Abridged version

KAWASAKI STEEL TECHNICAL REPORT
No.33 (January 1996)
Welding, Logistics, and Environmental Engineering

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1 Introduction

Construction of high-rise buildings was extremely active in Japan from the late 1980s to 1991, and heavy wall box columns and H-shapes with thicknesses of over 50 mm, which were the main welded structural parts of tall buildings, were in heavy demands. It was therefore especially important to shorten the fabrication period of such welded structural parts by developing a high-efficiency welding process to meet demand and reduce fabrication costs.

A high-efficiency submerged arc welding process had already been established for thick box columns,[1,2] but not for thick H-shapes. The H-shapes used in crane girders and heavy structures are usually welded in full penetration. In this type of welding, preliminary processes such as groove preparation, gouging and grinder finishing, and multipass welding have been indispensable, making it difficult to improve welding efficiency. To enable high-efficiency submerged arc welding of H-shapes, the welding materials and the most suitable welding parameters for full penetration fillet one pass per side welding of T-joints were examined from the viewpoints of penetration depth and weld defects, especially weld metal cracking.

This paper describes the high-efficiency submerged arc welding process for T-joints with web thicknesses of up to 25 mm without groove preparation and up to 80 mm with groove preparation.

2 Experimental Procedure

2.1 Materials and Equipment

Plates with thicknesses from 25 mm to 80 mm having a strength of 490 MPa grade were used; their chemical compositions are shown in **Table 1**. The newly developed fluxes KB-U without the addition of iron powder and KB-US containing iron powder were used in combination with wires of 4.8 mm and 6.4 mm in diameter, which were made from the same heat. The chemical composition of the wire is also given in Table 1. The carbon content of this wire was low enough to prevent weld cracking. The flux KB-U was applied to the welding of T-joints with web thicknesses of up to 25 mm without groove preparation and over 25 mm to 50 mm with groove preparation. The flux KB-US containing

* Originally published in *Kawasaki Steel Giho*, **26**(1994)4, 168–173

Table 1 Chemical compositions of base metals and wire (mass%)

Grade	Thickness (mm)	C	Si	Mn	P	S	Ni	Nb
Base metal (SM490B)	25	0.15	0.40	1.42	0.015	0.004	—	—
Base metal (SM490B)	80	0.14	0.34	1.37	0.012	0.003	0.14	0.026
Welding Wire (KW 50)		0.06	0.03	2.00	0.012	0.003	—	—

Table 2 Standard welding conditions used

Web thickness (mm)	Wire × Flux	Electrode	Wire diameter (mm)	Welding current (A)	Arc voltage (V)	Welding speed (mm/min)	Heat input (kJ/mm)
25	KW-50×KB-U	L	4.8	1 300	32	400	12.5
		T	6.4	1 000	42		
80	KW-50×KB-US	L	6.4	2 000	35	200	45.8
		T	6.4	1 500	55		

iron powder, on the other hand, was used for T-joints with web thicknesses of over 55 mm to 80 mm with groove preparation.

2.2 Determination of Optimum Welding Conditions

It is important to select the welding parameters for obtaining sufficient penetration depth and avoiding weld defects, particularly weld metal cracking. The AC-AC tandem wire submerged arc welding process was applied. The standard welding conditions for plates with web thicknesses of 25 mm and 80 mm are shown in **Table 2**. To obtain a full penetration welded joint without weld defects, the effects of the wire aiming point, electrode distance, and inclination of the specimen on penetration depth were investigated.

2.3 Weld Cracking Test

Though the weld cracking test method for T-joints is standardized in JIS Z 3153[3] (Japan Industrial Standard Z 3153), it is difficult to cause weld cracking with this method. Therefore, the welding cracking tests using the specimens shown in **Figs. 1** and **2** were carried out to study the limit of application of this welding process.

