Development of Welding Consumables and Welding Process for Newly Developed Steel Plates

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Abstract

Innovative steel plates have been developed to answer social needs getting severer, such as tensile strength, toughness in cryogenic use, fatigue property, corrosion resistance, and expanded use of heavy gauge steel plates. It is necessary to propose welding consumables and welding technology suitable for base metal when newly developed steel plates are launched. As examples of the latest welding consumables related for newly developed steel plates; such as steels for high strength shipbuilding, steels for cryogenic atmosphere, high strength steels, corrosion-resistant steels, fire-resistant steels are described. And low temperature transformation welding consumables and high efficiency welding process for extra heavy steel plates are also described.

1. Introduction

When constructing steel structures, such as ships, construction equipment, bridges, buildings, and storage tanks, it is indispensable to weld the steel plates used in them. In order to ensure that a steel structure performs the functions of the steel plates used in it, it is necessary that the welded joints too have functions comparable to those of the steel plates. In fact, there are cases in which the specifications of a specific steel structure are determined by the mechanical properties of welded joints. As described in this paper, the functions and qualities that are required of steel plates have become increasingly diversified and stringent—increasing the strength and design thickness of plates for larger steel structures, securing desired toughness of plates used at lower temperatures, offering plates displaying better corrosion resistance in severer corrosive environments. With a general-purpose welding material, a steel plate having special functions often fails to fully perform its functions. In such a case, it is necessary to develop a new welding material exclusive for the steel plate. Furthermore, there are diverse requests from customers pertaining to welding operations, such as the implementation of high-efficiency welding process with a high heat input, the reduction of preheating load during welding of high-strength steel, and the improvement of fatigue characteristic of weld.

At Nippon Steel & Sumitomo Metal Corporation, with the cooperation of the Plate R&D Department, new welding materials, as well as new steel plates, are developed to permit making the most effective use of the functions of newly developed steel plates. Moreover, in close cooperation with Nippon Steel & Sumikin Welding Co., Ltd.—an affiliate of Nippon Steel & Sumitomo Metal, the Corporation carries on welding and joining solution activities to meet diverse customer needs such as developing new welding process and proposing the optimum welding method to individual customer. Described below is the development of welding materials and welding technology in recent years.

2. Examples of Newly Developed Steel Plates and Exclusive Welding Materials

Table 1 shows examples of the welding materials that Nippon Steel & Sumikin Welding has developed exclusively for the newly developed steel plates of Nippon Steel & Sumitomo Metal. They include welding materials that were originally developed as exclusive ones but are now used as general-purpose ones. In the table, SMAW, GMAW, FCAW, SAW, and EGW represent covered electrode, solid wire for gas shielded arc welding, flux-cored wire for gas shielded arc welding, submerged arc welding electrode (wire × flux), and electrogas arc welding electrode, respectively.

3. Development of Welding Materials for Shipbuilding and Welding Technology

EH47 is a high-strength steel plate for super-large container ship designed with careful consideration given to the brittle fracture

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Table 1 Welding consumables used exclusively for newly developed steel plates

Type of steels	Developed steel plates	Developed welding consumables: Product names
High strength steel plates for shipbuilding	EH47	FCAW : NSSW SF-47E, EGW : NSSW EG-47T
Steel plates for LPG gas carrier	B36F, NV4-4	SMAW : NSSW N-12SN, SAW : NSSW NB-55LS × NSSW Y-3NI
Fire-resistant steel plates	NSFR™400, NSFR™490	GMAW : NSSW YM-40FR, NSSW YM-50FR, FCAW : NSSW SF-50FR, NSSW SM-50FR, SAW : NSSW YF-15FR × NSSW Y-DFR etc.
Seawater-resistant steel plates	MARILOY™	
Ni-added weathering steel plates	NAW-TEN™15	SMAW : NSSW CT-50N, NSSW CT-60N, GMAW : NSSW YM-3N, FCAW : NSSW SF-50WN, NSSW SM-60WN, SAW : NSSW NF-320M × NSSW Y-3NI
Sulfuric acid-resisting steel plates	S-TEN™1	SMAW : NSSW ST-16M, FCAW : NSSW SF-1ST, SAW : NSSW Y-1ST × NSSW NB-1ST
Sulfuric acid-resisting steel plates	S-TEN™2	SMAW : NSSW ST-16Cr, FCAW : NSSW FC-23ST
Corrosion resistant steel plates for crude oil tanker bottom plate	NSGP™-1	FCAW : NSSW SF-1·GP, NSSW SM-1F·GP
High tensile steel plates for building structures	BT-HT440	SAW : NSSW YF-15I × NSSW YM-55HF
HTUFF 50kHT steels for building structures	BT-HT355C-HF	ESW : NSSW YM-55HF × NSSW YF-15I, SAW : NSSW Y-DL·HF × NSSW NSH-53HF
HTUFF 650kHT steels for building structures	BT-HT440C-HF	ESW : NSSW YM-60HF × NSSW YF-15I, SAW : NSSW Y-D·HF × NSSW NSH-60HF, GMAW : NSSW YM-60C·HF
High-yield-point steel plates for bridges	SBHS700 (W)	SMAW : NSSW L-82, GMAW : NSSW YM-82C
950–980 N/mm² class high tensile steel plates	WEL-TEN™950, WEL-TEN™980	SMAW : NSSW L-100EL, GMAW: NSSW YM-100A, SAW : NSSW NB270H × NSSW Y-100

