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New Weathering Steels of Extremely-Low Carbon Bainitic Type with Excellent Weldability

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An extremely-low carbon bainitic steel with a C content of approximately 0.02mass% has been successfully advanced to new types of weathering steels for rural and coastal uses. The steels can be manufactured up to TS 570MPa grade by an as-rolled process and exhibit excellent weldability. Because of the extremely-low C content, the maximum hardness values for heat affected zone (HAZ) are about 270 in Vickers number even under arc-strike conditions, and the Charpy impact energy at a large heat input of up to 20kJ/mm is sufficiently high. The weathering corrosion resistance of the steel for rural use, which meets the chemical composition of JIS SMA570W specification, is similar to that of the conventional one. The steel for coastal use with a higher Ni content of 2.5mass% formed a protective rust layer after long-term exposure in coastal regions. The rust layer consisted mainly of amorphous rust and the corrosion rate of the steel decreased remarkably. The steel can exhibit excellent performance even in coastal regions where the conventional one could not be used.

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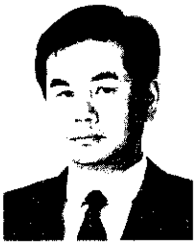
New Weathering Steels of Extremely-Low Carbon Bainitic Type with Excellent Weldability*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1 Introduction

A weathering steel (JIS G 3114) forms a dense protective rust layer on the surface in an atmosphere and the corrosion rate is reduced to an extremely low level. Unpainted steel bridges fabricated from weathering steel do not require initial painting or re-painting. This contributes to reducing the life cycle cost (LCC)[1]. For this reason, the percentage at which weathering steel is used for steel bridges has tended to increase. A survey by the Kozai Club indicated that 600 thousands to 700 thousands tons of steel is used annually for constructing steel bridges in Japan, of which weathering steel accounted for approximately 15% in 1999.

In coastal regions where airborne salinity content is high, conventional weathering steel on the present market sometimes does not develop a sufficient protective rust layer, and the corrosion rate is not suppressed[2]. Accordingly, guidelines issued in 1993 by the Public Works Research Institute of the Ministry of Construction in Japan restricted the unpainted use of weathering steel in coastal regions[3]. In recent years, the similar problems have been reported even in non-coastal regions where a large amount of road deicing salt is used in winter[4].

Further, some problems described below remain with regard to so-called rationally-designed bridges, that are composed of a smaller number of beams and are constructed by whole field welding. Although the smaller number of beams requires thicker and higher strength steels. Strengthening of steel by means of increasing C and alloy element contents leads to increased cold-cracking susceptibility, higher weld heat affected zone (HAZ) hardening, and reduced HAZ toughness from welding with high heat input.

Extremely-low carbon bainitic steel[5] was investigated to relax the restrictions imposed on the use of conventional weathering steel due to limitations in its weldability and resistance to chlorides. This induced the development of new weathering steels for rural and coastal uses. The characteristics of these newly-developed steels are described in this article.

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2 Improvement of Weldability and Resistance to Chlorides

2.1 Weldability

In order to improve the weldability, bainitic steels with extremely low carbon content[5] were developed that provide the required base metal strength in the as-rolled condition even though their carbon content is extremely low. **Figure 1** shows the relationship between the weld cracking parameter Pcm, plate thickness, and preheating temperatures for two types of 570 MPa level tensile strength steel plates that are used for bridges: an extremely-low carbon bainitic steel and a conventional quenched-and-tempered (Q–T) steel[6]. Since the extremely-low carbon bainitic steel can be produced with Pcm that is significantly-lower Pcm than that of the conventional steel over a wide range of thickness, the steel does not need to be preheated for welding.

2.2 Resistance to Chlorides

A number of reasons have been proposed to explain why the protective rust layer is not formed in coastal and other environments that contain high concentrations of chlorides. These include: (1) acceleration of corrosion by deliquescence of chlorides[7,8], (2) crystallization (coarsening) of rust[9,10], (3) enrichment of Cl at the interface between the rust layer and metal substrate[11], and (4) accelerated formation of Fe_3O_4 and β-FeOOH[12]. Based on the idea that the resistance to chlorides could be improved by restricting the effects of chloride compounds, the effects of various alloying elements on the resistance to chlorides were investigated.

