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Weldability of Advanced Extremely-low Carbon Bainitic Steel for Thick Plates of 570 MPa Grade through As-Rolled Process*



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1 Introduction

Following the increase in the scale of welded structures due to improved efficiency of welding processes, steel materials are increasingly required to have higher strength, higher toughness, better weldability and superior economy. However, increasing tensile strength by increasing carbon content results in hardening in weld heat-affected zones (HAZ), an increase of the cold cracking susceptibility and deterioration in the toughness. In order to overcome these problems, studies have been in progress to develop low carbon content high strength steel by means of the thermo-mechanical control process (TMCP) combined with controlled rolling and accelerated cooling. However, by means of conventional TMCP technique, it is impossible to make the entire microstructure of a plate from the surface to the center of thickness most suitable due to the cooling rate dependence of the microstructure and it is difficult to apply this technique to thick products exceeding 50 mm in thickness.

With the intention of solving these problems, Kawasaki Steel paid attention to the bainite structure of extremely-low carbon steel, particularly that with a carbon content of about 0.02 mass% or less, as well as to its transformation behavior and has found that it is possible to solve the problems with respect to structure control at the center part of thickness of the above-mentioned thick steel plates and those in HAZ. Thus the company has applied this knowledge to the development of new thick high strength steel products of a 570 MPa grade which can be produced through an as-rolled process.

This paper describes the metallurgical features of this extremely-low carbon bainitic steel together with the properties of the newly developed advanced steel.

2 Special Features of Extremely-low Carbon Bainitic Steel

When the carbon content in steel is limited to 0.02 mass%, the maximum solid-soluble limit to ferrite, carbon partitioning does not occur during $\gamma \rightarrow \alpha$ transformation and an intermediate stage transformation structure different from that of conventional low carbon steel can

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be obtained. This chapter describes the transformation behavior of such extremely-low carbon steel modified to a bainitic single phase structure by adjusting the chemical composition. Changes in the material's properties following this transformation are also described.

2.1 Continuous Cooling Transformation Behavior and Special Microstructure Features

Figure 1 shows the continuous cooling transformation (CCT) diagram with deformation for the extremely-low carbon bainitic steel of 0.016 mass% carbon and 1.58 mass% manganese shown in **Table 1**. The diagram shows a unique transformation behavior where no transformation other than bainite transformation occurs over a wide cooling rate range of 0.13~23°C/s. In addition, except for the case of the highest rate of 23°C/s, the Vickers hardness of structure changes little and falls in the range of 191~221 points. From the fact that the cooling rate for thick plate products under air cooling varies from 2.0°C/s to 0.1°C/s in the case of plate thickness range of 6~100 mm, it is possible to satisfy a strength level equivalent to that of thin steel plates even with thick steel plates of about 100 mm thick and it is possible to reduce scattering in strength due to microstructural changes caused by cooling rate differences within the plate thickness.

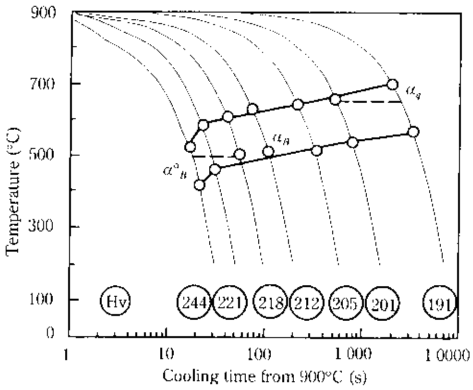
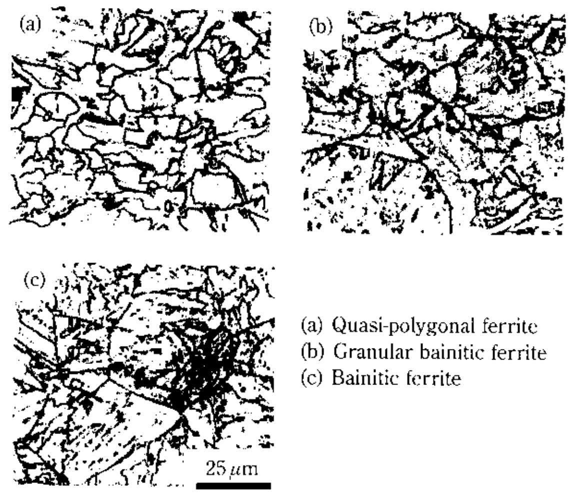


