NIPPON STEEL TECHNICAL REPORT No. 95 January 2007

UDC 621 . 791 . 7 / .8

Latest Advances and Future Prospects of Welding Technologies

Shigeru OHKITA*[1] Hatsuhiko OIKAWA*[1]

Abstract

Demands for properties of materials used in structures include many things such as strength, toughness, fatigue property, corrosion resistance and heat resistance, and these become to be higher level. On the other hand, demands for welding technologies become to be severe with these demands for properties, and these are wide variety such as high efficiencies, high qualities, many functions, labor saving and low cost. In this chapter, recent steels and titanium corresponded to these needs, and its welding technologies were described. At first, needs and development tendency in the fields of plates, sheets, pipes, stainless steels and titanium, and the examples of developed materials were described. Next, representative welding technologies in the fields of ship buildings, buildings, bridges, automobiles, home appliances, machines for building, tanks, pressure vessels, pipelines and power plants were described. Problems in the field of welding technologies are very wide, for example, application of newly developed steels in customers, stable operation of welding lines in steel works and welding procedures in the field of engineering. Further development is needed continuously in the field of welding.

1. Introduction

Structural materials are required to have a wide variety of properties according to factors such as the use environment, design and assembly method of the structure, and the same is true with weld joints of the materials. Therefore, metal materials must satisfy widely varied and demanding quality requirements for welded structures. Furthermore, labor saving and lower costs are also required for welding work. The requirements for metal materials and welding consumables have become increasingly sophisticated and demanding since 1995, when the last special issue on welding of Shinnittetsu Giho was published, and new quality properties not considered before have come to be newly required for steel materials.

In response to these increasingly demanding requirements, Nippon Steel Corporation has developed and supplied various steel products as well as welding materials of high functionality and high quality for each of requirement. Typical examples of such products include heavy plate products for building applications such as fire-resistant steels that maintain high strength at high temperatures and high-toughness steels that secure safety against earthquakes and are suitable for ultra-high-heat-input welding, high-strength plates for large container carriers for higher transportation efficiency for shipbuilding, weathering steels containing Ni, resistant to salt contamination in coastal locations, for bridges, and steel pipes of 120-ksi-class yield stress for linepipes[1].

In the field of thin steel sheet products, on the other hand, Nippon Steel has developed new automotive materials such as Pb-free sheets coated with an Sn-Zn alloy for fuel tanks to minimize environmental pollution, Al-coated sheets[2] and high-strength sheets[3] effective in reducing car weight and enhancing collision safety. For home-

*1 Steel Research Laboratories

appliance applications, the company has developed coated sheets with chromate-free post treatment[4] that minimize environmental pollution, pre-coated sheets[5] effective in preventing environmental pollution, reducing costs through process simplification and improving product appearance. The new coated sheet products for the building construction market include SUPER DYMA[6] excellent in corrosion resistance. Similarly, the company launched new stainless steel and titanium products to the market taking advantage of unique material characteristics.

The performance of a structure is often determined by the properties of welded joints rather than those of main materials. The Nippon Steel group companies have always been attentive to global trends of different industrial fields and customers' requirements, reflected them on the development of new products, and proposed new welding and joining methods to the market.

In the field of welding and joining technologies, the group companies have studied and developed various new welding methods; such methods cover the newly developed steel products such as those mentioned above as well as Nippon Steel's pipe production, in-line welders of steel processing lines and engineering business activities such as pipeline laying and construction of offshore structures. Furthermore, the group has been active in directly supporting customers in steel working by proposing solution technologies to solve widely varied joining-related problems and expand the freedom of customers' design work.

This paper presents some examples of new steel products for various industrial fields and their welding technologies developed and actually applied since 1995, and outlines future prospects and trends of welding technologies.

2. Latest Development Trends of Steel Products

2.1 Heavy plates

The principal market requirements for heavy steel plates have been higher strength, applicability of high-efficiency welding methods for lower fabrication costs and higher operating efficiency of structures in consideration of scale expansion of structures and consequent higher construction costs, higher toughness of welded joints in view of structure use in severer environmental conditions, and resistance to damage from fatigue and corrosion for longer service life of structures. To meet these increasingly sophisticated market requirements, efforts were bent on studies into new steel materials, and a wide variety of heavy plate products were developed and put into commercial application (see **Table 1**).

One of the most noteworthy among the developed technologies in terms of influence and effect is thermo-mechanical control process (TMCP) applied since the 1980s; a variety of new heavy plate products appeared taking advantage of the process. The TMCP enables, for example, to produce steels of a 490MPa class tensile strength with a carbon equivalent (Ceq) close to that of a mild steel, obtain the same strength as that of as-rolled products with smaller amounts of alloying elements; this makes welding work easier either by eliminating preheating or lowering preheating temperature. More recently, the strength of TMCP steels has increased significantly, and the application of the process has expanded to cover HT950 steel for penstocks and the material plates for X120 linepipes.

Requirements for labor saving, cost reduction and higher efficiency in the construction of steel structures have led to the need for wider application of higher-strength plates. Whereas steel plates were either as rolled or quenched and tempered conventionally, by the TMCP, they are produced through thermo-mechanical rolling (TMR) and accelerated cooling (AcC), and the microstructure of the TMCP products is finer and their toughness is higher than those of conventional products[7,8]. **Fig. 1** schematically shows sections of weld joints of heavy plates. To simplify welding work, heat input is increased or the sectional area of a groove is decreased. However, it has been known that if steel has a high content of carbon or alloying elements, the toughness decreases significantly in the zones adjacent to weld metal where austenitic grains grow coarse (coarse-grain zones) and the zones where the structure of the coarse-grain zones transforms into a hard structure under the heat of a subsequent pass (coarse-grain and dual-phase-heated zone).