2.2.1 Seawater spray test

Elements such as Ni, Cu, Cr, Mo, and P are considered to be effective for enhancing the resistance to chlorides. Extremely-low carbon bainitic steels were produced by adding these elements. The steel samples were then subjected to seawater spray tests (seawater sprayed for 1 h twice a week) to evaluate the effects of these elements on the corrosion rate of steels. The addition of Ni was found to be the most effective for minimizing the corrosion rate of steel. **Figure 2** shows the relationship between the duration of the seawater spray tests and the corrosion loss for conventional weathering steel and extremely-low carbon bainitic steels as a parameter of Ni content. The corrosion loss for extremely-low carbon bainitic steel with 1.0 to 2.5 mass% Ni was less than that of the conventional weathering steel. The corrosion loss decreased with an increase in Ni content. With a Ni content of 2.5 mass% the corrosion loss was approximately 15% of that of the conventional weathering steel after two years of testing. The corrosion rate also became sufficiently low, indicating that the rust was transformed into a stable state. Thus, for improving the resistance to chlorides the addition of 2.5 mass% or more Ni content was found to be effective.

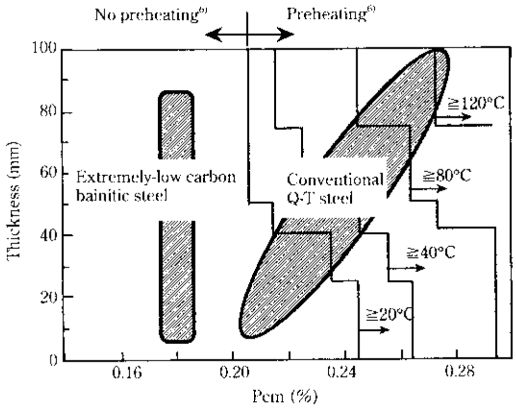


Fig. 1 Relationship between thickness, Pcm and the preheating temperature for extremely-low carbon bainitic and conventional Q-T steels

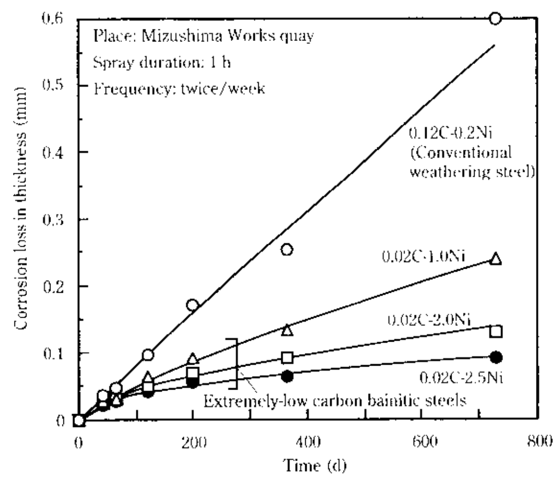


Fig. 2 Corrosion loss in thickness vs. time curves as a parameter of Ni content for extremely-low carbon bainitic steels and the conventional weathering steel, based on seawater spray tests

2.2.2 Structural analysis of rust layers

Based on the results described in Section 2.2.1, samples of conventional weathering steel and extremely-low carbon bainitic steel containing 2.7 mass% Ni (0.02C-2.7Ni steel) were subjected to exposure tests in Okinawa where airborne salinity was 0.8 mdd, for 1 year, and the resultant rust layers were then analyzed.

Photo 1 shows cross-sections of the rust layers observed under reflected polarized light. The dark rust layer formed underneath the bright rust layer is considered to be effective for preventing corrosion. However, in the conventional weathering steel, the dark rust layer is split by the bright rust layer that reached the metal substrate at considerably many sites. On the other hand, in the 0.02C-2.7Ni steel, the bright rust layer was com-

Table 1 Constituents of iron rusts for the 0.02C-2.7Ni steel and conventional one exposed in Okinawa for 1 year

(mass%)

	α-FeOOH	β-FeOOH	γ-FeOOH	Fe_3O_4	X-ray amorphous rust
0.02C-2.7Ni steel	14.4	2.4	15.6	0.6	67.0
Conventional weathering steel	14.5	2.7	26.1	0.9	55.8