Fig. 1 CCT diagram of extremely-low carbon bainitic steel

Photo 1 shows optical microscopic pictures of typical microstructures. The Bainitic structure of extremely-low carbon steels can be classified, depending on the shape, into quasi-polygonal ferrite (α_q: Photo 1(a)), granular bainitic ferrite (α_B: Photo 1(b)) and bainitic ferrite (α^o_B: Photo 1(c)).[1] When the bainite phases are classified on the CCT diagram with the deformation shown in Fig. 1, granular bainitic ferrite is created over the major portion within a range of cooling rates so that changes in hardness are small. From recent studies on extremely-low carbon bainitic steel, it has been known that the structure of steel attains a superior strength and toughness when the granular bainitic ferrite transforms at lower temperatures.[2] Therefore, by lowering the transformation temperature of granular bainitic ferrite through optimization of alloy element contents, it becomes possible to obtain a steel of high strength and high toughness of 490~570 MPa grades even with extremely-low carbon steel. Furthermore, steel can be made to be of a granular bainitic ferrite structure even with a low cooling rate, for example a rate of 0.1°C/s, therefore, it becomes possible to produce non-heat treated thick steel plates having a thickness of 75 mm or more which could not be produced by means of the conventional TMCP technique.



(a) Quasi-polygonal ferrite
(b) Granular bainitic ferrite
(c) Bainitic ferrite

Photo 1 Examples of microstructures of extremely-low carbon bainitic steel

Table 1 Chemical compositions of steels studied

(mass%)

	C	Si	Mn	P	S	Al	Ti	N	Others	Ceq	Pcm
Extremely-low carbon bainitic steel	0.016	0.32	1.58	0.014	0.003	0.029	0.012	0.002 8	Cu, Ni, Nb, B	0.300	0.144
Conventional TMCP steel (X80)	0.06	0.28	1.82	0.004	0.001	0.034	0.007	0.002 4	Cu, Ni, Nb, V	0.383	0.175
Conventional Q-T steel (SM570Q)	0.12	0.23	1.45	0.014	0.003	0.024	0.014	0.002 1	Cu, Ni, No, V	0.400	0.218

$Ceq = C + Mn/6 + Si/24 + Ni/40 + Cr/5 + Mo/4 + V/14$

$Pcm = C + Si/30 + Mn/20 + Cu/20 + Ni/60 + Cr/20 + Mo/15 + V/10 + 5B$

2.2 Hardenability

In order to confirm that only a little change occurs in the material's properties due to cooling rate dependence of microstructures in HAZ, the maximum hardness in HAZ was tested according to JIS Z 3101 using the extremely-low carbon bainitic steel shown in Table 1. For comparison purposes, the same tests were performed also for conventional TMCP type high strength steel with 0.06 mass% carbon content (X80) and for heat treated conventional steel with 0.12 mass% carbon content (SM570Q). The test results are shown in **Fig. 2**. For the extremely-low carbon bainitic steel, hardly no increase of hardness in HAZ could be recognized even when the test welding bead was short and the Vickers hardness was 268 even with short bead welding with the arc time of 1 s. This hardness is sufficiently low when compared with 330~380 points for conventional steel.

