

Progress of High Performance Steel Plates with Excellent HAZ Toughness

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Abstract

Nippon Steel & Sumitomo Metal Corporation has developed HTUFF™ technology to improve the heat affected zone (HAZ) toughness by dispersing fine particles in the steel matrix. A variety of high performance steel plates with high HAZ toughness as well as high strength, large thickness, formability, and applicability of high heat input welding have been developed and manufactured for practical use for buildings, ship-buildings, ocean structures, wind farms, line pipes etc.

1. Introduction

The performance of welded structures is substantially determined by the properties of welded joints, and for this reason, the properties of welded joints are required to be the same as those of the base metal. Structurally, however, stress tends to concentrate at welded joints, and in addition, they are subject to thermal structural change and residual stress due to welding. It is, therefore, not easy to obtain welded joints with high strength, toughness, fatigue properties, etc. The problem worsens when the heat input is increased to raise the efficiency of welding work. To solve these problems, the development of steel materials and welding technology has to be done in a coordinated manner. This paper focuses on the steel material side of the problems, and outlines the development activities of steels excellent in the toughness of the heat affected zones (HAZs) of welded joints.

2. History of HAZ Toughness Improvement

HAZ toughness is one of the most important issues in the functionality improvement of heavy plate products; its enhancement has been pursued in consideration of the needs for higher reliability, tougher use conditions, lighter weight and larger size of welded structures as well as higher welding work efficiency. The progress of HAZ toughness improvement of Nippon Steel & Sumitomo Metal Corporation is reviewed herein below.

The most important point in the HAZ toughness improvement is how to obtain as fine a metallographic structure of HAZ as possible. Especially in the zones near a fusion line, where the temperature rises to above 1400°C, γ grains coarsen during welding, and the structure forming through the transformation during the cooling thereafter

will also be coarse. In view of this, various methods for refining HAZ structure have been developed typically such as those given in Fig. 1.¹⁾ The gist of such methods consists of having fine and thermally stable particles dispersed in the steel matrix and using them in the thermal history of welding as the pins to impede the growth of γ grains or as the nucleation sites for ferrite transformation inside γ grains; the ferrite resulting from this latter transformation is called intra-granular ferrite (IGF).

Eventually, TiN steel entered commercial use in the 1970s as given in Fig. 1.²⁾ The technology for the TiN steel is to use particles of Ti nitride, tens to hundreds of nanometers in size, mainly for pinning the growth of γ grains, and at the same time, the effectiveness of the particles as the nucleation sites for IGF transformation was recognized.^{3,4)} Presently, TiN steel is widely used as a standard material to obtain high HAZ toughness. In the 1990s, TiO steel was brought into wide use, wherein Ti oxides several micrometers or less in size are dispersed in the steel by means of Ti deoxidation without Al addition, and used as the nucleation sites for IGF transformation;⁵⁾ this led to the concept of oxide metallurgy. Oxide metallurgy was further pursued throughout the first decade of the 21st century, and new steel products capable of making the HAZ structure even finer became widely used.^{6,7)} The technology employed therein consists of having oxides and sulfides containing Mg, Ca, etc., tens to hundreds of nanometers in size, scattered in the steel to strongly restrict the growth of γ grains near the weld line.

In addition to the above, other high-HAZ toughness steels were developed taking advantage of IGF; such include B-containing steels making use of BN, TiN-MnS steels utilizing TiN and MnS particles,⁸⁾ and Ti-B steels, wherein TiN is used in combination with

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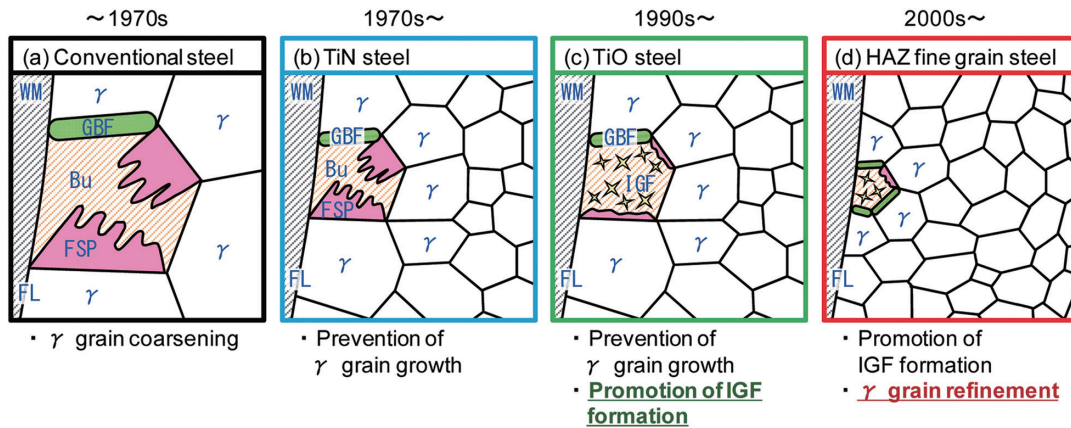