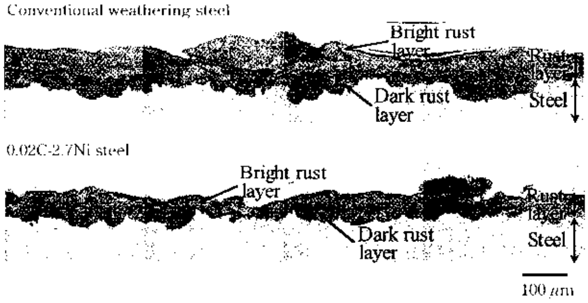


Photo 1 Observation of cross sections of the rust layers formed on the 0.02C-2.7Ni and the conventional weathering steels exposed in Okinawa for 1 year

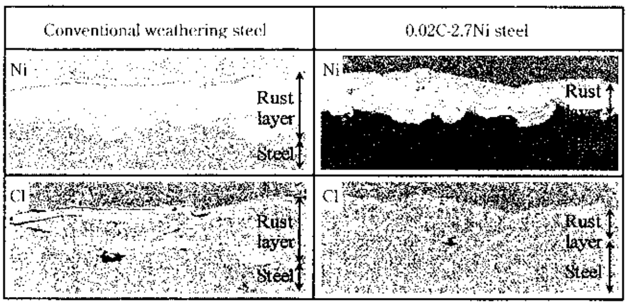


Photo 2 Distributions of Ni and Cl in rust layers formed on the 0.02C-2.7Ni and the conventional weathering steels exposed in Okinawa for 1 year

paratively thinner, and the dark rust layer covered the metal substrate almost throughout.

Photo 2 shows the distributions of Ni and Cl in the rust layers as measured by EPMA. In the conventional weathering steel, Cl was present at the rust-metal interface over a considerably wide area. On the other hand, in the 0.02C-2.7Ni steel, the presence of Cl in the rust layer was extremely rare. In addition, Ni was more densely present than in the conventional weathering steel and it was uniformly distributed over the entire dark rust layer.

Table 1 shows the constituents of rust for the conventional weathering steel and 0.02C-2.7Ni steel as measured by X-ray diffraction quantitative analysis using ZnO as the internal standard[13]. The majority of the rust in both the conventional weathering steel and the 0.02C-2.7Ni steel was amorphous by X-ray analysis. However, the ratio of the amorphous rust was approximately 10% higher in the 0.02C-2.7Ni steel than in the conventional

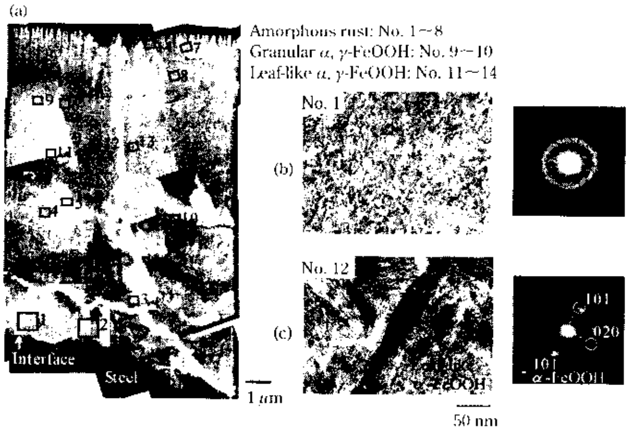


Photo 3 TEM images and electron diffraction patterns of rust layer formed on the 0.02C-2.7Ni steel exposed in Okinawa for 1 year

weathering steel. The X-ray amorphous rust percentage was obtained by subtracting the crystalline rust percentage from 100 mass%.

In order to investigate the microstructure of the dark rust layer adjacent to the rust-metal interface, thin-film specimens of cross-section of the rust layer were prepared by using the focused ion beam (FIB) technique and observed in detail by means of a TEM. **Photo 3** shows the results of TEM observation for the 0.02C-2.7Ni steel specimen. The regions marked by open squares with black lines in Photo 3 (a) were observed under high magnification, and diffraction patterns were also measured in the same regions. Examples are shown in Photos 3 (b) and 3 (c). The rust layer was found to have three types of regions: (1) regions (Nos. 1-8) mainly composed of amorphous rust, as shown in Photo 3 (b), (2) regions (Nos. 9, 10) mainly composed of fine granular grains, and (3) regions (Nos. 11-14) mainly composed of leaf-like grains of coarse α-FeOOH and γ-FeOOH, as shown in Photo 3 (c). Although these three types of region were also observable in the conventional weathering steel, the percentage of the area composed primarily of amorphous rust was approximately 20% higher in the 0.02C-2.7Ni steel than in the conventional weathering steel.