The lath width of the microstructure was measured at the maximum hardness point in HAZ of this extremely-low carbon bainitic steel by means of TEM observation, it was found to be 0.4 nm in average. Okamoto et al. have shown that the lath width of martensite of 0.04 mass% carbon steel is about 0.20 nm and is sufficiently small as compared with the 0.51~0.76 nm for bainite.[3] Therefore, even when the extremely-low carbon bainitic steel transforms at a very high cooling rate such as mentioned above, no martensite is formed and the hardness does not increase.[4]

2.3 Toughness in Weld Heat-Affected Zones

Within HAZ, the toughness in coarse grain HAZ (CGHAZ) in the vicinity of fusion lines deteriorates due to increases of the welding heat input. This is because austenite grains grow coarsely and in the case of conventional steel, the transformation structure is apt to form upper bainite structures containing hard M-A constituents and coarse intergranular ferrite as the cooling rate lowers.[5] In order to investigate the behavior of toughness variation in CGHAZ when welding heat input is changed in the case of extremely-low carbon bainitic steel which shows only a little change in microstructure, a series of Charpy tests were performed using the steel shown in Table 1 after applying heat cycles of various kinds. Namely, the steel was quickly heated up to 1 400°C, the maximum heated temperature one time, and then rapidly cooled down to room temperature corresponding to weld heat input.

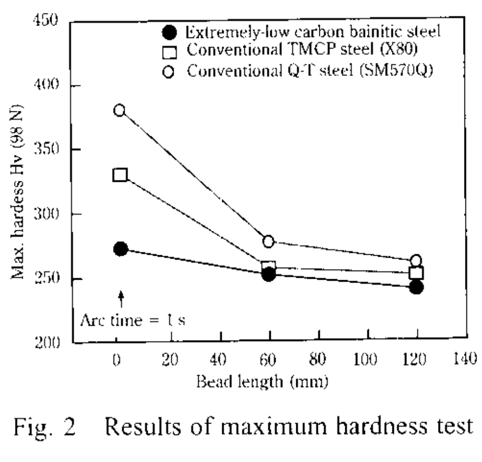


Fig. 2 Results of maximum hardness test

Figure 3 shows the effect of the cooling rate of the heat cycle on −5°C Charpy absorbed energy in synthetic CGHAZ. The absorbed energy of the extremely-low carbon bainitic steel was high and showed more than 200 J when the cooling rate was 25°C/s which corresponds to heat input of 2.0 kJ/mm. Furthermore, high absorbed energy was indicated even for a large estimated welding heat input of 20 kJ/mm.

Photo 2 shows the microstructures of synthetic CGHAZ of extremely-low carbon bainitic steel. For the condition of estimated heat input of 2 kJ/mm, the microstructure was a mixture of bainitic ferrite and

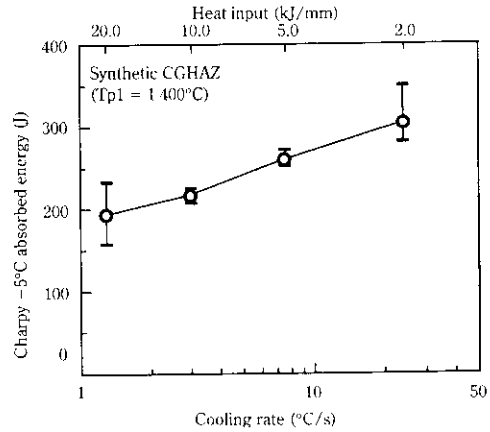


Fig. 3 Effect of cooling rate on Charpy absorbed energy of synthetic coarse grain HAZ (CGHAZ)

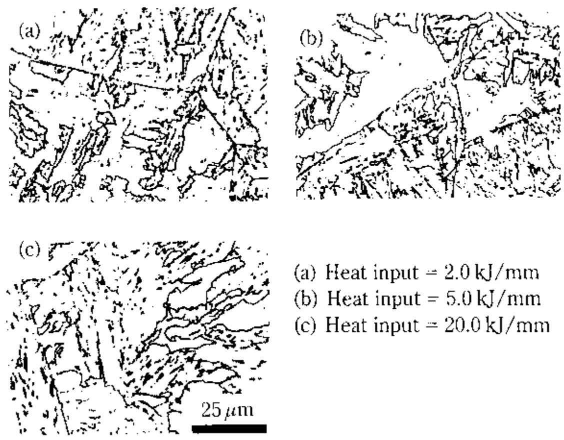


Photo 2 Examples of microstructure of synthetic CGHAZ

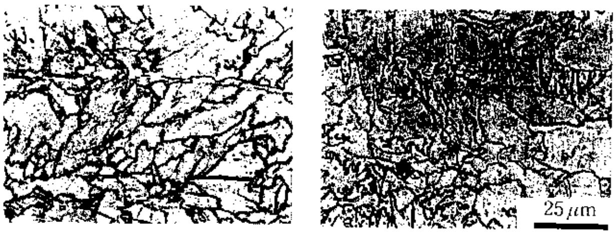
Table 2 Chemical compositions of extremely-low carbon bainitic steel produced