Especially when heat input is large, the coarsening of grains becomes conspicuous and the width of the coarse-grain zones increases; this significantly embrittles the weld joint. The TMCP makes it possible to decrease the contents of carbon and alloying elements, and it is possible to greatly mitigate the embrittlement of these zones. In addition to the above, new steels called HTUFF steels have been developed, wherein the microstructure of the coarse-grain zone in a heat-affected zone (HAZ) is refined by using fine particles (such as precipitates of nitride and oxide of Ti and those of Mg) to improve toughness under welding at ultra-high heat input. These steels have been effectively used for high-heat-input welding in the fields of building construction and shipbuilding.

Furthermore, plate products with high corrosion resistance and high fatigue resistance have been developed and used to extend the service lives of structures used in different types of corrosive environments. As a new weatherproof steel, a Ni-based steel, suitable for use in coastal regions without painting, was developed and commercially applied. S-TEN1 is another new corrosion-resistant steel having enhanced resistance to hydrochloric acid in addition to sulfuric acid; this steel has been used for industrial machinery.

2.2 Thin sheets

Worldwide concern about environmental issues such as global warming and pollution with harmful substances has been growing more and more. To handle these problems, the automobile industry has aggressively taken measures such as commercialization of hybrid cars, introduction of fuel-cell cars and reduction of car weight and use of environmentally harmful substances. On the other hand, better protection of pedestrians and passengers is imperative in today's motorized society. To respond to the need for environmental conservation and collision safety in the automotive industry, the steel industry has developed and supplied a wide variety of new steel sheet products.

The first of such movements was the decrease in the use of lead; Sn-Zn-coated and Al-coated steel sheets were developed for fuel tank applications[2].

To curb global warming, on the other hand, higher fuel efficiency and reduction of CO_2 emission were required, and measures to reduce car weight were studied. Use of lighter materials such as aluminum and magnesium is effective in car weight reduction, but owing to high prices and poor workability, their application is still limited. While hybrid body structure partially using aluminum was studied and commercially used for some models, the steel industry proposed intensive use of high-strength steel sheets[3].

At the same time, the need for enhanced collision safety became stressed, which spurred the demands for high-strength steel sheets for automobile structures. As a result, various types of steel sheet products with a tensile strength of 590MPa or higher were developed, some of them having tensile strength as high as 1470MPa.

While use of high-strength steel sheets is effective in reducing

Table 1 Needs, demands for properties in each industry field and examples of developed steels

Industry fields	Needs, Back grounds	Demands for properties	Examples of developed steels
Ship building	Liquefied gas carrier ship Container ship Corrosion resistance for crude oil carrier	HAZ toughness Arrest property High heat input weldability High tensile strength Small distortion High efficient fabrication Corrosion resistance Fatigue strength	Low temperature steels for LPG, LNG tanks Heavy plates by electro-gas welding for container ship High arrest steel New corrosion resistant steels High corrosion resistant SUS for chemical tanker
Architectures and its materials	Skyscraper Brittle failure resistance Fire resistance Corrosion resistance for building steel sheet	High strength High heat input High efficient welding fabrication High toughness Fire resistance High corrosion resistance	Low YR 490 to 780 MPa steels High HAZ toughness - high strength steels for high heat input welding Fire resistant 400-490 MPa class steels, Super Dyma
Bridges	Reduction of construction cost Reduction of life cycle cost	High efficient welding fabrication Corrosion resistance Fatigue strength	BHS steels Titanium-clad steel Ni type weathering steel
Automobiles	Reduction of environmental load materials Weight reduction Improvement of stiffness Improvement of safety in crashing	Lead-less High strength	Sn-Zn alloy coated steel sheet for fuel tank Aluminum coated steel sheet for fuel tank High strength steel sheet
Home appliances	Reduction of environmental load materials Reduce in cost by process abbreviation Design	Hexa valent chromium-less Appearance	Coated steel sheet with chromate-free treatment layer Prepainted steel sheet
Construction and industrial machinery	Reduction in weight Longer operating life	Higher strength Wear resistance	HT950 steel for crane Wear resistance steels
Boiler Pressure bessels	High temperature operation High pressure operation	Higher strength High efficient welding fabrication Creep resistance	Advanced 2.25Cr-1Mo steel
Tanks	Growth in size Lowering temperature	Higher strength Corrosion resistance	Steels for combination tanker of LPG and liquid ammonia 9%Ni thick plates High corrosion resistant stainless steel
Pipe lines	High pressure operation Operation at arctic region Corrosion resistance	Higher strength Low temperature toughness Sour gas resistance	X-100, X-120 steel pipes High HAZ toughness-high strength thick line pipes Sour gas resistant steel pipes
Penstocks	Growth in size	High strength Reliability High efficient welding fabrication	HT950 steel plate
Offshore structures	Growth in size Operation at arctic region	High strength High efficient welding fabrication Low temperature toughness	YP460, 500 MPa steels YP355, 420 MPa steels for arctic use

car weight and enhancing collision safety, changes in auto body structure are also promising; typical examples of such promising measures are use of tailored blank (TB) and hydro-forming (HF) components as shown in **Fig. 2**, and continuous welding employing a heat source such as laser. These new technologies are being studied in the ultra-light steel auto body (ULSAB) project.

