FRACTURE TOUGHNESS AND RESISTANCE TO FATIGUE CRACK GROWTH OF THREE VESSEL STEEL WELDED JOINTS WITH DIFFERENT WELDING PROCEDURES

Wu Qingke (吴清可) Xing Peizhao (邢培兆) Zhang Yuhuai (张毓槐)
Chao Wenying (晁文英) Li Jinping (李金萍) Li Yuqin (李玉琴)
Yue Jianping (岳建平) Gu Guifang (谷桂芳) Shen Lide (沈立德)
Lin Zhixiong (林志雄)
Zhengzhou Research Institute of Mechanical Engineering,
Zhongyuan Road, Zhengzhou, China

INTRODUCTION

Welded-joints of vessel steel plate, made with three different welding procedures and different heat-treatments, were studied using fracture mechanics testing, metallography, electron fractography, etc. The fracture parameters measured are: fracture toughness J_{Ic}, COD, $\frac{P_{max}}{B(w-a)}$, da/dN, etc. The choice of the three welding procedures and relevant heat-treatment has been made by evaluating and comparing the experimental results.

EXPERIMENTAL PROCEDURE

This vessel steel is a fine-grained steel usually used in nuclear power stations. Vessel steel plate with a thickness of 80 mm was used in our programme. Its composition is shown in Table 1, Table 2 gives the details of welding conditions and heat-treatments of the specimens.

There were two kinds of three-point-bend specimen to be used. The dimension of the first was 38×76×370 mm (according to ASTM E399—76), the other was 20×24×100 mm (GB 2038—80). All 79 specimens were precracked in fatigue with a/w = 0.5. The positions of the precracked notches are shown in Fig. 1.

The fracture toughness tests were performed on a hydraulic testing machine. Force, clip-gage displacement, potential drop, events of acoustic emission were recorded on two sets of three X-Y recorders. J_{Ic}, $\frac{P_{max}}{B(w-a)}$ were measured from P-Δ curves, and COD from P-V curves.

Fatigue crack growth tests were conducted under constant load with stress ratio R = 0.2, crack length a and number of cycles N were recorded from a/w = 0.3 to 0.5 (according to ASTM E647—78T).

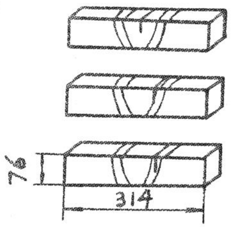


Fig. 1 Positions of notches on specimens

RESULTS AND DISCUSSION

Fig. 2a and 2b are the results of fracture toughness J_{Ic}, COD and $\frac{P_{max}}{B(w-a)}$ of weld metal, fusion line(and its vicinity), HAZ, and parent metal.

The data of fracture toughness of various welded-joints assume a Log-Normal distribution[1]. According to the student t distribution we may evaluate the lower bounds with 99.5% confidence. The results were given in Table 3[2].

It appears that the weld metal of E_1 is provided with coarse ferrite net structures (see Fig. 3a and b), which result in very poor toughness.

Recent studies revealed that hot strain embrittlement could be one of the reasons for this type of problem in low alloy ferritic steels[3,4]. In our work, this problem may be solved by E_2 heat-treatment provided by the Manufacturing Plant. After this treatment, the welded-joints have fine grains (Fig. 3c) and a little portion of ferrite, which enhance the resistance of crack growth[5] and result in a higher fracture toughness J_{Ic}. J_{Ic} of E_2 is about four times higher than that of E_1 in weld metals.

It is noted that the J_{Ic} of narrow gap welded-joints (as welded) is the same as that of S_1.

The curves of the fatigue crack growth rate da/dN versus stress intensity factor range ΔK at stage II for the weldedjoints with different welding procedures are shown in Fig. 4. The fatigue crack growth rates are expressed in the form of Paris formula and some of them are as follows:

N_3: in the vicinity of fusion lines, $\frac{da}{dN} = 0.3491\times10^{-10}\ \Delta K^{3.3272}$

in H. A. Z. $\frac{da}{dN} = 0.2244\times10^{-8}\ \Delta K^{2.3703}$

Table 1 Chemical Composition of the Parent and Weld Metals

Composition,%		C	Si	Mn	S	P	Ni	Cr	Mo	Nb	Al	Ti	Cu
Parent Metal		0.15	0.36	1.51	0.003	0.015	0.83	0.35	0.34	0.01	0.031	-	-
Weld Metals	N_2	0.1	0.41	1.59	0.014	0.014	0.88	0.094	0.5	0.003	0.01	0.016	0.1
	N_3	0.1	0.4	1.6	0.013	0.014	0.89	0.068	0.5	0.003	0.01	0.014	0.1
	E_1	0.14	0.26	1.39	0.006	0.018	0.76	0.15	0.31	0.003	0.01	-	V% 0.26
	S_1	0.05	0.32	1.55	0.016	0.026	0.23	0.062	0.43	0.003	0.01	-	-

Table 2 Welding Parameters and Heat-Treatment Conditions

Types of Welding		Current I_a, (A)	Voltage V,(Volt)	Welding Speed v,(m/hr)	Heat Input (KJ/cm)	Type & Diameter of Electrode	Heat-Treatment Conditions
Narrow Gap Welded Joints	N_1	430	27	16.5	25.4	H08Mn2SiNiMo, φ3 mm	*
	N_2	"	"	15	27.4		none
	N_3	"	"	18	23.22		none
Submerged Arc Welded Joints	S_1	bottom 600—650 upper 650—750	28—30 35—38	32 26—28	upper 33.6	H08Mn2MoAl, φ5 mm	*
	S_2	bottom 600—650 upper 650—750	28—30 35—38	32 26—28	"	"	none
Electroslag Welded Joints	E_1 E_2	500—520	36	1.2	1101.6	H10MnMoNiVA φ3 mm×2	** ***

* Stress relief annealing, 620°C×8hr, furnace cooling.