(mass%)

C	Si	Mn	P	S	Al	Ti	N	Others	Ceq	Pcm
0.012	0.30	1.56	0.009	0.003	0.029	0.011	0.0028	Cu, Ni, Nb, B	0.294	0.137

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



75 mmt (1/4 t) 75 mmt (1/2 t)

Photo 3 Examples of microstructure of 570 MPa grade extremely-low carbon bainitic steel

Table 3 Tensile test results of steel plates

Thickness (mm)	Position	Direction	0.2%PS (MPa)	TS (MPa)	El (%)	YR (%)
38	1/4 t	L	459	596	31	77
		T	480	627	30	77
	1/2 t	L	458	591	29	77
		T	485	626	29	77
75	1/4 t	L	470	587	31	80
		T	472	599	29	79
	1/2 t	L	439	576	30	76
		T	458	596	27	77

granular bainitic ferrite in which almost no M-A constituents could be observed. The M-A constituents are presumably the cause for the deterioration of toughness.[6~8)] This microstructure is scarcely affected by any increase of the estimated heat input. Namely, in the case of extremely-low carbon bainitic steel, a bainite structure, in which M-A constituents do not form, is formed also at low cooling rates, therefore, a high Charpy absorbed energy can be obtained in CGHAZ even with a large welding heat input corresponding to 20 kJ/mm.

3 Properties of the Newly Developed Steel

By utilizing the special features of extremely-low carbon bainitic steel explained in the above, it is possible to produce 570MPa grade thick high strength steel plates of 75 mm thick or thicker through an as-rolled process. As typical examples, various properties of 38 mm and 75 mm thick steel plates manufactured to the JIS SM570TMC standard are described in this chapter. These plates were commercially manufactured and were as rolled and cooled.

3.1 Mechanical Properties of Base Metal Plates

The ladle analyses of the newly developed steel are shown in **Table 2**. The C content was adjusted to 0.012 mass%. The Mn content was adjusted to 1.56 mass% so that the JIS SM570TMC standard could be satisfied and doped with Cu, Ni, Nb and B in order to make the material's structure granular bainitic ferrite. Compared with conventional steel of 570 MPa grade, the Ceq and Pcm contents are extremely low, and 0.294% and 0.137% respectively.

The microstructures of 75 mm thick steel plates at the 1/4 and 1/2 positions in the thickness are shown in **Photo 3** as examples. Both structures are controlled to

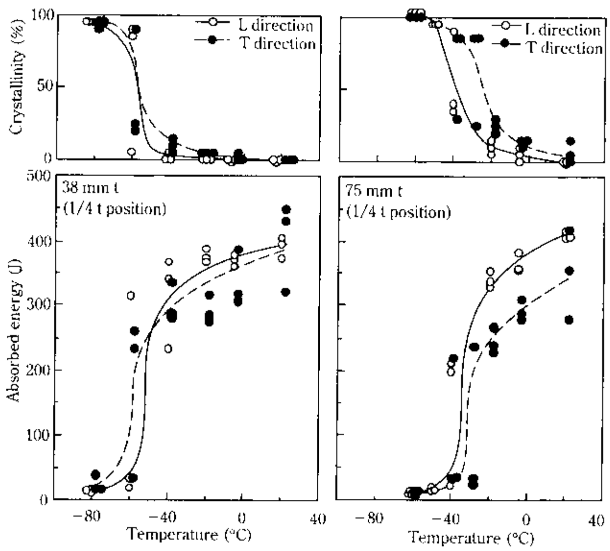


Fig. 4 V-notch Charpy transition curves

be mainly of granular bainitic ferrite and no difference can be observed due to differences in cooling rates depending on the position in plate thickness.