As the use of high-strength steel sheets and changes in auto body structure advance, the hurdles that welding has to overcome are increasingly higher, and new technologies for clearing them are being developed. Both car weight reduction and enhanced collision safety will surely be achieved through improved reliability of weld joints by optimizing the chemistry and metallographic structure of high-strength sheets and developing new welding processes (power supply and work methods). How to apply high-strength sheets to a car body in a most suitable manner constitutes a big challenge. The steel industry has proposed optimum structures that enhance the impact absorption capacity and rigidity of a car body and developed new welding technologies from this viewpoint.

Environmental problems due to harmful substances have been a serious problem also in the home appliance industry. The development of coated sheets with chromate-free post treatment[4] having good weldability is a response to this. Pre-coated sheets[5] were developed to prevent environmental pollution, reduce customers' costs through process simplification and improve product appearance.

Steel sheets coated with Zn-based alloys are widely used for building construction because of excellent corrosion resistance; the

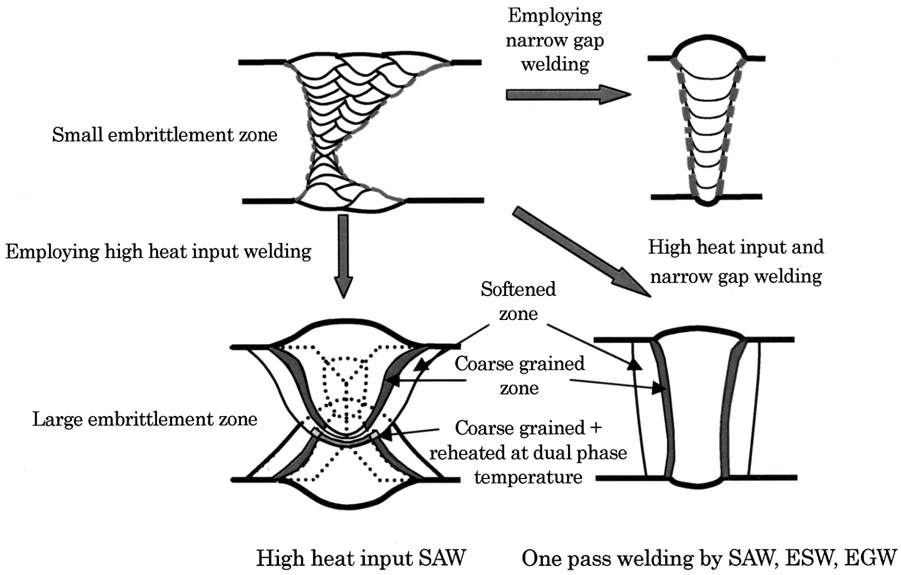

Fig. 1 High efficiency welding and the embrittlement zone

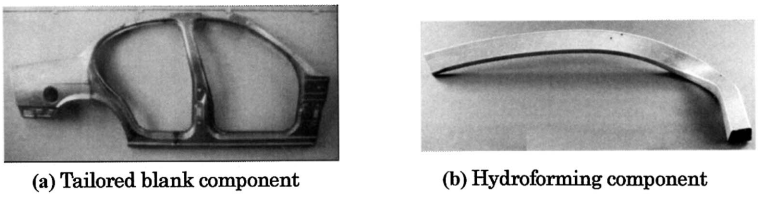

Fig. 2 Examples of Tailored blank and Hydroforming component

application of recently developed SUPER DYMA[6], which has corrosion resistance comparable to that of stainless steel, is expected to expand.

2.3 Steel pipes

Steel pipes are used in many fields of industry such as automobiles, industrial machinery, boilers, structures, plant and building piping, pipelines and oil wells. Steel pipes are classified by manufacturing process into UOE, spiral-welded, electric-welded, butt-welded, seamless pipes and so forth; all these except for seamless pipes are manufactured by welding material sheets or plates.

In response to the requirements described earlier in relation to thin sheet products, Nippon Steel has developed high-strength steel pipes and supplied them to the automotive and industrial machinery industries. With regard to automotive exhaust systems, pipes of highly heat-resistant and workable ferritic stainless steel were developed for exhaust manifolds, and pipes of highly corrosion-resistant ferritic stainless steel for mufflers.

In the field of plant construction, super-austenitic stainless steel pipes, NSSC®270, were developed for applications to water desalination plants and plants for salt-containing food (NSSC® is the trademark of Nippon Steel & Sumikin Stainless Steel Corporation).

For boiler applications, high-strength and highly corrosion-resistant steel pipes such as NF709R and XA704 were developed for use for power plants, where high-temperature and high-pressure operation is becoming common practice to raise power generation efficiency. High-quality, electric-welded boiler tubes were developed and applied in response to the need for reducing construction costs. The operating conditions of many industrial and municipal waste incineration boilers are highly corrosive, and high-Cr, low-C NF709R pipes excellent in the resistance to inter-granular corrosion were developed especially for such applications. New S-TEN1, which is a sulfuric-acid-resistant steel with improved resistance also to hydrochloric acid, is available in the form of pipe products as well.

Steel pipes for civil and building construction use are required to have a wide variety of properties such as corrosion resistance, seismic resistance, high strength and good appearance. Recently, Nippon Steel has supplied tapered steel pipes for uses such as lighting posts; these pipes often have U-shaped ribs welded at the works to the base portion to prevent falling due to fatigue.

More and more pipelines are laid at arctic regions or deep seabed, and to reduce steel weight and construction costs and improve transportation efficiency, higher and higher strength is required for linepipes. In view of this market trend, Nippon Steel included X100 class linepipes in its product line-up, and in addition, developed linepipes of a X120 class jointly with ExxonMobil, and is making itself ready for their commercial production. For oil/gas exploration projects in corrosive environments, the company also has developed and supplied corrosion-resistant linepipe materials.