With the 25-mm-web-thick plate, the length of the specimen was 1 000 mm and the fillet welding was carried out first on the backing side. Triangle restraint plates with scallops were then welded on the backing side of the test bead at an interval of 210 mm. In addition to the triangle restraint plates, other restraint plates were also welded on the back side of flange at the same interval as the triangle restraint plates. Test beads were then welded on specimens with various carbon contents.

With the 80-mm-thick plate, a specimen with a length of 2 000 mm was used. The triangle restraint plates were welded at both ends of the specimen on the back side

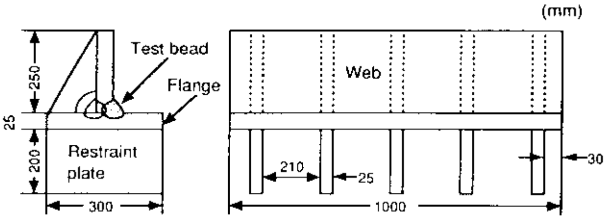

Fig. 1 Restraint cracking test method for fillet welded joint with 25-mm-thick web

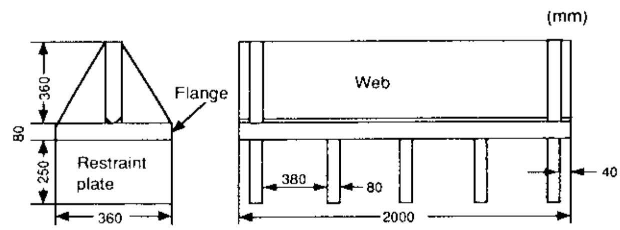

Fig. 2 Restraint cracking test method for fillet welded joint with 80-mm-thick web

and the test bead side. The restraint plates on the back side of the flange were welded at an interval of 380 mm. Test beads were then welded on specimens with different carbon contents.

After 48 hours, the specimens were cut at an interval of 100 mm and cracking was examined by liquid penetrant testing.

2.4 Mechanical Test of Welded Joints

The mechanical properties of the welded joints with the web thickness of 25 mm and 80 mm were examined by the Charpy impact test at 0°C and the tensile test.

2.5 Fatigue Test of Welded Joints

Since fatigue strength is important, for example, in crane girders, the fatigue tests of cruciformed full penetration fillet welded joints with a web thickness of 20 mm made by the conventional and newly developed welding methods were carried out. **Figure 3** shows the geometry of the specimen, which is of the load-carrying type. The axial loading of the zero-tension test was adopted.

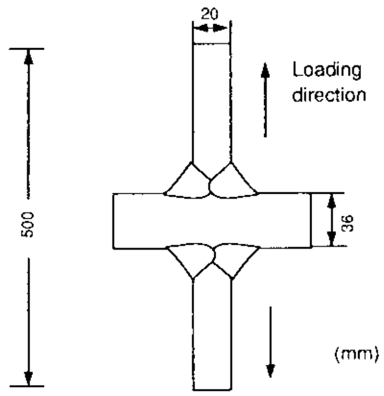

Fig. 3 Dimensions of specimen for fatigue test

3 Experimental Results and Discussion

3.1 Selection of Welding Materials

Bonded flux, which in general has a higher softening temperature than fused flux, is usually used in one pass welding of thick plates with high heat input. The wide bead resulting from the small bulk density of the bonded flux is also favorable for preventing hot cracking of weld metal.[4]

Many bonded fluxes were investigated to develop a new flux of a SiO_2-MgO-Al_2O_3 system (KB-U) having a bulk density of about 1.0 g/cm^3. This newly developed flux is suitable for fillet welding of T-joints with web thicknesses of up to 25 mm without a groove and up to 50 mm with a groove. CO_2 gas is generated by the decomposition of the carbonate contained in the flux during welding and decreases the partial pressure of the hydrogen in the arc cavity and lowers the diffusible hydrogen content in the weld metal.