Fig. 1 Progress of HAZ toughening technology HTUFF™ in Nippon Steel & Sumitomo Metal

B precipitates such as $Fe_{23}(C,B)_6$, $Fe_3(C,B)$ or BN .⁹⁻¹²⁾ The above high-HAZ toughness measures utilizing fine inclusion particles are collectively referred to in the company as HTUFF™ (pronounced “aitch tough” and standing for high-HAZ toughness technology with fine microstructure imparted by fine particles).

In addition to the measures to obtain the fine HAZ structure presented above, control of brittle phases is also effective at enhancing HAZ toughness. The adverse effects of brittle phases in the HAZ have long been recognized. As steels of higher strength began to be widely used, the formation of a brittle structure, called the martensite-austenite (MA) constituent, became widely known as the cause of low HAZ toughness.^{13, 14)} In this regard, methods are being developed for suppressing the formation of brittle MA phases by decreasing the contents of C, Si and Al.¹⁵⁻¹⁷⁾

3. High-performance Heavy Plates of High HAZ Toughness

Making the most of the HTUFF™, Nippon Steel & Sumitomo Metal has developed a series of new heavy plate products as the world leader in the field, and supplied them for actual use for a wide variety of applications in and outside Japan; such products include steels for high heat input welding used for ships, buildings and wind turbine power plants, high-strength steels for off-shore structures subject to the guarantee of crack tip opening displacement (CTOD) at low temperature, and steel plates for line pipes in cold regions. The high technical level of steelmaking constitutes the backbone of the quantity production of these high-end products. The following sub-sections briefly introduce Nippon Steel & Sumitomo Metal’s high-performance heavy plate products making the most of the HTUFF™.

3.1 Steel for large-heat-input welding for buildings

With increasing height and span of building structures, steel materials are required to be stronger, thicker and compatible with higher-efficiency welding for steel frame fabrication. To improve welding efficiency, welding methods of large heat input such as electro-slag welding (ESW) and multi-electrode submerged arc welding (SAW) are employed, for example, for welding diaphragms and corners of square-section columns, whereby the heat input is sometimes as high as 50 to 100 kJ/mm. When conventional steel for building use is welded under such a high heat input, it is feared that the microstructure of the HAZ is markedly coarsened and toughness is de-

creased. To solve the problem, the development of new steels capable of maintaining high HAZ toughness even after welding at high heat input was anticipated for building frame use.

In response, Nippon Steel & Sumitomo Metal has developed high-HAZ toughness steels for building structures, BT-HT355C-HF and BT-HT440C-HF, applying the HTUFF™, and launched them onto the market.¹⁸⁾ Fine particles of oxides and sulfides of sizes on the order of nanometers are scattered in their matrices,⁷⁾ and even under a large welding heat input, the γ grains near the weld line are prevented from growing large, which makes the transformation structure forming from γ grain boundaries fine and raises the material toughness. The Charpy absorbed energy at 0°C of the welded joints of inner diaphragms (1 pass by ESW) and corners (1 pass by 2-electrode SAW) of square-section columns of the developed steels exceeds 70 J on average, evidencing excellent HAZ toughness of the products.

3.2 TMCP steel for off-shore structures

As the demand for energy increases, off-shore structures of increasingly larger sizes are being constructed, and as a result, the loads that their support columns have to bear are increasing rapidly. For this reason, steels of higher strength are eagerly sought to decrease the weight of their platform structures above the water. On the other hand, the search for ocean resources has expanded to cold polar waters, and accordingly, high toughness at increasingly lower temperatures has become a requirement of heavy steel plates for marine structures.