The results of the tensile tests are shown in **Table 3**. Both plates satisfied the values of 0.2% proof stress, tensile strength and elongation specified in the JIS SM570TMC standard. Furthermore, the difference in strengths between the 1/4 and 1/2 positions in thickness is sufficiently small and was only 31 MPa at the maximum. This is proof that the effect of cooling rate dependence on the microstructure is small.

Figure 4 shows Charpy transition curves for steel plates at the 1/4 position in thickness. Absorbed energy of both plates at −5°C was greater than 250 J, a sufficient value compared to the standard JIS value of 47 J.

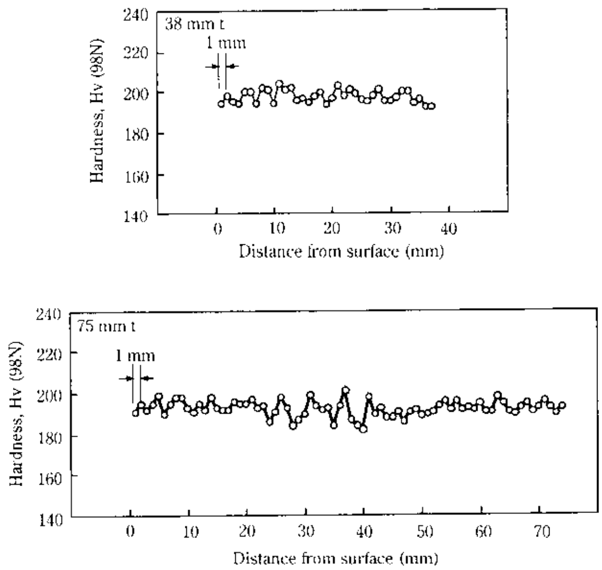


Fig. 5 Hardness destributions for extremely-low carbon bainitic steel

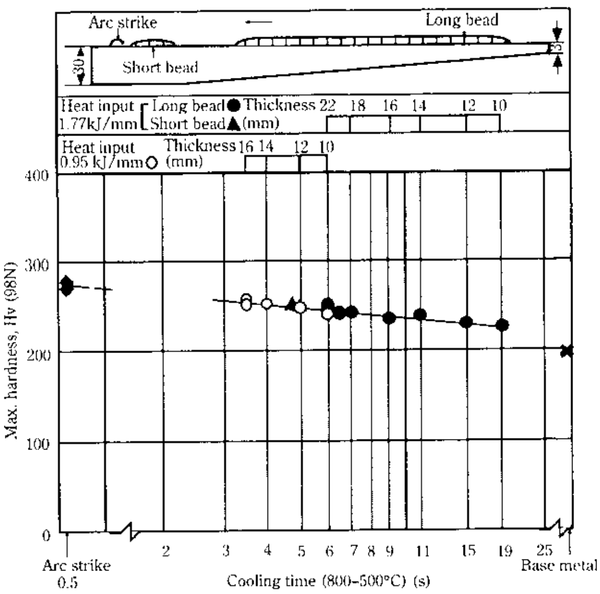


Fig. 6 Results of HAZ taper hardness test

Table 4 Welding condition for y-groove weld cracking test and results

Thickness (mm)	Atmosphere		Preheat temp. (°C)	Welding conditions				Crack ratio		
	Temp. (°C)	Humidity (%)		Rod	Current (A)	Voltage (V)	Speed (mm/s)	Surface (%)	Sectional (%)	Root (%)
50	5	80	5	LB62UL (4 mmϕ)	170	25	2.5	0.0	0.0	0.0
								0.0	0.0	0.0
								0.0	0.0	0.0
	30	80	30	LB62 (4 mmϕ)				0.0	0.0	0.0
								0.0	0.0	0.0
								0.0	0.0	0.0

Figure 5 shows the results of measuring the Vickers hardness at steel plate sections. It was shown that both plates have flat distributions of hardness of about 190 points in the thickness direction. Almost no difference was observed in hardness for the differences in the plate thickness.