As described above, exerting its technologies of ladle refining, oxide and precipitate control and the TMCP, Nippon Steel has commercialized various types of steel pipe products that meet widely varied market requirements[1].

2.4 Stainless steel

Besides being highly resistant to corrosion, stainless steels have various advantages over low-alloy steels. Austenitic, ferritic, martensitic, dual-phase and other types of stainless steels are used in many fields of industry making the most of their characteristics according to application.

The topics in the latest technical development of stainless steel include things such as further improvement in quality such as corrosion resistance, technical development for exploring new markets by quickly responding to customers' requirements, substitution of austenitic stainless steels with ferritic stainless steels as a measure against rising prices of Ni and Mo, and enhancement in productivity[9].

To cite some examples, NSSC®260A for chemical tankers and NSSC®270 for tanks for salt-containing food were newly developed, together with respective welding technologies, by improving the corrosion resistance of conventional stainless steels. NSSC®180 for automobile exhaust systems is a ferritic stainless steel with improved workability; because it does not contain Ni or Mo, it is produced more economically than austenitic stainless steels.

Even after Nippon Steel & Sumikin Stainless Steel Corporation was established as responsible for the whole stainless steel businesses of Nippon Steel and Sumitomo Metal Industries, Nippon Steel continues supporting the development of the company of its products and application technologies including welding.

2.5 Titanium

Titanium and its alloys are used for applications such as heat exchangers, chemical plants and aircraft by virtue of their excellent corrosion resistance, light weight and high strength. The productivity of titanium products has improved, and as a result, their application, which was once limited to special fields, has expanded to cover more common structures such as housing roofs and car components. Nippon Steel has supplied titanium products in the forms of cold-rolled sheets, heavy plates, welded pipes, wire rods and so forth[10].

Inert-gas-shielded welding such as TIG and plasma welding were generally employed to weld titanium and its alloys, because they were used mainly in the form of thin sheets. Recently, their use has expanded to include offshore structures and ships in the form of heavy plates, and high-efficiency welding methods such as MIG and electron beam welding will be used more widely.

3. Development of Welding Technologies for Different Fields of Industry

The Japanese word "*yosetsu-sei* (weldability)" is generally used for expressing the performance of a weld joint of a material. The word originally meant the ease of welding of a steel material, and it also meant, rather vaguely, the resistance to the occurrence of welding defects such as high- and low-temperature cracks. More recently, it began to mean also the ease of welding of steel material including welding work efficiency and the soundness and performance of weld joints, and now, it is used in a broader sense including availability of welding materials and stability of welding work[7]. This section describes some examples of welding technologies researched and developed in different fields of industry to enhance the weldability of steel materials, and trends of welding technology.

3.1 Shipbuilding

To improve the productivity of shipbuilding work such as butt welding of large plates and block joining, one-side, single-pass SAW and electrogas arc welding are widely applied. To transport more cargo containers at higher speeds, the size of container carriers is increasing lately, and as a result, heavy plates of YP390MPa steels 50 mm or more in thickness have come to be used for sheer strakes and hatch coamings[11]. To weld these heavy plates efficiently, the large-heat-input, single-pass, two-electrode, electrogas arc welding method was developed and widely applied. Further improvement of the product is under way to attain higher strength.

As explained earlier, the toughness of the HAZ of large-heat-input welding has been improved through combination of measures such as the following: lowering carbon equivalent (Ceq) based on the TMCP technologies; suppressing the coarsening of crystal grains by use of TiN and other precipitates; refining in-grain transformation structures using different kinds of oxides; and decreasing embrittled structures. Low-temperature steel plates[12] for LPG carriers and their weld joints must have high toughness at low temperatures (-68 to -53℃), which, together with requirements for high-efficiency welding work, makes it very difficult to satisfy required joint performance. Like in the case of the steels for container carriers, the technologies of high-heat-input welding were applied to the improvement of the HAZ toughness of this low-temperature steel. In addition, in consideration of demand for elimination of work such as stress relieving at shipyards, and based on new technologies to enhance high-temperature strength of steel plates and weld metal and to control their transformation temperatures, Nippon Steel proposed low-strain steel plates and welding consumables specially designed for them; their field application is now under study[13]. For applications in highly corrosive conditions such as chemical tankers, a new corrosion resistant stainless steel, NSSC®260A and welding consumables for it were developed; they are now actually used for the intended applications.

3.2 Building construction

After the Hanshin-Awaji Earthquake in 1995, the brittle fracture of beam-to-column joints of building frames attracted attention as a serious problem, and related industries studied preventive measures under the leadership of the then Ministry of Construction (now Ministry of Land, Infrastructure and Transport). As a result, it was proposed that the performance of a steel structure should be defined by setting out regulations for structural design, steel materials, welding consumables and welding conditions[14]. In addition, to meet the requirements of plastic design to enhance seismic safety, steels for building structure were newly standardized (JIS G 3136, SN), and an upper limit of yield ratio (YR: yield strength / tensile strength) and the range of yield strength were stipulated. Furthermore, the JIS system newly included a steel grade specifying an upper limit of S content and a lower limit of reduction of area in the z (thickness) direction to secure good resistance to lamella tear at welding.