The results of the analysis are summarized as follows. In the rust layer of the 0.02C-2.7Ni steel, (1) the dark rust layer covering the metal substrate was more continuous, (2) Ni was densely present and uniformly distributed in the dark rust layer, (3) the dense rust composed mainly of amorphous rust was present at a higher percentage, and (4) the smaller amount of Cl was present at the rust-metal interface. Accordingly, the 0.02C-2.7Ni steel is considered to have superior characteristics for resisting chlorides because the dark rust layer, which is a dense layer of mostly amorphous rust with an uniform distribution of Ni, prevents Cl from penetrating to the surface of the metal substrate.

3 Characteristics of Developed Steel

Based on the above described findings, two types of extremely-low carbon bainitic weathering steel were developed: one for rural use and the other for coastal use. Their characteristics are described below.

3.1 Chemical Compositions

Table 2 shows chemical compositions of the newly-developed rural and coastal weathering steels. The new weathering steel for rural use contains Ni, Cu, and Cr as alloying elements to increase the weathering resistance and conforms to the chemical composition specified by JIS G 3114. The new weathering steel for coastal use contains 2.7 mass% Ni to improve the resistance to chlorides, as described in Section 2.2, and steels with strength levels of 400, 490, and 570 MPa were produced mainly by varying the Mn content.

3.2 Mechanical Properties of Base Metal

Steel plates with thicknesses of 25-75 mm were produced in the as-rolled condition from slabs with the chemical compositions shown in Table 2. Their mechanical properties are listed in **Table 3**. The new weathering steel for rural use satisfied the mechanical property requirements of JIS SMA570W at both the 25 and 75 mm in thickness. The coastal steels satisfied the mechanical property requirements for JIS SMA400CW, 490CW, and 570W at both 25 and 50 mm in thickness.

3.3 Weld Cracking Susceptibility

The new 570 MPa grade weathering steels for rural and coastal uses were subjected to maximum hardness tests (JIS Z 3101) under the arc-strike welding condition of JIS Z 3115. **Figure 3** shows the results of the tests along with those for the conventional Q-T steel. The maximum Vickers hardness values of the new weathering steels for rural and coastal uses were 265 and 275 points, respectively. These values are significantly lower than 350 points, which is generally accepted as the upper limit of HAZ hardness for preventing weld cracking. The results suggest that these newly-developed steels have superior weldability, futhermore indicate that

Table 2 Chemical compositions of new weathering steels

(mass%)

Steel	Grade	C	Si	Mn	P	S	Cu	Ni	Cr	Ceq	Pcm
Rural use steel	570 MPa	0.02	0.32	1.37	0.011	0.004	0.49	0.24	0.51	0.37	0.16
Coastal use steel	400 MPa	0.02	0.29	0.30	0.011	0.002	0.42	2.75	0.02	0.15	0.11
	490 MPa	0.02	0.30	1.02	0.009	0.003	0.38	2.67	0.02	0.27	0.15
	570 MPa	0.02	0.29	0.99	0.011	0.003	0.37	2.70	0.02	0.27	0.15
JIS G 3114 specification	400 MPa	≦0.18	0.15~0.65	≦1.25	≦0.035	≦0.035	0.30~0.50	0.05~0.30	0.45~0.75	—	—
	490 MPa			≦1.40						≦0.41* ≦0.43**	≦0.24* ≦0.26**
	570 MPa									—	—

Ceq = C + Mn/6 + Si/24 + Ni/40 + Cr/5 + Mo/4 + V/14
Pcm = C + Si/30 + Mn/20 + Cu/20 + Ni/60 + Cr/20 + Mo/15 + V/10 + 5B