3.2 Susceptibility to Weld Cracking

Taper hardness tests in weld heat-affected zone were performed according to JIS Z 3115 using steel plates of 38 mm thick. The results of measuring the maximum hardness in HAZ are shown in **Fig. 6**. The results show that the increase in hardness due to an increase of the cooling rate accompanied with an increase of the test piece thickness is extremely small. Even with arc-strike welding, in particular, the Vickers hardness was lower than 280 points indicating that the hardness is sufficiently low compared to the 350 points which in generally considered as an index for the upper limit of the maximum hardness in HAZ required for prevention of welding cracks.

Table 4 shows the results of y-groove weld cracking tests according to JIS Z 3158. No generation of cracks was observed at an atmospheric temperature of 5°C even without preheating.

3.3 Mechanical Properties of Welded Joints

Multi-layered GMAW (gas metal arc welded) joints, multi-layered SAW (submerged arc welded) joints and single-layered EGW (electrogas arc welded) joints were produced using steel plates of 38 mm and 75 mm thick and the mechanical properties of welded joints were investigated. The welding conditions are shown in **Table 5**.

Figure 7 shows the distribution of hardness of welded parts at 2 mm below the surface of each joint. In the case of the multi-layered GMAW joints and multi-layered SAW joints, no softening was observed in HAZ. On the other hand, in the case of the single-layered EGW joints, the minimum value of the Vickers hardness in HAZ was about 175 points indicating that slight softening had occurred.

Table 6 shows the tensile and bending properties of these joints. The tensile strength of welded joints was

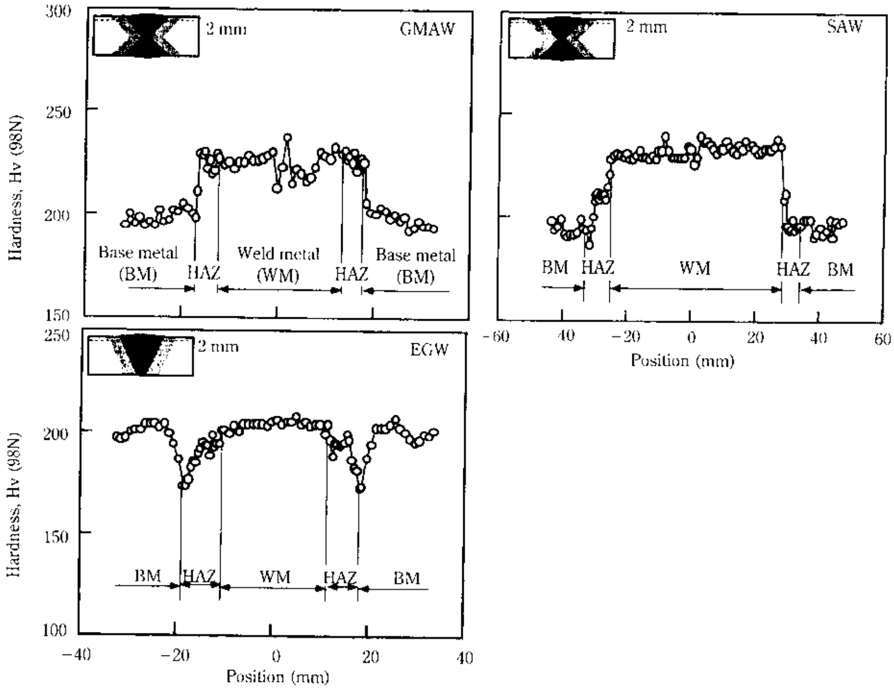


Fig. 7 Hardness destributions of welded joints

Table 5 Welding conditions for evaluation of weld performance of extremely-low carbon bainitic steel