To meet this requirement, Nippon Steel & Sumitomo Metal has commercially launched steel for off-shore structures having a yield strength of 500 MPa with CTOD guarantee at $-10^{\circ}C$, as the world’s first of this type.¹⁹⁻²¹⁾ Here, the HTUFF™ are effectively employed to enhance HAZ toughness, and at the same time, a high strength of 500 MPa yield point and good CTOD performance at $-10^{\circ}C$ are produced through the combined application of micro-alloying and the thermo-mechanical control process (TMCP) at plate rolling. More than 50000 tons of plate of the developed steel have been commercially produced and used for their intended applications, demonstrating the intended properties stably.

To meet the requests for even higher strength, the company has developed steel for off-shore structures having a yield strength of 550 MPa with CTOD guarantee at $-10^{\circ}C$; this product has actually been used for real off-shore structures.¹⁷⁾ Cu precipitation hardening

and decrease in C content effectively produced both the high strength and high HAZ toughness.

On the other hand, in response to the requirement for low-temperature use, steel of 420-MPa yield point and for CTOD guarantee at -20°C (plate thickness 100 mm) has been developed and commercially launched.^{22,23)} The HAZ structure refining ability of TiO steel, one of the technologies of the HTUFF™, is effectively used for this product to improve HAZ toughness at low temperature. The key point of TiO steel is that particles of Ti oxide dispersed in steel absorb Mn, and Mn-depleted regions are formed around them, which accelerates the formation of IGF to refine HAZ structure. With respect to the effects of Mn, in addition to the formation of the Mn-depleted regions of conventional TiO steels, the formation of coarse ferrite side plates (FSPs) is suppressed by using Mn segregating at γ grain boundaries, and as a result, the HAZ structure is successfully made finer than with conventional plate products.²⁴⁾

To satisfy the requirement for good CTOD performance of welded joints at -35°C or lower as was required for the Sakhalin oil and gas exploration project, steel plates for use at ultra-low temperature having yield points of 355 and 420 MPa have also been made available for real use.^{25,26)} Thanks to the HTUFF™, these steels exhibit high HAZ toughness: in fact, joints of 75-mm-thick plates welded at heat inputs of 1, 5, and 10 kJ/mm demonstrated satisfactory CTOD properties at -50°C .

The use of H-section steel for off-shore structures is increasing. Making the most of the base metal and HAZ structure refining effect of fine TiN and V(C,N) precipitates, Nippon Steel & Sumitomo Metal has developed H-section steel for low temperature use having a yield point of 335 MPa for this application.²⁷⁾ The welded joints of this product have high toughness at -50°C , while its base metal shows a high toughness (ductile-brittle transition temperature of -70°C or lower).

3.3 High-strength, high-toughness steel for shipbuilding

Increasingly larger container carriers are being built for higher transportation efficiency; some of the latest ships being constructed exceed 20 000 TEUs (twenty-foot equivalent units, meaning the number of containers the vessel can carry in terms of 20-ft containers). The larger the ships, the thicker and stronger the steel plates used for their structural parts are required to be. Moreover, welding methods of larger heat input are employed to raise work efficiency and cut shipbuilding costs.

To cope with this latest trend, Nippon Steel & Sumitomo Metal has developed YP47 steel, steel for high-strength heavy plates excellent in brittle crack arrest toughness and having a yield strength over 460 MPa; this product has been actually used for real ships.²⁸⁻³⁰⁾ In this steel, γ grains near the weld line are prevented from coarsening, and fine HAZ structure is maintained owing to the HTUFF™, and fine structure is obtained in the base metal thanks to the TMCP. As a result, crack formation at welded joints is suppressed, and even if one occurs, its propagation is effectively stopped at the base metal to prevent the ship hull from being torn.

Cryogenic steels are used for the tanks of LPG carriers, and increasingly higher strength is required for them as the size of the vessel and tanks increase and the inside pressure of the tanks becomes higher for better transportation efficiency. For the application to multi-purpose LPG carriers, which carry liquefied ammonia as well as LPG, steel materials are requested to be resistant to the stress corrosion cracking (SCC) due to ammonia, in addition to the properties required for steels for common LPG tanks.

To meet these requirements, low-temperature alloy steel resistant

to ammonia SCC having a tensile strength of 530 MPa has been developed and used for real vessels.³¹⁾ Thus, high strength and good low-temperature toughness of welded joints (excellent CTOD performance at -48°C) are obtained through combination of the HTUFF™ and the TMCP based on the continuous on-line control process (CLC) of plate rolling.