*Thickness (t): $t \leqq 50$ mm
**Thickness (t): 50 mm $< t \leqq 100$ mm

Table 3 Mechanical properties of new weathering steels

Steel	Grade	Thickness, t (mm)	Tensile properties*: Thickness position	Test piece	YS (MPa)	TS (MPa)	El (%)	V-notch Charpy properties**: Thick. position	Test piece	vE_0 (J)	vE_{-5} (J)	vE_{-20} (J)
Rural use steel	570 MPa	25	Full thickness	No. 5	494	670	29	1/4t	No. 4	—	270	258
		75	1/4t	No. 4	459	615	28	1/4t	No. 4	—	292	299
Coastal use steel	400 MPa	25	Full thickness	No. 1A	395	499	37	1/4t	No. 4	388	—	362
		50	1/4t	No. 4	382	481	37	1/4t	No. 4	397	—	395
	490 MPa	25	Full thickness	No. 1A	447	568	23	1/4t	No. 4	341	—	333
		50	1/4t	No. 4	448	580	33	1/4t	No. 4	357	—	310
	570 MPa	25	Full thickness	No. 5	514	664	30	1/4t	No. 4	—	322	263
		50	1/4t	No. 4	483	629	28	1/4t	No. 4	—	292	261
JIS G 3114 specification	SMA400CW	$16 < t \leqq 40$	Full thickness	No. 1A	≧235	400~540	≧21	1/4t	No. 4	≧47	—	—
		$40 < t \leqq 75$	1/4t	No. 4	≧215		≧23	1/4t	No. 4	≧47	—	—
	SMA490CW	$16 < t \leqq 40$	Full thickness	No. 1A	≧355	490~610	≧19	1/4t	No. 4	≧47	—	—
		$40 < t \leqq 75$	1/4t	No. 4	≧335		≧21	1/4t	No. 4	≧47	—	—
	SMA570W	$16 < t \leqq 40$	Full thickness	No. 5	≧450	570~720	≧26	1/4t	No. 4	—	≧47	—
		$40 < t \leqq 75$	1/4t	No. 4	≧430		≧20	1/4t	No. 4	—	≧47	—

*T-direction, **L-direction

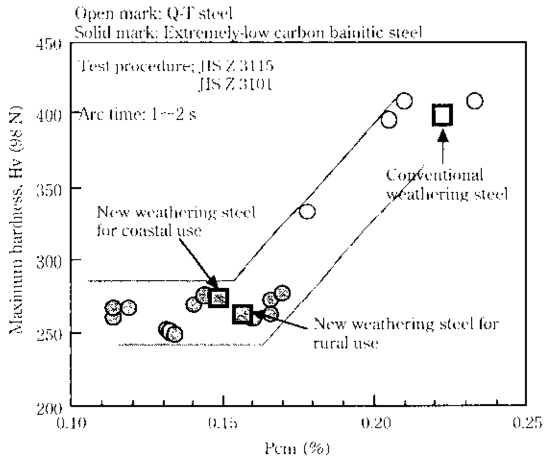


Fig. 3 Effect of Pcm on maximum hardness for 570 MPa grade weathering steels in arc strike welding

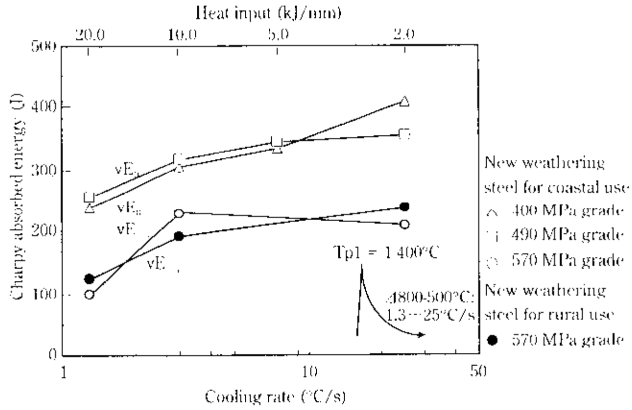


Fig. 4 Effect of cooling rate on Charpy absorbed energy of simulated HAZ

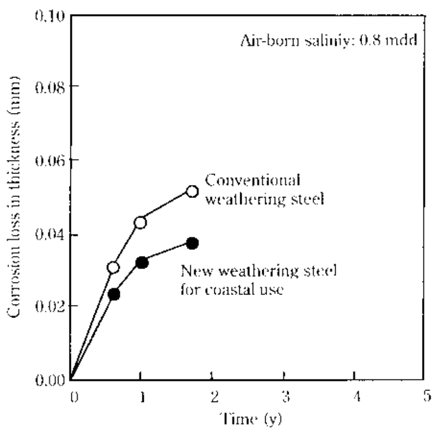


Fig. 5 Corrosion loss in thickness vs. time curves for the new weathering steel for coastal use and conventional one exposed in Okinawa

these steels can also tolerate arc strikes.