toughness and brittle crack arrestability. In putting EH47 into practical use, improving the efficiency of welding thick plates together was an especially important problem to solve. **Figure 1** shows a typical example of working on the longitudinal strength members of a container ship along with the applied welding methods. Joining the hatch-side coamings or sheer strakes (side plates) together requires vertical welding in the field. Therefore, in this joining work, the high-efficiency EGW process—one-pass welding with a high heat input—has been employed.[1] In addition, multi-pass CO_2 arc welding is applied for flat position welding, fillet welding, and so on.

As in the case of the base metal, the welding material that is applied to thick EH47 steel plates for extremely large container ships is designed to meet the specifications[2] of brittle fracture toughness and brittle crack arrestability. As a welding material for CO_2 arc welding, a seamless flux-cored wire (NSSW SF-47E) has been developed. With respect to EGW, a higher efficiency welding process—the two-electrode vibratory electrogas arc (VEGA™) welding process—and a new welding material for EH47 steel plate was exclusively developed. After obtaining qualification for the welding procedure, in 2007, it was applied to Mitsubishi Heavy Industries container ships employing EH47 steel plates.[3]

The two-electrode VEGA welding process is an automatic vertical welding method in which two welding torches are moved reciprocally to uniformly distribute heat energy and restrain lack of fusion. In addition, in order to avoid the arc interference caused by a magnetic field when the electrodes are made to come close to each other, the two electrodes are reversed in polarity, thereby maintaining the proper distance between them. As shown in **Fig. 2**, the efficiency of this welding method is estimated to be about two times that of the conventional one-electrode VEGA welding process and
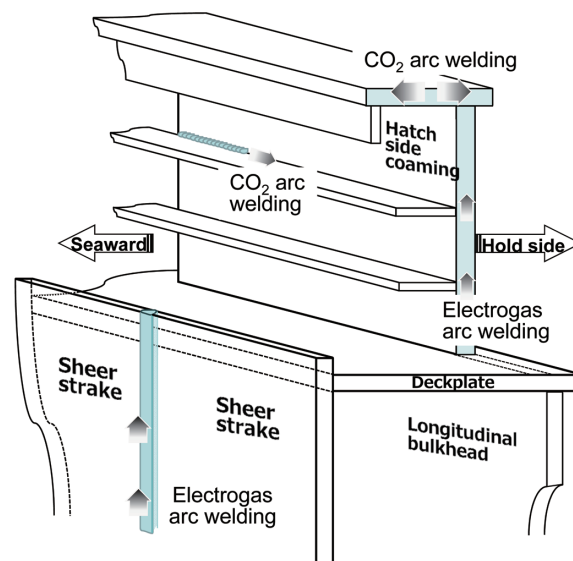

Fig. 1 Schematic diagram of upper hull structure around hold of container ship and applicable welding process

about eight times that of the CO_2 arc welding.