In the fillet welding of T-joints with web thicknesses of over 55 mm to 80 mm with groove preparation, on the other hand, the deposited metal should be of a volume which will fill the groove and give penetration depth as well. Although the amount of deposited metal can be increased by increasing the welding current and decreasing the welding speed, these changes tend to deteriorate the bead appearance and mechanical properties of the welded joint because of the increase in weld heat input. Therefore, a new flux of a SiO_2-MgO-CaO-Al_2O_3 system (KB-US) containing iron powder and having a high softening temperature was developed. The addition of iron powder to the flux is beneficial to the increase in deposition rate without increasing the weld heat input.[1] The above mentioned flux made it possible to obtain both depth of penetration and a sufficient amount of deposited metal with a lower heat input.

The low carbon wire KW-50 is recommended to avoid weld metal hot cracking with the combination of fluxes KB-U and KB-US.

3.2 Optimum Welding Conditions for High-Efficiency Welding

3.2.1 Optimum welding conditions for T-joints without groove preparation

The determination of the optimum welding parameters for ensuring penetration depth and avoiding weld defects, such as undercutting and solidification cracking, is very important in one pass SAW with large heat input for heavy section plates.

Figure 4 shows the effect of the inclination angle of the flange (θ) on penetration depth (P) when the aiming position (explained below) was kept constant. The definitions of θ and P are shown in **Fig. 5**. The penetration depth increased with the inclination angle of the flange. Undercuttings occurred in the flange, however, when the inclination angle was larger than about 65°, because of flange side molten metal hanging down on the web side. When the inclination angle of the flange

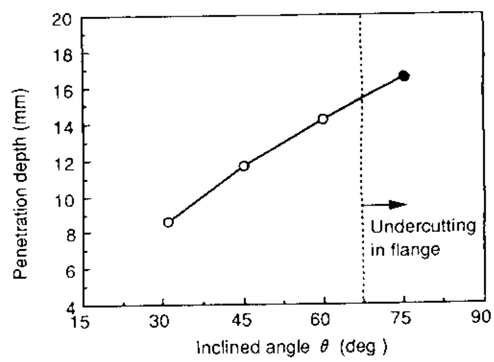

Fig. 4 Effect of inclined angle of flange on penetration depth and occurrence of undercutting

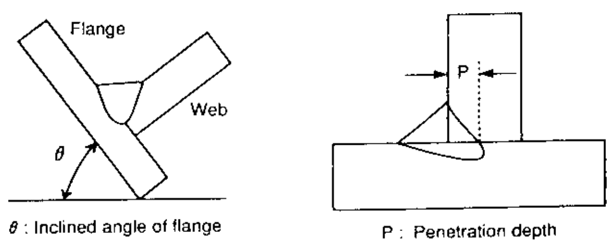

Fig. 5 Inclination of flange and depth of penetration

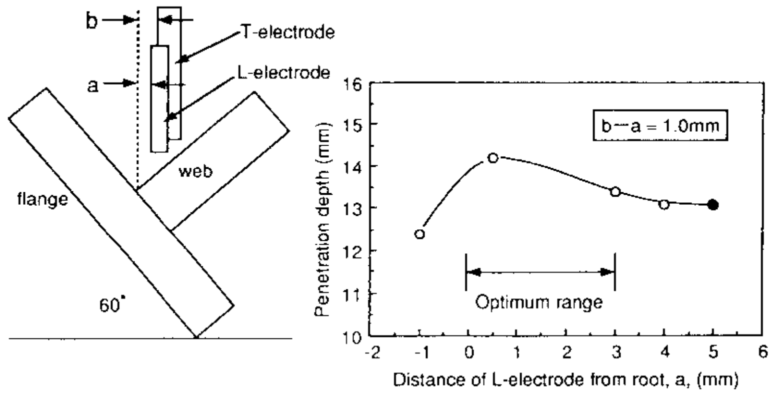

Fig. 6 Effect of wire location on penetration depth in fillet welding without groove

was smaller than about 45°, it was difficult to obtain sufficient penetration. Therefore, the inclination angle of 60° was considered appropriate from the viewpoints of penetration depth and undercutting.