The Y-groove weld cracking tests specified by JIS Z 3158 were carried out to evaluate weld cracking susceptibility. The parameters for the tests of the rural use steel were a thickness of 50 mm, the SMAW welding process, a 4.0 mmϕ welding electrode equivalent to JIS Z 3214 DA5816W, operating conditions of 170 A-25 V-2.5 mm/s, and a humidity of 60%. The parameters used for welding the coastal use steel were a thickness of 50 mm, the FCAW welding process, a 1.2 mmϕ, FG-60SSW weld wire operating conditions of 250 A-30 V-5 mm/s, and a humidity of 60%. The crack percentages observed at the surface, root, and section were 0% at 20°C for both types of steel.

3.4 Toughness of Weld Heat Affected Zones

The HAZ toughness was evaluated by heat cycle tests with a peak temperature of 1 400°C. **Figure 4** shows the effects of the cooling rate over a range of 800 to 500°C, along with the estimated heat input, on the Charpy absorbed energy for the simulated HAZ. For both rural and coastal use steels, the Charpy absorbed energy values at the temperature specified by JIS G 3114 exceeded the minimum requirement of 47 J over a heat input range equivalent to 2-20 kJ/mm. These results indicate that high heat input welding up to 20 kJ/mm can be applied with the newly-developed steels.

3.5 Weathering Resistance

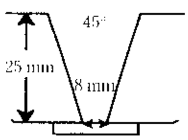
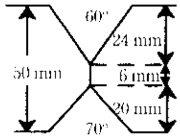
3.5.1 New weathering steel for coastal use

Figure 5 shows the relationship between the duration and the corrosion loss for the new weathering steel for coastal use as tested in Okinawa (airborne salinity: 0.8 mdd). The corrosion loss of the new weathering steel for coastal use after an exposure of one year and nine months was 70% of that of the conventional weathering steel. This result confirms the superior characteristics of the newly developed steel for resisting chlorides. In this exposure test, specimens of the conventional weathering steel developed conspicuous orange rust. On the other hand, dark-brown rust was formed on the new weathering steel for coastal use. The exposure test in Okinawa is still ongoing, and additional exposure tests are being carried out at other sites throughout Japan under different environmental conditions such as airborne salinity.

3.5.2 New weathering steel for rural use

The new rural use steel and the conventional weathering steel showed the same corrosion loss of 0.020 mm after one year of exposure at Kurashiki City. Characteristics of the rust formed on the two steels are similar from the standpoint of continuity of the dark rust layer at the rust-metal interface, the distribution of alloying elements that increase weathering resistance (Cr, Cu, Ni), and the constituents of the rust. These results indicated that the weathering resistance of the new weathering steel for rural use is similar to that of a conventional weathering steel.

Table 4 Mechanical properties of welded joints and welding conditions for evaluation of weld performance of 490 MPa grade new weathering steel for coastal use

Welding method	Welding material	Welding condition		Tensile test*		Side bend test**	V-notch Charpy impact test***		
				TS (MPa)	Position of fracture		Position	vE_0 (J)	vE_{-20} (J)
FCAW	Wire: FG-60SSW (1.2 mmϕ)		· No preheat · Shielding gas: 100%CO_2 · Current: 250 A · Voltage: 30 V · Speed: 3.0 mm/s · Heat input: 2.5 kJ/mm	604	Base metal	Good	Weld metal	82	71
							Bond	105	87
							HAZ1****	130	99
							HAZ3****	315	331
SAW	Wire: KW-60SW (4.0 mmϕ) Flux: KB-SW		· No preheat · Current: 650 A · Voltage: 35 V · Speed: 4.7 mm/s · Heat input: 4.9 kJ/mm	609	Base metal	Good	Weld metal	141	130
							Bond	255	286
							HAZ1****	319	320
							HAZ3****	321	324