Based on the above, a performance regulation was set out to the effect that a beam-to-column joint should have a specific Charpy impact value in accordance with design condition, and specifications on steel chemistry, welding consumables and welding conditions to realize the required value were set out. As a result, the equation, $fHAZ = C + Mn / 8 + 6 (P + S) + 12N - 4Ti \text{ (mass \%)} \leqq 0.577$, for estimating the Charpy impact value of a HAZ from steel chemistry was established. In response to this, a high-toughness welding wire YM55C (JIS YGW18) suitable for high-efficiency welding (high heat input and high inter-pass temperature) was developed for use with 490MPa class steels.

More recently, more demanding toughness regulations have been applied not only to beam-to-column joints but also to various weld joints of square-section columns. **Fig. 3** shows the toughness of diaphragm joints of a square-section column welded by electro-slag

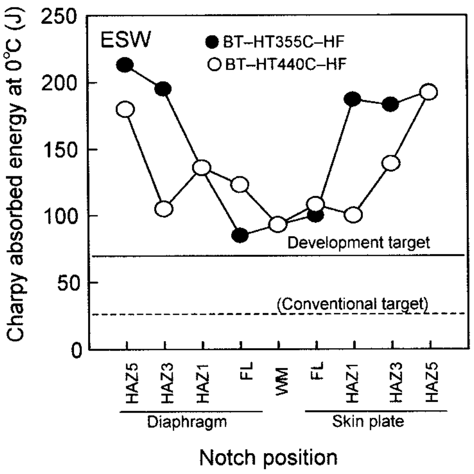

Fig. 3 Toughness at the welds of diafram of box column of HTUFF steel

welding. A new weld metal having an optimum chemistry with Ti and B forms fine acicular ferrite, and thus, makes it possible to attain a high absorbed energy value of 70 J or more at 0℃ in large-heat-input welding of HTUFF steels[15].

A steel of 590MPa class tensile strength (SA440) that satisfies P_{cm} = 0.22, a requirement for preheating-free welding, and the welding consumables for the steel were developed for applications to high-rise buildings, and has been commercially used[16]. HT780 steel has been used for the steel frames of some buildings.

Fire-resistant steel (FR steel) for building frames was first commercialized in 1988 as SM490-FR; its proof stress at 600℃ is 2/3 or more that of SM490 at room temperature. The FR steel is excellent in the resistance to softening under fire, and thus its use enables to reduce the thickness of fireproof coating or eliminate it to decrease construction costs. The latest increase in high-rise buildings spurred the demand for high-strength steels for building structure use, and in response, a FR steel of a 590MPa class tensile strength was developed[17]. This steel, which is excellent in fire resistance while satisfying the basic requirement for building structural steel (YR = 0.8), is produced through metallographic control at rolling and heat treatment. A line-up of welding consumables for these FR steels, principally of matching materials, has been made available.

As for thin sheet products for building use, galvanized sheets are widely used, and for this reason, an important issue is how to prevent blowholes and spatters due to zinc vapor during welding. In this respect, Nippon Steel has proposed adequate conditions and consumables for welding of SUPER DYMA and other highly corrosion-resistant sheet products to support the expansion of their use. Another important issue is the corrosion resistance of weld joints; suitable paints for coating weld joints and corrosion-resistant welding consumables need to be developed.

3.3 Bridge construction

In bridge construction, use of high-strength steel is advantageous for reducing dead weight. However, because there is a certain limit to the reduction of material thickness in consideration of the fatigue properties under the variable load of traffic, steels of tensile strengths up to 570MPa have been widely used. Exceptionally, a great quantity of 780MPa class steel (HT780) was used for some large bridges such as the Akashi Kaikyo Bridge[18]. The principal requirements for welding high-strength steels are decrease in preheating and large heat input; in view of the above, Nippon Steel studied measures to improve strength while maintaining good weldability using precipitation of Cu, and developed HT780 steel that allowed decreased preheating.

Corrosion of steel has always been one of the major problems of bridges, and in response to the need for reducing the life-cycle costs of bridges, the use of weather-resistant steels for welded structures containing elements effective in improving corrosion resistance such as Cu, Cr, P and Ni has increased. Nippon Steel developed Ni-based weather-resistant steels for the first time in the world, and their application to bridges is expanding. Naturally, the same degree of corrosion resistance is required for weld joints, and for this reason, welding consumables of matching materials are used. However, since Ni increases sensitivity to high-temperature cracking, it was necessary to elaborate the chemistry of the welding consumables and welding work conditions to establish the actual applicability of the Ni-based weather-resistant steels[19]. For the piers of the Aqualine Bridge across Tokyo Bay, the company proposed steel plates coated with titanium sheets, highly resistant to seawater, together with the method for welding titanium to steel, and the titanium-clad steel plates were used for the piers as the first case of this type of construction.

3.4 Automobiles

In consideration of requirements such as environmental conservation and improved collision safety of automobiles, new steel sheet products for automotive applications have been developed, and welding and joining methods have been studied.

Environmental considerations required suppressed use or elimination of lead, and in response, product such as Sn-Zn-coated sheets and Al-coated sheets were developed for fuel tank applications[2]. Because the weldability of these products was different from that of conventional Pb-Sn-coated sheets, joining methods by seam welding, spot welding and soldering were studied, and as a result, a commercially applicable joining method was established through improvement of coating and adequate control of welding conditions. Optimum welding conditions for materials free of hexavalent chromium were studied, and at present, their field application is being promoted.

To curb global warming, on the other hand, car weight reduction has been pursued. Use of light-weight materials such as aluminum and magnesium is effective in reducing car weight, but despite many studies on joining methods of these materials, steel has been found superior to them in terms of reliability and cost. Hybrid structures partially using aluminum were also studied, and for joining steel and aluminum, methods such as self-pierce riveting, friction spot joining[20], direct welding, soldering and welding using aluminum-coated steel sheets[21] were proposed.