Recently, it has been found that in the application of thick EH47 plates (50 to 70 mm in thickness), the matching of strength between weld metal and HAZ is important from the standpoint of securing the required brittle fracture toughness (Kc) of 2-electrode VEGA welded joints.[4] Formerly, it was considered that there was a certain correlation between the value of Kc and the Charpy absorbed energy. However, as shown in **Fig. 3**, it was found that in the case of EH47 steel joints obtained by welding with a high heat input, when
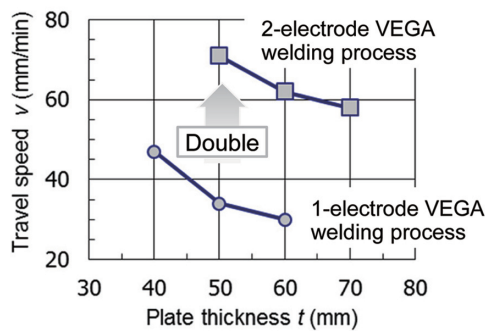
Fig. 2 Comparison of travel speed with single- and two-electrode VEGA welding process
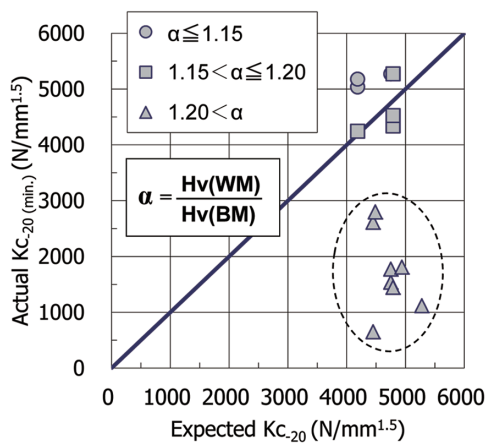

Fig. 3 Dependency of actual brittle fracture toughness (Kc) for EH47 steel welds on the ratio of weld metal to base metal tensile strength α

the hardness (strength) ratio (α) between the weld and base metals exceeds 1.2, the actual fracture toughness becomes much lower than the fracture toughness estimated from the Charpy absorbed energy.

An FEM analysis of the above phenomenon suggested that the value of Kc of welded joint decreased as the local stress in the bond increased. As a result, an innovative new concept was derived, that is, setting an upper limit to weld metal hardness (strength) applicable to EH47 steel in order to secure the required fracture toughness of joints. This concept is reflected in NSSW EG-47T [5]—a welding material developed for 2-electrode VEGA welding of EH47 steel plate. Namely, through optimization of hardenability and effective use of fine acicular ferrite, the welding material has made it possible to secure the required Kc value of welded joints by keeping the weld metal hardness low while retaining adequate strength and toughness required of welded joints.

4. Development of a High-Efficiency Welding Technology with High Heat Input

Steel structures which are newly constructed in diverse fields are increasing in scale. Accordingly, steel plates used for them are increasing in thickness. In multi-pass welding of thicker plates, the number of passes increases markedly, lengthening the welding time and increasing the possibility of slag inclusions and other welding defects. As mentioned in the preceding section, for EGW using the one-pass vertical welding method, the two-electrode VEGA welding process is applied to thick plates for shipbuilding. The maximum
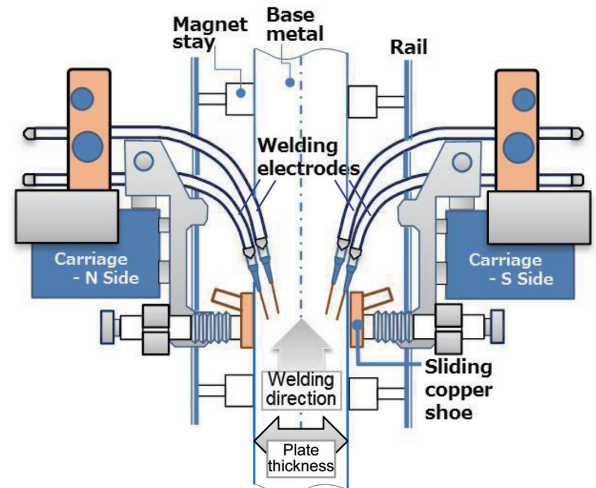

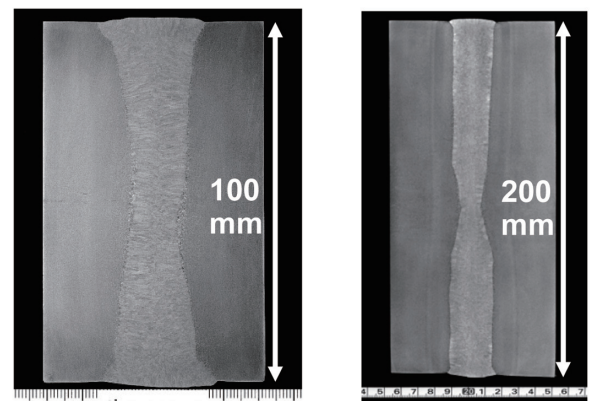Fig. 4 Schematic diagram of four-electrode VEGA welding process