*JIS Z 3121 (No. 1A)
**JIS Z 3122 ($R = 2t$)
***JIS Z 3128 (Position: 7 mm below the surface (FCAW), 1/4t (SAW))
****HAZ1: 1 mm from fusion line
HAZ3: 3 mm from fusion line

3.6 Mechanical Properties of Welded Joints

3.6.1 New weathering steel for coastal use

New weld consumables for welding the new weathering steel for coastal applications were newly developed by adding Ni in an equivalent to that in the base metal, because consumables should have similar weathering resistance. Multi-pass FCAW and SAW joints of the new 490 MPa grade coastal weathering steel were prepared using these weld consumables, and the resulting mechanical properties were evaluated. **Table 4** shows the welding conditions and the results of tensile tests, side-bend tests, and Charpy impact tests of the welded joints. The tensile strength of the joints exceeded that of the base metal, and the joints also demonstrated excellent bending property. The toughness of the joints was evaluated by Charpy impact tests with notch locations at the weld metal, fusion line, HAZ 1 mm (1 mm apart from the fusion line) and HAZ 3 mm (3 mm apart from the fusion line). High values of absorbed energy at −20°C were demonstrated at all notch locations.

3.6.2 New weathering steel for rural use

The new weathering steel for rural use can be welded using the same weld consumables for conventional weathering steel. The welded joint was fabricated from 25 mm thick plates using SAW with a double-vee groove. A weld consumable equivalent to JIS Z 3183 S582-AW (4.8 mmϕ) was used at a heat input of 5.0 kJ/mm. The mechanical properties were then evaluated. The tensile strength of the welded joint was 687 MPa, and the toughness was excellent, with values of 210 J for vE_{-5} and 196 J for vE_{-20}. The side-bend test results were also excellent.

4 Conclusion

Two kinds of new types of extremely-low carbon bainitic weathering steels were developed, in which the carbon content was reduced to approximately 0.02 mass% and the characteristics were evaluated. The results are summarized below.

(1) The new weathering steel for coastal use, which contains at least 2.5 mass% Ni, demonstrated a corrosion loss that was 15% compared with a conventional weathering steel after a two-year seawater spray test. The corrosion loss after one year and nine months exposure in Okinawa was 70% of that of a conventional weathering steel. The results of analysis of the rust suggest that the new weathering steel for coastal use has superior resistance to chlorides because of its dark rust layer. This dense layer, which is mainly composed of amorphous rust and contains an uniformly distributed Ni, prevents Cl from penetrating to surface of the metal substrate.

(2) The new weathering steel for rural use satisfies the tensile and toughness requirements of the 570 MPa grade, also the new weathering steels for coastal use satisfy the requirements for 400 MPa, 490 MPa, and 570 MPa grades, all in the as-rolled condition.

(3) The weathering resistance of the new weathering steel for rural use is equivalent to that of conventional weathering steel from a standpoint of corrosion loss and the characteristics of the rust.

(4) Under severe low heat input welding conditions, such as in arc strikes, the new 570 MPa grade weathering steels for rural and coastal uses showed a maximum Vickers hardness of approximately 270 points in the heat affected zone, demonstrating their superior resistance to weld hardening. Furthermore, no cracking was observed in y-groove weld cracking tests at 20°C.

(5) The new weathering steels for rural and coastal uses showed Charpy energy values that exceed the minimum requirement of 47 J in an estimated weld heat inputs range up to 20 kJ/mm, indicating that high heat

input welding up to 20 kJ/mm can be applied.

(6) Two types of new weld consumables for the new weathering steel for coastal use were developed, and multi-pass FCAW and SAW joints were fabricated. Evaluation of the properties of these welded joints revealed excellent strength, toughness, and bending property on the weld.

This development made it possible to produce steel plates that have superior rural and coastal weathering resistance along with excellent weldability. In particular, these plates have outstanding material properties in the as-rolled condition, which shortens the delivery time. These products are expected to provide an important contribution to the reduction of construction and maintenance costs of bridges and other steel structures.

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