The depth of penetration was affected not only by the inclination angle of the flange but also by the aiming position of the wire. The effect of wire location on penetration depth in fillet welding without a groove is shown in **Fig. 6**. It was found that the maximum penetration depth was obtained when the aiming position of the leading electrode was slightly toward the web side. When the distance of the aiming point from the root was over 5 mm, incomplete side wall penetration of the flange was observed, as shown in **Photo 1**. The optimum range of the leading wire was 0 to 3 mm from the root, as shown in Fig. 6.

The leading electrode, with the diameter of 4.8 mm, has the role of ensuring penetration, while the trailing electrode, with the diameter of 6.4 mm, has a role of making and widening the final bead. Consequently, the aiming position of the trailing electrode is different from that of the leading electrode.

The welding parameters already listed in Table 2 were determined according to the knowledge obtained in a study of the large heat input welding process.[1]

The effect of the distance between the leading and trailing electrodes on the penetration depth was also examined. Little effect was observed in the range between 25 mm and 75 mm. Solidification cracking, however, tends to occur when the electrode distance is short because of the inferior cross sectional profile of the weld metal produced by having only one molten pool. Therefore, the electrode distance of 50–75 mm was selected, and the molten pool seemed to be of a semi one-pool type.

An example of the cross-sectional view of a one pass per side T-joint with a web thickness of 25 mm without groove preparation is shown in **Photo 2**, and has sound penetration depth and a good cross-sectional profile.

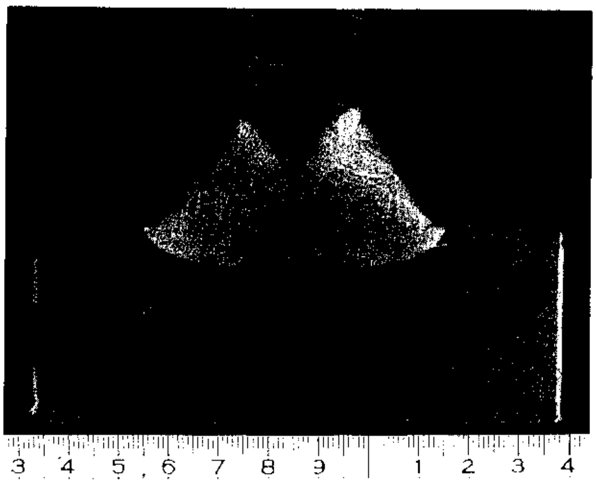

Photo 2 Macro section of full penetration fillet welded joint with 25-mm-thick web

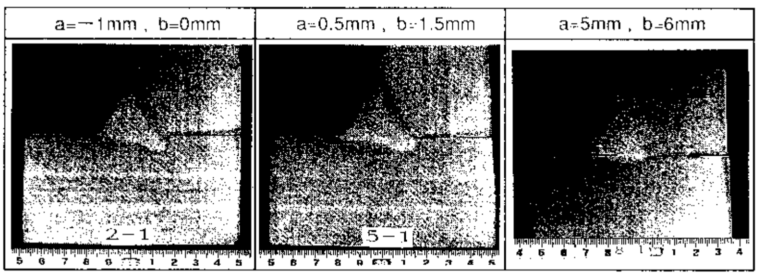

Photo 1 Effect of wire location on shape of penetration

3.2.2 Optimum welding conditions for T-joints with groove preparation

Basically, the optimum welding conditions for T-joints with groove preparation are the same as those for T-joints without groove preparation mentioned above. Wires with the diameter of 6.4 mm were used in both the leading and trailing electrodes, because the welding current of the leading electrode was as high as 2 000 A in the case of a 80-mm-thick web. The depth of the groove had to be about one third of the web thickness to obtain full penetration, and the angle of groove had to be more than 45°.

An example of the macro-section of a T-joint with an 80-mm-thick web welded using the optimum welding parameters mentioned above is shown in **Photo 3**, which indicates sufficient penetration on the same level as that with the 25-mm-thick web specimen in Photo 2.

