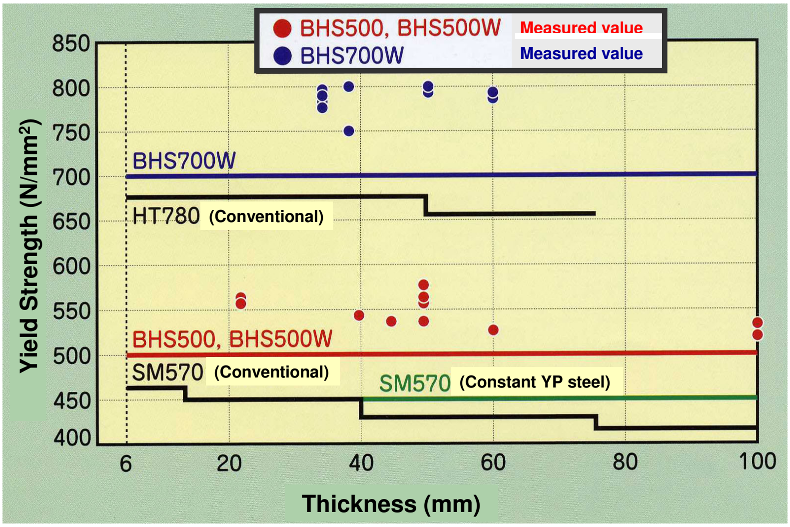


Figure 14. Yield strength of BHS steel [17].

It has been decided that BHS 500 is to be used for the bridges on the Tokyo Port Bayside Highway that have been ordered by the Kanto Regional Development Bureau and the Tokyo Metropolitan Government. Of the 4,000 tonnes of steel used for the North-South Canal Bridge, 1,200 tonnes were BHS. For the main bridge girders of the Tokyo Port Bayside Bridge, 9,600 tonnes of BHS (out of a total of about 20,000 tonnes) are to be used.

Conclusions

Since TMCP was put to practical use in Japan, its various applications had spread around the world during the 1980s and 1990s. At present, however, some steelmakers have given up this technology because of the difficulty involved in controlled cooling. TMCP has been actively used in Japan because Japanese steelmakers have carefully examined what happens in the individual processes and have re-organized the knowledge of TMCP as the comprehensive technology based on the examination results. Meanwhile, the sophisticated applications and processing technologies have been developed in close cooperation with the many steel users, like shipbuilding, energy and construction industries, as described in this paper. Niobium should keep playing the vital role for TMCP technology to expand its applications further.

Acknowledgements

The authors thank to Dr. A. Usami of Nippon Steel for his helpful support and discussion.

References

1. A.Yoshie, "Steel Plate 2", Nippon Steel Monthly, (2005.6), 9.

2. A.Yoshie, "Steel Plate 3", Nippon Steel Monthly, (2005.7), 16.

3. S.Nagatsuka, "Outlook of mega-container ships", KANRIN, 11(2007), 10.

4. Y.Yamaguchi et al., "Development of mega-container ships", KANRIN, 3(2005), 70.

5. Shipbuilding Research Association of Japan, SR147 committee report, "Evaluation of brittle fracture toughness of welded joints of ship under high welding heat input", (1976).

6. T.Inoue et al., "Long brittle crack propagation of heavy-thick shipbuilding steels", Journal of Japan Society of Naval Architects and Ocean Engineers, 3(2006), 359.

7. T.Ishikawa et al., "High crack arrestability endowed steel plates with surface-layer of ultra fine grain microstructures", Tetsu to Hagane, 85(1999), 544.

8. Y.Yamaguchi et al., "Technical requirements to ensure structural reliability for mega container ships", Proc. Design and Operation of Container Ships, (2006), RINA, 43.

9. S.Sasaki et al., "Development of two-electrode electro-gas arc welding process", Nippon Steel Tech. Report, 380(2004), 57.

10. Y.Yoshida, Proc. Symposium on Structural Steel, (2006), Tokyo, Japanese Society of Steel Construction, 11.

11. K.Takanashi et al., Journal of Japanese Society of Steel Construction, 1(1994), 1.

12. Y.Watanabe et al., "Development of 590N/mm2 class steel with good weldability for building structures", Nippon Steel Tech. Report, 380(2004), 45.

13. K.Tokuno et al., “780N/mm2 class high tensile strength steel plates with large heat input weldability and low weld-cracking susceptibility for architectural construction”, Nippon Steel Tech. Report, 365(1997), 37.

14. Nippon Steel Monthly, “Seismically isolated structure of Nippon Steel”, (2005.6), 1.

15. Japan Iron and Steel Federation, New structural system buildings using innovative materials (HP).

16. A.Kojima et al., “Super high HAZ toughness technology with fine microstructure imparted by fine particles”, Nippon Steel Tech. Report, 380(2004), 33.

17. The Committee of Steels for Bridges, Japan Iron and Steel Federation, Bridge High Performance Steels, (2007.2).

18. C.Miki, “High performance steel for bridge structures (BHS)”, Bridge and Foundation Engineering, 2005-8, 41.

19. A.Yoshie, “Recent Progress of Plate Products fro Ships, Infrastructures and Transportations”, Proc. the 191th Nishiyama Memorial Lecture, Iron and Steel Institute of Japan, (2007), 127.

20. I.Kozasu, Proc. Intn’l. Sympo. on Accelerated Cooling of Steel, AIME, (1986), 3.

21. A.J.DeArdo, Proc. Intn’l. Sympo. on Accelerated Cooling of Rolled Steel, CIM, (1988), 3.

22. K.Okamoto et al., Proc. Intn’l. Sympo. on Physical Metallurgy of Direct-Quenched Steels, TMS, (1993), 339.

23. A.Yoshie, Journal of Japan Society of Naval Architects and Ocean Engineers, 885(2005), 49.

24. S.S.Hansen et al., Metall. Trans., 11A(1980), 387.

25. A.Yoshie et al., ISIJ International, 36(1996), 444.