Fig. 5 Macrostructure of welds 100 mm and 200 mm thick with four-electrode VEGA welding process

thickness of plates to which the two-electrode process is applicable is 80–90 mm. For high-efficiency welding of thicker plates in the range 100–200 mm, the four-electrode VEGA welding process has been developed.

As shown in **Fig. 4**, the four-electrode VEGA welding process employs two electrodes at the front and back surfaces of the plate that function as one-half of the plate thickness. By selecting a suitable root opening and root face, a passage for the molten weld metal is provided along the plate center to prevent lack of fusion. **Figure 5** shows macrostructures of welded joints 100 and 200 mm thick. Even in one-pass welding of a 200-mm-thick plate, a good through-thickness penetration with no welding defects is obtained.

We consider that in the future the new welding technology described above will be used for high-efficiency welding of extra-thick plates for large steel structures.

5. Welding Materials for Low-Temperature Steel Plates

More and more crude oil is being drilled in cold regions, such as the North Sea and the Arctic Ocean. In recent years, therefore, the demand for steel plates having superior low-temperature toughness has become increasingly strong. When using a steel structure in a cold region, it is extremely important to secure adequate toughness

of the weld metal, as well as the base metal, from the standpoint of avoiding a brittle fracture of the steel structure. The most important thing to do to secure the desired low-temperature toughness of weld metal is refine the microstructure of the weld metal. In the 1980s, intragranular transformation technology [6–8] using nonmetallic micro-inclusions (e.g., oxide of Ti) as ferrite nucleation site was established. Since then, as the microstructure of high-toughness weld metals not exceeding 590 N/mm² in strength, fine acicular ferrite has been mainly used. Since acicular ferrite is characterised by large-angle boundaries between the ferrite grains, it effectively reduces the fracture facet in the propagation of a fracture. Therefore, it can offer a high-toughness weld metal.

By applying the intragranular transformation, a high-toughness welding material (NSSW Y-3Ni × NSSW NB-55LS) has been developed.[9] With it, for example, in submerged arc welding with a high heat input (10 kJ/mm), the 2 mm V-notch Charpy absorbed energy at −70°C exceeds 100 J. This welding material is applied to multipurpose LPG carriers.[10] In addition, as shown in **Fig. 6** and **Table 2**, covered electrode having good crack arrestability at −50°C and applicable to LPG tanks have been developed.[11]

6. Welding Materials for High-Tensile Steel Plates

In the field of construction equipment, the use of steels having higher strength has been ever increasing. Namely, there is an on-going shift from a steel having a tensile strength (TS) of 590 N/mm² to a TS 780 N/mm² steel (WEL-TEN™780) to a TS 950 N/mm² steel (WEL-TEN950) or TS 980 N/mm² steel (WEL-TEN980).

Unlike weld metals whose tensile strength is 590 N/mm² or under, weld metals having a tensile strength of 780 N/mm² or over cannot secure the prescribed strength with a microstructure consisting mainly of acicular ferrite. Therefore, their microstructure must

Test temperature: − 50°C, Heat input: 2.4 kJ/mm
$\sigma = 329$ MPa: σy (SLA365) × 0.9

Fig. 6 Fracture surface after duplex ESSO test [11]

Table 2 Summary of duplex ESSO test [11]

Applied stress (MPa)	Arrested crack length (mm)	Kca (MPa m$^{1/2}$)	Result
329	248	327	Arrest (no go)

consist mainly of fine-grain bainite. In order to secure both high strength and high toughness, it is important not only to refine the weld metal microstructure but also to reduce the concentration of oxygen in the weld metal.
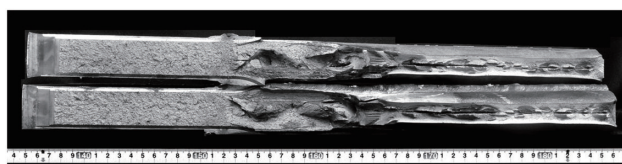
As welding materials for the above high-tensile steels, especially 950 N/mm² and 980 N/mm² steels, the covered electrode (NSSW L-100EL), submerged arc welding wire and flux (NSSW Y-100 × NSSW NB-270H), and solid wire for gas shielded arc welding (NSSW YM-100A) have been developed. **Table 3** shows examples of strength and toughness of weld metals. It can be seen that all the weld metals have not only the required strength but also good low-temperature toughness.[12]