Figure 7 is a schematic illustration of a comparison between the new high-efficiency one pass per side fillet welding method and the conventional multipass welding method.

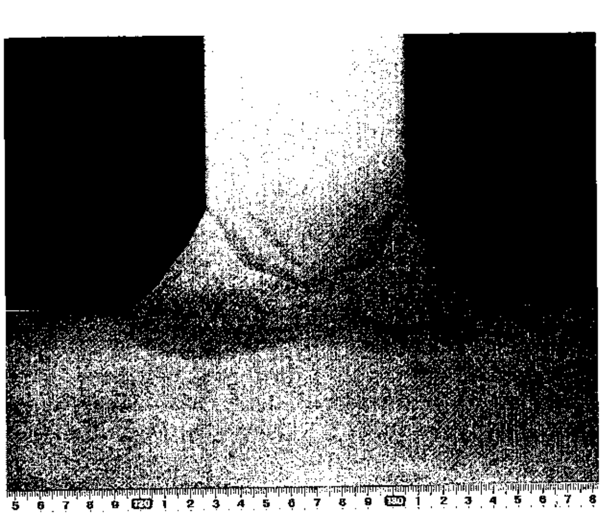

Photo 3 Macro section of full penetration fillet welded joint with 80-mm-thick web

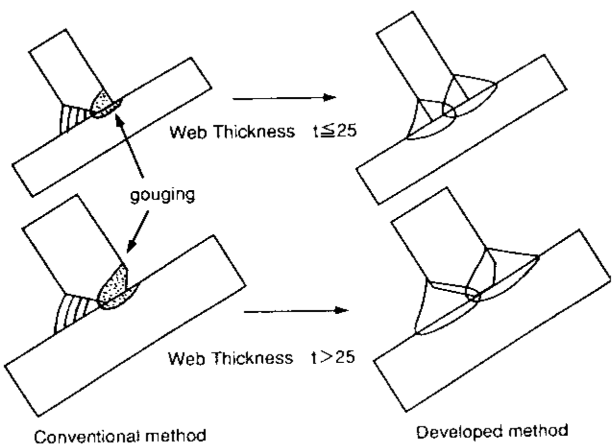

Fig. 7 Comparison of high efficiency fillet welding method with conventional one

3.3 Results of Restraint Cracking Tests

3.3.1 Results of restraint cracking test for 25-mm-thick specimen

One of the reasons why the high-efficiency welding process was not practically used for some time was misgivings about cracking of the weld metal.

The melting ratios of the web, flange, and wire in the weld metal of a T-joint with a 25-mm-thick web without groove preparation were 39%, 22%, and 39% respectively, and these melting ratios were independent of plate thickness and nearly constant in the case of non-groove fillet welding. About 61% of weld metal comes from the base metal (web and flange) and 39% from the wire. This result suggests that the chemical composition of base metal, especially its C content, must be restricted within a certain range to avoid weld metal cracking because the solidification temperature range of a high C weld metal is wide and impurities tend to segregate in cell boundaries.

The results of the restraint cracking test for 25-mm-thick specimen performed according to the method explained in Fig. 1 are shown in **Fig. 8**. The horizontal axis shows the C content of the weld metal calculated on the basis of the melting ratio, as explained above, on the assumption that the yield of C is 100%. The vertical axis shows the actual C content of the weld metal determined by chemical analysis. Although C was consumed by reaction with oxygen, a linear relationship was obtained between the calculated C content and the actual C content of the weld metal. Cracks were observed when the actual C content of the weld metal exceeded 0.12 mass%. The calculated C content in this case was 0.135 mass%. From the results shown in Fig. 8, the calculated