In response to the need for car weight reduction, the steel industry proposed use of high-strength steel sheets[3]. The need for higher collision safety arose at the same time, and this encouraged the use of high-strength steel sheets. Consequently, a variety of steel sheet products having tensile strength of 590MPa or higher were developed, and welding methods for these products were studied vigorously.

The automobile industry has employed spot welding, arc welding, projection welding and many other joining methods, but recently, in consideration of work efficiency, ease of one-side welding of closed-section components and continuous welding work, laser welding and laser brazing came to be used[21], and the application of these methods to high-strength steel sheets was studied. Laser welding has shown remarkable technical advance: methods typically such as fiber laser and disc laser realized higher output, and welding methods using remote laser or scanner laser is being studied[22]. Applying high-strength steel sheets to a car body in the best suitable manner is a big challenge, and body structures for enhancing impact absorption and rigidity have been proposed to find an optimum solution. New welding technologies are being developed from this viewpoint.

What is required for the welding of high-strength steel sheets in the first place is the reliability of weld joints. Usually, carbon equivalent of steel increases and so does the HAZ hardness as strength increases. Consequently, stress concentration at a weld joint is likely to cause failure near the joint, leading to poor joint strength. Many things are necessary for enhancing the reliability of a weld joint. These include accumulating a database on joint strength, defining the welding condition for obtaining high strength, and proposing desirable joint shapes according to stress conditions. Improvement of steel chemistry and proposals of measures for improving joint performance such as the cooling rate after welding and selection of the best suitable flux for arc welding are also important. Various proposals were made to respond to these requirements, and efforts are being bent in this direction.

A second problem with the welding of high-strength steel sheets is the softening of HAZs. This occurs as a result of tempering of bainite and martensite in steel owing to the heat of welding and consequent decrease in hardness. This deteriorates joint strength because failure occurs in the softened portion under tensile stress. The measures against the softening so far proposed include: (1) use of steel resistant to the softening and (2) employing spot welding or laser welding, by which heat input is low and cooling rate is high. What is important is the combination of steel material with the most adequate welding process.

Fatigue strength is another problem with weld joints of high-strength steel sheets: while the fatigue strength of steel becomes higher as its tensile strength increases, the fatigue strength of a weld joint does not. This constitutes a problem in increasing the use of higher-strength and thinner steel sheets. What has been proposed as measures to improve fatigue strength includes: for arc welding, (1) increasing bead-end radius by remelting and (2) introducing compressive residual stress to a bead end by shot peening or using flux having a low transformation temperature[23]; and for spot welding, introducing compressive residual stress to the region around a nugget by (1) post-heating or (2) post-loading. Study of measures to improve fatigue strength in consideration of welding workability is required.

Other measures required for the welding of high-strength steel sheets include: (1) measures against hydrogen embrittlement and (2) establishment of quality assurance methods for weld joints. With respect to the hydrogen embrittlement, it is necessary to understand the phenomenon more precisely and propose standards for use of weld joints, and with respect to the quality assurance methods, it is necessary to establish technologies for in-process control and non-destructive inspection.

Besides the above, change in the body structure is promising for reducing car weight and enhancing collision safety. Typical examples of such measures are use of tailored-blank (TB) and hydro-forming (HF) components and continuous welding using a heat source such as laser.

The TB is a technology to join steel sheets by butting sheet ends and welding by laser, mash-seam or plasma welding; since it is capable of joining steel sheets of different thicknesses and strengths and enables combination of optimum thicknesses and strengths for different parts of a component, it is an effective means to reduce car weight and enhance collision safety. The technical problems now being studied in relation to TB include: (1) establishment of work practice (groove accuracy, gap tolerance, etc.), (2) defect prevention, and (3) establishment of quality assurance technologies[24].

The HF, on the other hand, is a technology to form a steel sheet or pipe by hydrostatic pressure. Compared with conventional manufacturing methods by press forming and welding, the HF is more effective in car weight reduction owing to advantages such as: (1) smaller number of parts, (2) elimination of flanges, and (3) high forming accuracy and large deformation[25].

However, since an HF component lacks flanges, a one-side welding method such as laser or arc welding is indispensable for joining it to another. While laser welding is fast and excellent in bead appearance and causes only small deformation, it requires precise gap control. In contrast, arc welding allows a large gap tolerance but it causes large deformation and the appearance of its beads is relatively poor. Thus, it is necessary to select either of these methods in consideration to the component shape and material. Development of a new one-side welding method is also required. Laser welding and arc welding are typical continuous welding methods. Laser welding is attracting attention recently because of the advantages of high welding speed, good bead appearance and small deformation, and enhanced car body stiffness by application of laser welding is under study.

The technical problems of laser welding include: (1) precise gap control, (2) welding defects due to zinc vapor in joining galvanized sheets and (3) reliability of weld joints; measures to solve these problems are being studied. High-rigidity car bodies through structural optimization by the use of high-strength steel sheets will enable use of thinner sheets and reduction of body weight without sacrificing collision safety.

While the requirements for welding become increasingly demanding and stringent as the use of high-strength sheets and change in car body structure advance, technologies to satisfy them are being developed. The reliability of weld joints will be enhanced through optimization of steel chemistry and metallographic structure and development of new welding processes (power supply, work practice, etc.), and this will bring lighter car bodies with better collision safety into reality.