3.4 Steel for large-heat-input welding for wind turbine power plants

The use of heavy steel plates more than 40 mm in thickness for large wind power plants is increasing. In consideration of the latest trend for larger and larger wind turbines, cost reduction of welding work for thick plates, or welding efficiency improvement, is essential for the expansion of wind power generation.

Large-heat-input welding, by which the number of welding passes is much decreased, is effective at improving welding efficiency. With higher heat input, however, HAZ structure coarsens significantly, and it becomes difficult to ensure good toughness at 0 to -40°C widely required for off-shore wind turbines. In view of the situation, TMCP steel for large-heat-input welding having a yield strength of 355 MPa, KE36-TM, has been developed by applying the HTUFF™, and the use of heavy plates of this steel grade for the foundations of floating off-shore wind farms has begun.^{32,33)} Specimens of welded joints were prepared using plates of the developed steel, 40 to 50 mm in thickness, by three high-efficiency welding methods (single-groove 1-pass SAW of 31 kJ/mm heat input, 1-pass electro-gas welding of 20 kJ/mm, and 2-pass SAW of 12 kJ/mm), and their impact properties were evaluated. As a result, the ductile-brittle transition temperature ($v\text{Trs}$) of any one of them was -20°C or lower, demonstrating excellent low-temperature toughness of the joints.

3.5 High-strength steel for line pipes in cold regions

High-strength line pipes are being developed in view of the requirements for higher transportation efficiency of long-distance natural gas pipelines by pressure increase and for lower construction costs by the use of thin-wall thickness pipes. To effectively arrest ductile fracture and prevent brittle failure, good low-temperature toughness is required for both the base metal and the HAZs of high-strength line pipes. On the other hand, for efficient pipe laying work, good weldability is important. Nippon Steel & Sumitomo Metal applied TiO steel, an HTUFF™ steel, to the material plates for line pipes, and supplied API X70 class UOE pipes for the North Sea project.³⁴⁾

Pipelines in frozen-soil or seismic regions are subject to large bending moment due to ground deformation, and to prevent consequent ductile fracture, good deformability (high uniform elongation and low yield ratio) is required for line pipes. To satisfy the demand, new UOE pipes of X60 to X80 classes with excellent HAZ toughness and high deformability have been developed.^{35,36)} High HAZ toughness is realized by applying the HTUFF™, and a critical CTOD value of welded joints of 0.2 mm or less at -35°C was obtained. In addition, the dual-phase structure of the product brought about by the TMCP rolling improves uniform elongation and yield ratio; API X60 UOE pipes of this steel were used for the Sakhalin project.³⁷⁾ Two other new steel grades, one having a high HAZ toughness³⁸⁾ and the other having a high uniform elongation³⁹⁾, have been developed for yet stronger X100 class line pipes.

To cope with the need for higher toughness at yet lower temperatures, the development of X80 class low-temperature, high-strength line pipes has been completed.⁴⁰⁾ This product exhibits excellent HAZ toughness (Charpy impact properties) at as low as -60°C

thanks to the combination of the HTUFF™, effective use of B and low carbon concentration.

4. Future Prospects

The mechanisms for the HTUFF™ were clarified owing to the advances of analysis technologies. In the IGF transformation, for example, the Mn-depleted regions near Ti oxide particles play an important role; this was verified through the use of a focused ion beam (FIB) system and a field-emitting transmission electron microscope (FE-TEM).⁴¹⁻⁴³⁾ Clarification of metallurgical mechanisms by effectively utilizing advanced analysis technology is essential for adding new functions to steel materials.

Clarifying the factors that govern material toughness and working out methods for its prediction are essential for establishing fundamental technologies to improve HAZ toughness. The factors that determine the CTOD properties were identified based on micro-metallurgical fracture dynamics in the 1980s. More recently, regarding large-heat-input welding, the effects of alloying elements and thermal history over factors governing steel toughness have been formulated, and models for HAZ toughness prediction have been devised. It is essential to continue promoting this type of fundamental research.

To actually enjoy the benefits of high HAZ toughness, it is indispensable to develop novel welding materials. Taking advantage of having Nippon Steel & Sumikin Welding Co., Ltd. as a group member, Nippon Steel & Sumitomo Metal has developed various welding materials best suited to high-HAZ toughness steels, and provided the market with such steel products and welding materials in packages. This development framework of the group has to be further strengthened, for it will continue to be effective at encouraging and accelerating the actual use of new steel materials for welded use.

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