As a welding material for gas shielded arc welding of a 780 N/mm² steel plate, NSSW SF-80A—a flux-cored wire (FCW)—has been developed.[13] This welding material not only offers good all-position weldability and welding efficiency, which are general characteristics of flux cored wires. It also has the advantageous features of the seamless flux-cored wires of Nippon Steel & Sumikin Welding.

The ordinary flux-cored wire is a wire having a certain flux filled inside its outer metallic sheath that has a seam (gap). In the case of a seamless flux-cored wire, the gap is eliminated by electric welding in the manufacturing process, thereby allowing for high-temperature dehydrogenation treatment and wet-type surface treatment (e.g., copper plating). All this imparts several advantages to the seamless flux-cored wire—excellent resistance to moisture absorption and rust; weld metal of extra-low hydrogen concentration; good wire targetability. Nippon Steel & Sumikin Welding is the only manufacturer of seamless flux-cored wires in Japan. NSSW SF-80A allows reduction of the hydrogen concentration of weld metal through high-temperature dehydrogenation, thereby making it possible to lower the preheating temperature.

7. Welding Materials for Structural Steels

Nippon Steel & Sumitomo Metal's fire-resistant structural steels (NSFR™ Series) are steel products that guarantee a minimum yield strength of about 2/3 that of the specified yield strength at normal temperature (F value) even at a temperature as high as 600°C. By specifying the yield strength of a specific structural steel at a certain high temperature, it becomes possible, for example, to simulate the conditions of a fire of a steel structure (e.g., drive-in parking garage) and, depending on design conditions, to plan a steel construction without fireproof covering. For fire-resistant structural steels, welding materials appropriate for various welding methods (SMAW, GMAW, FCAW, SAW, ESW (electro-slag welding)) have been developed and put on the market. **Table 4** shows examples of the mechanical properties of weld metals of 490 N/mm² fire-resistant steel (NSFR490) obtained by GMAW and FCAW, respectively.[14] At

Table 3 Properties of welding consumables for TS 950 N/mm² steel plates

Welding process	Welding consumables product names	Wire dia.	Preheat temp.	Heat input	Tensile properties		CVN properties	y-groove weld cracking test	
					0.2%PS	TS	vE-40°C	Heat input	Critical preheat temperature
		(mm)	(°C)	(kJ/mm)	(N/mm²)	(N/mm²)	(J)	(kJ/mm)	(°C)
SMAW	NSSW L-100EL	4.0	100	1.7	919	980	62	1.7	100
SAW	NSSW NB270H × NSSW Y-100	–	100	3.4	892	997	93	3.5	100
GMAW	NSSW Y-100A	1.2	120	1.8	889	1 019	52	1.7	75

Table 4 Properties of welding consumables for fire-resistant steel plates

Welding consumables	Wire type	Shielding gas	Plate thickness	Wire dia.	Heat input	Tensile properties				CVN properties
						Room temperature		600°C		
						YP	TS	YP	TS	vE 0°C
			(mm)	(mm)	(kJ/mm)	(N/mm²)	(N/mm²)	(N/mm²)	(N/mm²)	(J)
NSSW YM-50FR	Solid	100% CO₂	40	1.4	2.9	584	660	446	541	111
NSSW SF-50FR	FCW	100% CO₂	20	1.4	1.8	564	621	297	337	59
NSSW SM-50FR	FCW	100% CO₂	20	1.6	2.2	604	666	337	366	86

600°C, all the weld metals show a yield strength well over 2/3 of the F value of the steel. Their 2 mm V-notch Charpy impact characteristics at 0°C are also good.