3.5 Home appliances

Coated sheets with chromate-free post treatment[4] were developed and commercially applied in the home appliance industry to reduce the use of environmentally hazardous substances. Spot welding is often used for coated steel sheets, and these sheet products are so designed to exhibit excellent weldability when welding conditions are adequately controlled.

Pre-coated sheets[5] were developed to prevent environmental pollution, cut customers' costs through process simplification and improve product appearance. Since the electrical conductivity of the coating films of pre-coated sheets is low, it is difficult to join them by spot welding. In addition, if they are spot welded by rendering the coating films conductive, welding marks will remain on the outer surface. For this reason, pre-coated sheets are joined mainly by mechanical joining methods such as screwing, tog-lock, TOX, self-pierce riveting and blind riveting. Although data accumulation on the work conditions and joint properties of the above joining methods was insufficiently at the beginning, many studies have lead to their successful application.

3.6 Construction and industrial machinery

High-tensile, wear-resistant and corrosion resistant steels are used for construction and industrial machines according to applications.

HT950 steel has been used for large cranes since the early 1990s to reduce machine weight, and HT590 steel for the arms of shovel loaders, but since good fatigue properties are required for this application, use of higher-strength steels is considered difficult. Wear-resistant steel sheets are used for the carriers of dump trucks; in this application, weld cracks always constitute a major problem, and different welding practices such as use of soft weld metal are applied according to use condition and welding design. Acid dew-point corrosion is a major problem with smoke stacks of industrial plants, and a new corrosion-resistant steel (S-TEN1) having enhanced resistance to hydrochloric acid in addition to sulfuric acid was developed for this kind of application; the steel is now widely used. Since conventional welding consumables did not always bring about sufficiently good corrosion resistance, new welding consumables of a material matching with S-TEN1 were developed[26].

3.7 Tanks and pressure vessels

Steels for high-temperature use are used for boilers and pressure vessels to enhance their operating efficiency. As the operating temperature becomes higher, steel must have better acid resistance and high-temperature strength, and for this purpose, Cr and Mo contents of steel are increased. The advanced 2.25Cr-Mo steel with improved high-temperature strength and resistance to hydrogen corrosion was developed by adding V to conventional 2.25Cr-Mo steel (SCMV4), a typical steel for this kind of application. Recently, V and Nb came to be added to 9Cr-1Mo steel (A387 Gr. 91), which has improved high-temperature strength through precipitation hardening, and thus, the steel can be used now at temperatures up to 575℃.

Steels such as (9-12)Cr-Mo(-W) were developed for use at temperatures up to 600℃, and they came to be commercially applied recently. Of steels for high-temperature applications, those containing Cr and Mo harden easily because of high alloy contents, and thus, preheating is applied to avoid low-temperature cracking during welding, and post-heating immediately after welding, if necessary. For applications at higher temperatures exceeding 700℃, austenitic stainless steels are used; steel pipes for boiler tube applications (NF709, XA704, etc.) with improved resistance to intergranular corrosion have been developed and commercially used in combination with their respective welding consumables[27].

Fracture toughness, especially the ability to arrest crack propagation, is required for steels for low-temperature tanks of liquefied gasses such as LPG and LNG; Al-killed carbon steels (SLA under JIS G 3126) and Ni-containing steels (SLN under JIS G 3127 and 2.5%-, 3.5%-, 5%-, and 9%-Ni steels) are used for these applications. The size of such tanks is growing larger lately, and use of thicker plates is increasing. Accordingly, the thickness range of 9%-Ni steel plates for LNG tanks, which was up to 30 mm or thereabout, has been expanded to 50 mm[28]. Welding consumables of Ni-based systems such as inconel and hastelloy are used for welding these steels.

3.8 Pipelines and hydraulic power plants

UOE steel pipes of API 5L X65 (yield strength of 65 ksi, 445MPa) were first used for a pipeline in the late 1960s, and ever since the strength of linepipes increased decade by decade: X70 was used in 1973, X80 in 1985, and X100 in the 1990s for trial use in some pipelines. Then, X120 linepipes have been developed and are presently being tested in a commercial pipeline[29,30]. Single-pass submerged arc welding (SAW) of a comparatively large heat input is applied from both the sides to weld steel plates to form these pipes at the steelworks, and small-heat-input MAG automatic welding for joining work at construction sites. Because of the very high material strength, care must be taken to secure high toughness and good resistance to low-temperature cracking at the welding at either the steelworks or the sites. The material of X120 linepipes is a low-C steel with a lower bainitic structure, and the weld metal has, as shown in **Fig. 4**, a microstructure of fine acicular ferrite to secure good weldability.

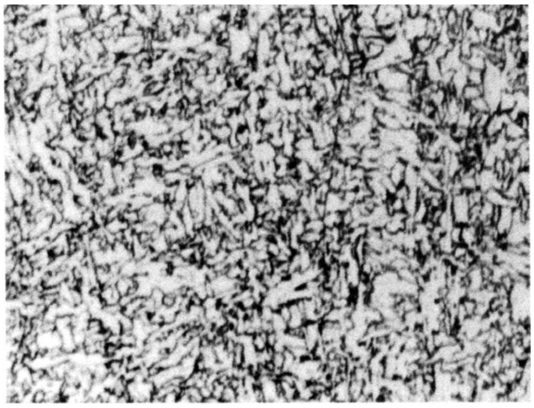

Fig. 4 Microstructure of X-120 class SAW steel weld

A 780MPa class high-tensile steel was used for penstocks in Japan in 1972, and recently, a 950MPa class high-tensile steel was developed and used for penstocks for the first time[31]. To secure high work efficiency in the construction of the large-size penstocks, it was necessary for the 950MPa steel to be weldable under the same conditions (preheating, heat input, etc.) as those for the 780MPa steel. This was realized by welding consumables developed in parallel and specially designed for the steel to exhibit good toughness and low-temperature cracking properties.