		GMAW	SAW	EGW
Thickness	(mm)	38	75	38
Welding wire		KM60 1.2 mmϕ	KW101B 4.8 mmϕ	DWS60-G 1.6 mmϕ
Welding flux		—	KB110	—
Shielding gas		Ar80% + $CO_2$20%	—	$CO_2$100%
Preheating temperature	(°C)	23	24	21
Current	(A)	307	808	380
Voltage	(V)	32	36	42
Speed	(mm/s)	3.2	5.0	0.8
Heat input	(kJ/mm)	3.0	6.0	20.4
Groove shape		X, K	X, K	V

Table 6 Mechanical properties of welded joints

Welding method	Groove Shape	Tensile test			Bend test
		Thickenss (mm)	TS (MPa)	Position of fracture*	Side bend R = 2.0 t
GMAW	X	38	647	BM	Good
			648	BM	
SAW	X	75	628	BM	Good
			631	BM	
EGW	V	38	613	HAZ	Good
			613	HAZ	

*BM: Base metal
HAZ: Heat affected zone

Table 7 V-notch Charpy impact test results of welded joints

Welding method	Groove shape	Absorbed energy at −5°C (J)		
		Weld metal	Bond	HAZ
GMAW	K	196	318	280*
SAW	K	187	319	301**
EGW	V	102	172	328***

*1 mm from fusion line
**1.5 mm from fusion line
***5 mm from fusion line

equivalent to or higher than that of the mother material even for the single-layered EGW joints in which some softening was observed in HAZ. In addition, there was no problem in the bending properties of these joints.

The results of the Charpy impact tests on these joints are shown in **Table 7**. The notch positions were selected at the weld metal, bond (on the side of HAZ in the vicinity of the fusion line without including the weld metal) and the center of HAZ (distance from the fusion line 1 mm for multi-layered GMAW joints, 1.5 mm for multi-layered SAW joints and 5 mm for single-layered EGW joints). At each position, it was shown that the toughness is sufficient regardless of the welding method or heat input. Even with the EGW joints with the largest heat input. The Charpy absorbed energy at −5°C was sufficient and was 102 J at the weld metal and 172 J at the bond.

4 Conclusion

A new type of non-heat treated thick high strength steel plates of TS570 MPa grade has been developed. By reducing the carbon content to about 0.02 mass% or less and by doping alloy elements, the microstructure of this steel is made mostly of granular bainitic ferrite for a wide range of cooling rates. As a result of evaluating the properties, the following conclusions were obtained.

(1) Even with as-rolled steel plates of 75 mm thick, high strength was achieved with 0.2% proof stress ≧ 430 MPa and tensile strength ≧ 570 MPa. The chemical composition satisfies the JIS SM570TMC standard.

(2) The Vickers hardness of the steel plate at sections is 185~210 points and is distributed extremely evenly in the thickness direction and scattering of the strength in the thickness direction is very small.

(3) The Charpy absorbed energy at −5°C was more than 250 J and satisfies the JIS SM570TMC standard.

(4) Even with severe small heat input unsteady welding conditions such as arc-strike welding, the highest Vickers hardness in HAZ was lower than 280 points and superior weld hardening resistance characteristics were verified. Furthermore, in y-groove weld cracking tests, the crack prevention preheating temperature was 5°C at an atmospheric temperature of 5°C and 80% humidity.

(5) Within the range of welding heat inputs up to 20% kJ/mm, the tensile strength of joints satisfied the value equivalent to or higher than that of the mother material. Furthermore, Charpy absorbed energy at −5°C was more than 100 J at the weld metal and more than 170 J at the bond and the newly developed steel is applicable to large heat input welding of up to 20 kJ/mm.

By developing this new steel, it has become possible to quickly supply 570 MPa grade thick high strength steel plates up to 75 mm thick in as-rolled conditions. This steel has made welding process entirely free from preheating and can be welded with a large heat input of up to 20 kJ/mm. At present, application of this steel to bridges has begun and extension of application to the civil and architecture fields is scheduled.

In connection with the development and property evaluation of this steel, Kawasaki Steel had a great deal of cooperation and support from Kobe Shipyard and Engine Works, Mitsubishi Heavy Industries, Ltd., and the authors are grateful to those concerned for their cooperation.

Preferences

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