8. Welding Materials for Corrosion-Resistant Steels

8.1 Welding materials for S-TEN™1

S-TEN 1 is a low-alloy corrosion-resistant steel having superior corrosion resistance to sulfuric acid and hydrochloric acid. In order to make the most effective use of the advantageous characteristics of S-TEN 1, it is desirable to use an exclusive welding material to make the corrosion resistance of welded joints equal or superior to that of the base metal. **Table 5** shows the chemical composition[15] of a weld metal obtained by using NSSW SF-1ST—a flux-cored wire exclusive for S-TEN 1. Since NSSW SF-1ST does not contain large amounts of alloying elements, such as Cr and Ni, it seldom causes cold and hot cracking.

First, test pieces were collected from a welded joint obtained by welding S-TEN 1 with NSSW SF-1ST and from a reference welded joint obtained by welding SS400 steel plate with NSSW SF-1—an ordinary flux-cored welding wire. Then, they were immersed in hydrochloric acid (10.5%, 80°C) and sulfuric acid (20%, 40°C), respectively, for 24 hours. Cross sections of the test pieces observed after immersion in hydrochloric acid and sulfuric acid, respectively, are shown in **Figs. 7** and **8**.[15] From those results, it can be seen that NSSW SF-1ST is equal or superior to the base metal in resistance to both hydrochloric acid and sulfuric acid. In addition to NSSW SF-1ST, covered electrode NSSW ST-16M, TIG welding wire NSSW YT-1ST, and submerged arc welding wire and flux NSSW Y-1ST × NSSW NB-1ST are available as welding materials exclusive for S-TEN 1. It is expected that the application of these welding materials in corrosive environments with a high concentration of chloride ions will further expand in the future.

8.2 Welding materials for NSGP™-1

The NSGP-1 corrosion-resistant steel for crude oil tanker bottom plate has not only good weldability and workability but also excellent corrosion resistance more than five times that of conventional steel plates, without painting.[16] NSSW SF-1 GP and NSSW SM-1F GP—flux-cored wires made by Nippon Steel & Sumikin Welding—are welding materials exclusive for NSGP-1. Taking advantage of the seamless type of flux-cored wires, they allow for high-efficiency welding, reduction of fumes and spattering, and lowering of hydrogen concentration of weld metal. In addition, the weld metals have corrosion resistance comparable to that of the base metal.

9. Solution Technology Using Welding Materials and Analysis for Technological Foundation

9.1 Low-temperature transformation welding materials

Nippon Steel & Sumitomo Metal has developed the FCA (Fatigue Crack Arrester) steel that restrains the propagation of fatigue

Table 5 Chemical compositions of weld metal with NSSW SF-1ST[15]

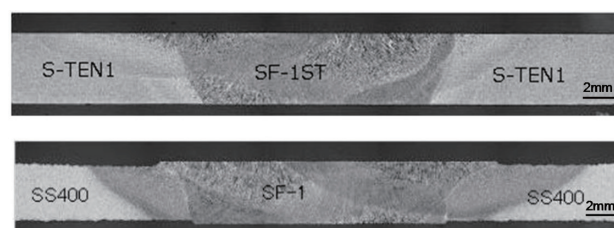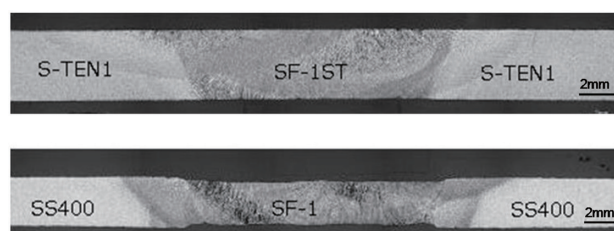| Welding consumables	Product name	Chemical compositions (mass%)						
		C	Si	Mn	P	S	Cu	Sb
FCAW	NSSW SF-1ST	0.05	0.60	1.41	0.012	0.013	0.39	0.10

Fig. 7 Cross section of welded joints after 24 hours immersion in HCl 10.5% 80°C

Fig. 8 Cross section of welded joints after 24 hours immersion in H₂SO₄ 20% 40°C

cracks, UIT (Ultrasonic Impact Treatment) technology that applies a compressive residual stress to welded steel members by means of an ultrasonic treatment, and the LTT (Low Transformation Temperature) welding material that applies a compressive residual stress to the weld metal utilizing the behavior of transformation. These are used singly or in combination to propose solution technology for improving the fatigue life of steel products. With ordinary welding materials, the transformation starts and ends at high temperatures and hence a tensile residual stress occurs in the weld metal and weld toe because of a thermal shrinkage after the welding. Therefore, a fatigue crack in the weld metal tends to occur easily. On the other hand, the LTT welding material lowers the transformation start temperature of the weld metal by alloy adjustment so as to allow the compressive stress occurring during the transformation expansion to remain even after the temperature is lowered to room temperature. Thus, a compressive residual stress is applied to the weld metal to improve its fatigue characteristic.[17]