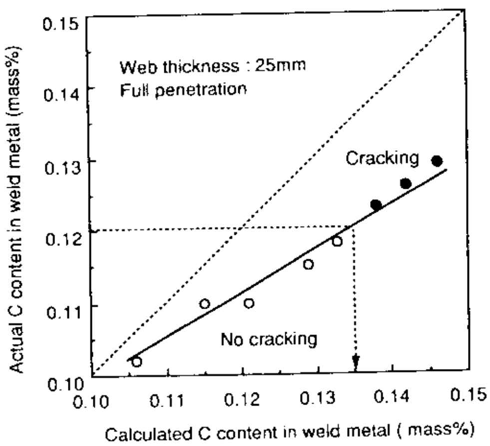

Fig. 8 Effect of C content on weld metal cracking in restraint cracking test

C content of the weld metal for preventing cracking in the range of the experiment is expressed by Eq.(1).

$$C_{WM_{cal}} = 0.39C_{web} + 0.22C_{flange} + 0.39C_{wire} \leqq 0.135\,(\text{mass\%}) \quad \cdots\cdots (1)$$

where, $C_{WM_{cal}}$: Calculated C content of weld metal (mass%)
C_{web}: C content of web (mass%)
C_{flange}: C content of flange (mass%)
C_{wire}: C content of wire (mass%)

It is possible to predict the occurrence of weld metal cracking using Eq.(1) without knowing the actual chemical analysis of the weld metal if the C contents of the base plates and the wire are already known. The maximum allowable C content of the base plates can be calculated as 0.18 mass% when the low C wire KW-50 (0.06 mass% C) is used.

3.3.2 Results of restraint cracking test for 80-mm-thick specimen

The upper limit of C content for the base plates for preventing weld metal cracking decreases as the plate thickness increases because of the increase in the degree of restraint. **Figure 9** shows the results of a whole cracking test conducted with various plates, although not all the test results are described in this paper. The allowable C content of the weld metal without cracking decreases as the plate thickness increases. With 80-mm-thick plate, the C content of the weld metal must be kept 0.096 mass% or below.

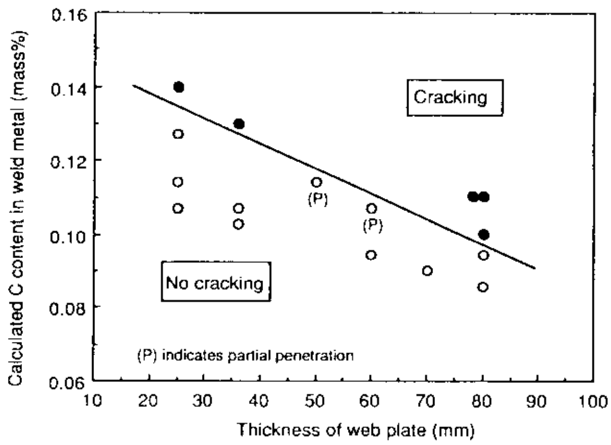

Fig. 9 Effects of web thickness and calculated C content in weld metal on weld metal cracking

It is also possible to predict the occurrence of cracking from the melting ratios of the web, flange and wire in the same manner as shown in Eq.(1) in T-joints with groove preparation and with flux containing iron powder. Eq.(2) gives the allowable calculated C content of the weld metal for 80-mm-thick specimen without cracking. It is difficult to prevent weld metal cracking when the carbon content of the base metal exceeds 0.14 mass% in welding with the wire KW-50, whose carbon content is 0.06 mass%.

$$C_{WM_{cal}} = 0.28C_{web} + 0.22C_{flange} + 0.50C_{wire} \times 0.85 \leqq 0.096\,(\text{mass\%}) \quad \cdots\cdots (2)$$

where, $C_{WM_{cal}}$: Calculated C content of weld metal (mass%)
C_{web}: C content of web (mass%)
C_{flange}: C content of flange (mass%)
C_{wire}: C content of wire (mass%)

The coefficient of 0.85 for C_{wire} is based on the effect of the iron powder which is contained in the flux.