3.9 Marine structures

Ever larger marine structures are being constructed in colder regions, and in response, higher-strength steels have been developed for use in arctic environments with guaranteed figures of ultra-low-temperature toughness[32]. Applying the technologies of HTUFF mentioned earlier, Nippon Steel lately developed a new steel, YP500MPa, with CTOD guarantee; its use for commercial structures is expanding[33]. Welding consumables for this steel was developed in parallel, and they brought about satisfactory joint performance.

4. Closing

A wide variety of properties such as strength, toughness, fatigue resistance, corrosion resistance and heat resistance are required for steel materials, and new property requirements have arisen one after another. Accordingly, quality assurance requirements for joints of steel materials have become more and more demanding. Arc welding by conventional equipment and work practice still remains to be the main assembling method for steel structures made of heavy plates. The efficiency of arc welding is improving through measures such as high heat input, narrow gap and automatic welding. On the other hand, regarding thin steel sheets, laser welding is showing remarkable technical advance. The power of laser welding has increased significantly, and the method began to be applied also to heavy plates.

Against such a background, Nippon Steel has developed and commercialized not only steel products but also a variety of welding and joining technologies. To develop high-efficiency and easily practicable welding processes capable of realizing high-quality joints, it is important to figure desirable forms of material joining through thoroughgoing studies of welding equipment, practice and consumables.

This paper has given an overview of the trends in the development of new steels and welding technologies for the steels over the last years, citing some examples. To continue to manufacture reliable steel structures efficiently, it is increasingly important to develop steel materials and welding consumables of higher quality based on good understanding of the basic phenomena of welding and joining steel materials, and respond to customers' need based on understanding of their field practice of joint design, welding work and control.

References

1) Special Issues on Plate and Steel Pipe. Shinnittetsu Giho. (380), (2004)
2) Kurosaki, M.: Shinnittetsu Giho. (378), 46 (2003)
3) Takahashi, M.: Ferrum. 7 (11), 870 (2002)
4) Morishita, A. et al.: Shinnittetsu Giho. (377), 28 (2002)
5) Kanai, H. et al.: Shinnittetsu Giho. (371), 47 (1999)
6) Morimoto, Y. et al.: Shinnittetsu Giho. (378), 22 (2002)
7) Yurioka, N. et al.: Welding & Joining of Steel Materials. Sampo Shuppan (in Japanese)
8) Uemori, R.: Technical Trend of High-performance Steel Plates. Proceedings of 182nd and 183rd Nishiyama Memorial Technical Conference, 2004, p.89,
9) Nippon Steel Monthly. (Nov. 2005)
10) Special Issue on Titanium. Shinnittetsu Giho. (375), (2001)
11) Minagawa, M. et al.: Shinnittetsu Giho. (380), 6 (2004)
12) Nagahara, M. et al.: Shinnittetsu Giho. (380), 9 (2004)
13) Kasuya, T.: Reduction of Welding Deformation Using Steel Materials and Welding Consumables. 14th Seminar of Association for Weld Joining Technology Promotion, p.67
14) Building Research Institute: Guidelines for Prevention of Brittle Fracture of Beam End Weld Joints for Steel Structure - Commentary. (1st Ed.). Building Center of Japan, 2003, p.39
15) Kojima, A. et al.: Shinnittetsu Giho. (380), 33 (2004)
16) Watabe, Y. et al: Shinnittetsu Giho. (380), 45 (2004)
17) Mizutani, Y.: et al.: Shinnittetsu Giho. (380), 38 (2004)
18) Okamura, Y. et al.: Shinnittetsu Giho. (356), 38 (1995)
19) Kihira, H. et al.: Shinnittetsu Giho. (380), 28 (2004)
20) Gendoh, T. et al.: Proc. of 2005 JSAE (Society of Automotive Engineers of Japan) Annual Congress. No. 18-06, 2006, p.1
21) Sasabe, S. et al.: Proc. of Committee of Joining and Material Processing for Light Structures of Japan Welding Society. MP-391-2006, 2006
22) Proc. 5th European Automotive Laser Application. 28/29, Jan. 2004
23) Tohyama, K. et al.: Proc. National Conference of Japan Welding Society. 72, F-39, 2003
24) Miyazaki, Y. et al.: Shinnittetsu Giho. (378), 35 (2003)
25) Kuriyama, Y.: Journal of the Japan Society for Technology of Plasticity. 45 (524), 715 (2004)
26) Usami, A. et al.: Shinnittetsu Giho. (380), 21 (2004)
27) Ishitsuka, T. et al.: Shinnittetsu Giho. (380), 91 (2004)
28) Hoshino, M. et al.: Shinnittetsu Giho. (380), 17 (2004)
29) Fairchild, D.P. et al.: Proc. Int. Offshore and Polar Eng. Conf. 2003, p.26
30) Asahi, H. et al.: Shinnittetsu Giho. (380), 70 (2004)
31) Nishiwaki, Y. et al.: Journal of Japan Society of Civil Engineers. No. 672/VI-50, 37-56 (Mar. 2001)
32) Kojima, K. et al.:18th International Conference on Offshore Mechanics and Arctic Engineering (OMAE). St. John's, Newfoundland, Canada, July 1999
33) Nagai, Y. et al.: Shinnittetsu Giho. (380), 12 (2004)