An example of improvement of fatigue characteristic by the LTT welding material[18] is discussed below. **Figure 9** shows a test piece

of a corner boxing welded joint. Corner boxing welding is subject to a marked stress concentration and can determine the fatigue strength of the entire welded structure. After the corner boxing welding, the test piece was subjected to additional bead welding with an LTT welding material to evaluate the effect of the LTT welding material on the fatigue strength of the weld metal. As the LTT welding material, 10% Ni-added covered electrode NSSW N-19 (transformation start temperature: 350°C) was used.

Figure 10 shows the results of a fatigue test. When no fatigue cracks occurred after 5 000 000 cycles of loading, it was assumed as the fatigue limit. From the figure, it can be seen that the LTT welding material dramatically improved the fatigue limit, especially on the low-stress side, by two classes in the JSSC Classification. Thus, the LTT welding material can effectively be applied to the toes of weld where fatigue cracks tend to occur easily. For example, applying it as an additional bead to the toe of the top layer of weld in multi-pass welding is easy and economical. In addition, it can be expected that the optimum combination of LTT and UIT technology
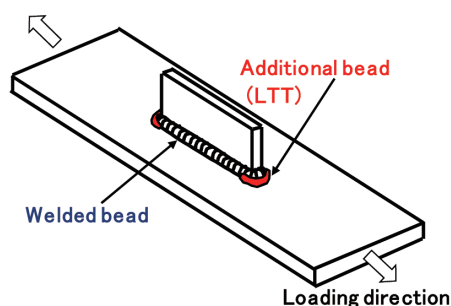

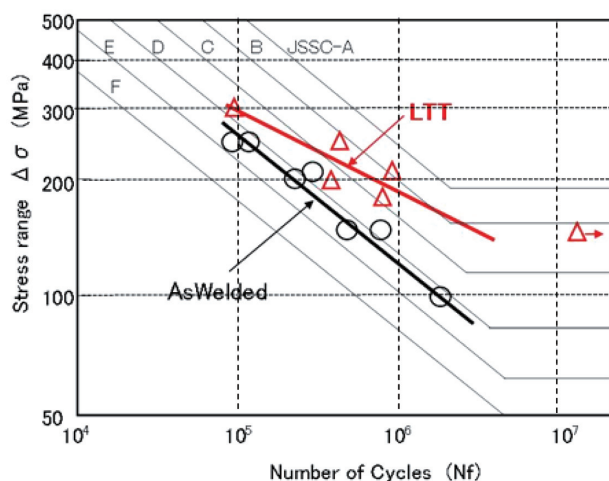**Fig. 9 Fatigue test specimen of welded joint**

Fig. 10 Results of fatigue tests

will produce a dramatic effect.[19]

As applicable welding materials, the covered electrode (NSSW N-19) and flux-cored wire (NSSW SM-10N) are used for gas shielded arc welding. The main alloying element used in them is only 10% of Ni. Compared with other similar welding materials, they have high toughness and excellent weldability. The application thereof to steel bridges, etc. is now being studied in earnest.[20]

9.2 Indexes used to estimate preheating temperature for preventing cold cracking and cold cracking sensitivity of Cu precipitation-hardened 780 N/mm² high-tensile steel

In a broad sense, the term "weldability of steel plate" embraces all the characteristics of the weld zone, including the mechanical properties. In a narrow sense, however, it refers to the hardness and cold cracking sensitivity of the heat-affected zone (HAZ). In general, P_{CM}, carbon equivalent (CEN), and so on are used as indexes of weldability. In the case of high-tensile steels, the higher the tensile strength, the larger the proportion of alloying elements. Namely, with the increase in tensile strength of steel, the values of P_{CM} and CEN of the steel become larger. In order to prevent the occurrence of cold cracking in a steel plate having higher tensile strength, therefore, it is necessary to preheat the steel plate at a higher temperature. For CEN, in particular, a technique to predict the preheating temperature required for preventing cold cracking has been established based on relevant data obtained by subjecting various types of steel to the y-groove weld crack test specified in JIS Z 3158.[21]