3.4 Mechanical Properties of Welded Joints

The mechanical properties of welded joints with a web thickness of 25 mm without a groove and with a 80-mm-thick web with a groove are shown in **Table 3**. The Charpy absorbed energy and tensile strength of these welds satisfied the required values of 27 J at 0°C and TS ≧ 490 MPa for the JIS SM-490B grade.

3.5 Fatigue Strength of Welded Joints

The fatigue strength of the cruciformed full penetration fillet welded joints with a 20-mm-thick web without a groove is compared with that of joints produced by the conventional multipass welding method shown in **Fig. 10**. The test specimen was of a load-carrying type, and the axial loading zero-tension test was adopted. The welded joint made with KB-U showed a higher fatigue

Table 3 Mechanical properties of welded T-joints

Web thickness (mm)	YS (MPa)	TS (MPa)	El (%)	RA (%)	Charpy absorbed energy at 0℃ (J)				
					Weld metal	Fusion line	HAZ 1mm	HAZ 3mm	HAZ 5mm
25	505	582	28	65	62	129	54	66	85
					34	78	34	93	140
					72	58	44	87	110
80	498	615	32	58	81	122	97	108	190
					66	107	82	141	178
					76	91	130	174	192

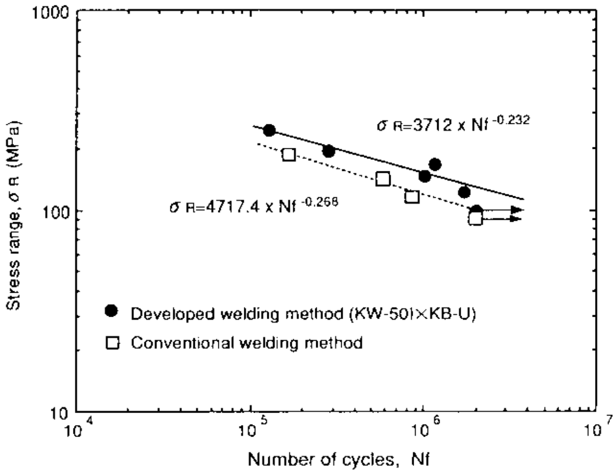

Fig. 10 Fatigue test results of cruciformed fillet welded joint by conventional and developed welding methods

strength than that made by the conventional multipass welding method. The reason for this seemed to be that the welded joint made by the newly developed method had smaller residual stress and a better shaped toe geometry than the joint made by the conventional method.

The fatigue life of the welded joints made by the newly developed method exceeded 2×10^6 cycles, which is required for crane girders subjected to a stress of 120 MPa. This process was applied to the welding of an actual crane girder in the Steelmaking Shop of Kawasaki Steel's Chiba Works.

4 Conclusions

The most appropriate submerged arc welding materials and welding parameters for T-joints were determined to enable high-efficiency full penetration fillet one pass per side welding. The results obtained are summarized as follows:

(1) A full penetration one pass per side submerged arc fillet welding process for T-joints with web thickness of up to 25 mm without groove preparation and up to 80 mm with groove preparation was developed in combination with the low C wire and newly developed fluxes.

(2) The maximum allowable C content of the weld metal without cracking was determined by the restraint cracking test. From the results, the maximum allowable C content of the base metals for preventing weld metal cracking was calculated as 0.18 mass% for a T-joint with a 25-mm-thick web without groove preparation, and 0.14 mass% for a T-joint with a 80-mm-thick web with groove preparation when the low C wire KW-50 (0.06 mass% C) was used.

(3) The Charpy absorbed energy and tensile strength of the welds satisfied the required value of 27 J at 0°C and TS ≧ 490 MPa for the JIS SM-490B grade, even though the weld heat input was large.

(4) T-joints with a 20-mm-thick web without a groove made by the newly developed method showed the higher fatigue strength than joints welded by the conventional multipass welding method.

This report has discussed a full penetration welding process for T-joints with heavy sections. This process is also applicable to an already-developed partial penetration welding method[5] by modifying the welding parameters such as the welding current and speed.

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