** Normalizing, tempering, and stress relief annealing.

*** Provided by Manufacturing Plant.

Table 3 Mean Values and Standard Deviations of ln J_{Ic}

Types of Welding	$\bar{\mu}$ of ln J_{Ic}	σ_{n-1}	Confidence Level	Lower Bounds of $\bar{\mu}$	J_{Ic}
N_1	2.2697	0.1978	99.5%	2.1024	8.186
N_2	2.3606	0.2060	"	2.1861	8.9
N_3	2.4259	0.2163	"	2.2599	9.582
S_1	2.4169	0.2007	"	2.237	9.365
S_2	2.3314	0.1975	"	2.164	8.706
E_1	1.816	0.5125	"	1.3264	3.767
E_2	2.4686	0.128	"	2.433	11.393

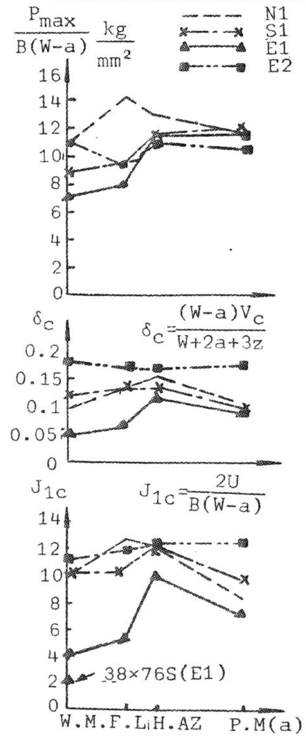
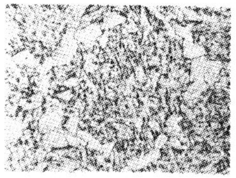
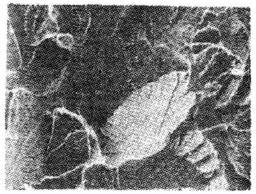


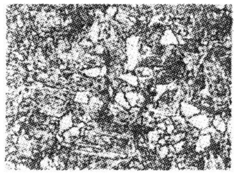
Fig. 2 Comparison of values from different specimens



a. Ferrite Net (from E_1)



b. Quasi-Cleavage (from E_1)



c. E_2 W. M. × 200

Fig. 3 Structures of weld metals

S_1: welded metal stress relieved

$$\frac{da}{dN} = 0.88508\times10^{-14}\,\Delta K^{5.3145}$$

vicinity of fusion line

$$\frac{da}{dN} = 0.78453\times10^{-13}\,\Delta K^{4.9641}$$

H.A.Z $\frac{da}{dN} = 0.64589\times10^{-11}\,\Delta K^{3.685}$

E_2: vicinity of fusion line

$$\frac{da}{dN} = 0.98273\times10^{-9}\,\Delta K^{2.4463}$$

H.A.Z $\frac{da}{dN} = 0.8589\times10^{-10}\,\Delta K^{2.9977}$

parent metal

$$\frac{da}{dN} = 0.8969\times10^{-10}\,\Delta K^{3.0525}$$

where da/dN is in mm/cycle, ΔK in kg·mm$^{-3/2}$.

N_3 and S_1 have the same crack growth rate da/dN. In N.H.T. N_3, cracks are easy to grow through the boundaries of column crystal, as shown in Fig. 5.

In E_2, the cracks grow slowly and make a detour from ferrite or stop before ferrite (Fig. 6).

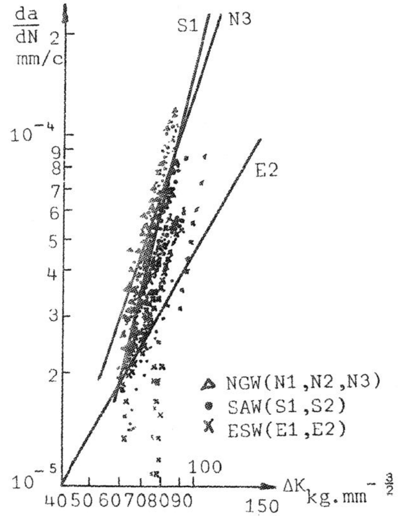


Fig. 4 Fatigue crack growing rates

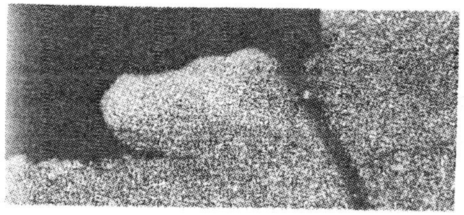


Fig. 5 Cracks grow through the boundaries of column crystal

Fig. 6 Crack stops at ferrite crystals

CONCLUSIONS

1. The weld metal for electroslag welded joints with nor .+temp.+ann. treatment exhibits embrittlement resulting in very poor toughness.

2. This problem of embrittlement may be solved by E_2 heat-treatment of the Manufacturing Plant.

3. The J_{Ic} and da/dN of narrow gap welded-joints without stress relief have the same values as those of submerged arc welded-joints with stress relief.

4. A little content of ferrite can improve the resistance to fatigue propagating of cracks in electroslag welded-joints.

5. The cracks are easy to grow through the crystal boundaries in narrow gap welded-joints without stress relief.

6. It is an effective method to evaluate and compare the properties of welded-joints by using probability theory and statistical method to treat the fracture toughness of inhomogeneous welded-joints.

ACKNOWLEDGEMENTS

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