Employing the TMCP (Thermo Mechanical Control Process) technology, Nippon Steel & Sumitomo Metal has developed many steel products that have both high strength and good weldability by controlling the contents of alloying elements properly. In particular, the Cu precipitation-hardened 780 N/mm² high-tensile steel (hereinafter simply referred to as the Cu-precipitated steel) has an exceptionally low sensitivity to cold cracking, whereas its tensile strength is as high as 780 N/mm². The excellent weldability of this steel cannot be explained in terms of the conventional carbon equivalent (P_{CM}, etc.).[22]

However, the secret has been disclosed by a recent study. The Cu-precipitated steel contains 1% Cu. The precipitation hardening by Cu is utilized to increase the strength of the base metal while keeping the carbon content low. **Table 6** shows the chemical composition of the Cu-precipitated steel (780 N/mm² steel), together with the chemical compositions of reference steel products—Steel A utilizing the precipitation hardening by Cr or Mo carbide and Steel B applying mainly the dislocation hardening of martensite. In the table, "*p*" signifies the rate of hydrogen escape from the trap site at 273 K in the following McNabb & Foster formula[23] (Equation 1). The values of *p* shown here were calculated from the results of measurement of hydrogen diffusion by the thermal desorption process applied to simulated thermal cycle test pieces near the fusion line and the base metals of the three types of steels. Compared with the two reference steels, the value of *p* of the Cu-precipitated steel is larger in the neighborhood of the fusion line and is smaller in the

Table 6 Chemical compositions of materials used and *p* factor of fusion line and base metal

Material	Chemical compositions (mass%)									$p \times 10^{-5}$	
	C	Si	Mn	Cu	Ni	Cr	Mo	V	P_{CM}	Fusion line	Base metal
Cu precipitation steel	0.06	0.25	1.33	1.17	1.47	0.60	0.43	0.036	0.28	4.45	1.96
Steel A	0.11	0.24	0.85	0.17	–	0.78	0.42	0.031	0.24	2.55	2.42
Steel B	0.18	0.25	1.52	–	–	0.45	–	–	0.29	2.24	12.2

base metal. Since p signifies the speed with which hydrogen escapes from its trap site, the larger value of p implies the smaller hydrogen trapping effect, or the speedier hydrogen diffusion.

Namely, in the base metal of the Cu-precipitated steel, the diffusion of hydrogen is delayed by the hydrogen trapping effect of precipitated Cu, whereas in the HAZ near the fusion line where cold cracking tends to occur most easily, the precipitated Cu returns into solid solution, causing the hydrogen trapping effect to decline and the hydrogen diffusion rate to increase. Thus, when compared with the two reference steels (tensile strength: 780 N/mm^2), the Cu-precipitated steel shows a higher hydrogen diffusion speed near the fusion line. Since the hydrogen diffused into the base metal is trapped by the precipitated Cu, the hydrogen concentration in the HAZ near the fusion line tends to decrease. This is advantageous from the standpoint of preventing cold cracking.[24] The technology incorporated in the Cu precipitation-hardened 780 N/mm^2 high-tensile steel is applied to Nippon Steel & Sumitomo Metal's high-performance steel for bridge SBHS 700 (JIS G 3140), structural steel BT-HT630, etc.

$$\frac{\partial c}{\partial t} + N \frac{\partial \theta}{\partial t} = D\nabla^2 c, \qquad \frac{\partial \theta}{\partial t} = kc - p\theta \qquad (1)$$

Where, c denotes the concentration of free hydrogen; D, the coefficient of hydrogen diffusion when there are no trap sites; N, the trap site concentration per unit volume; k, the speed with which hydrogen is trapped; p, the speed with which hydrogen is released from trap site; θ, the proportion of trap site capturing hydrogen atoms; and t, the elapsed time.

10. Conclusions

It is considered that the performance requirements of steel plates will become increasingly severe in the future. In order for us to be able to continue proposing the optimum welding materials and processes that permit making the most effective use of the functions of steel plates, we press ahead with the development of new welding materials and processes, as well as new steel plates. In addition, in order to ensure that the customer can use our steel plates with the feeling of complete safety and satisfaction, we intend to continue making strenuous efforts to propose total solutions embracing advanced new welding materials and welding technologies.

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