EFFECT OF SPECIMEN SIZE AND CONFIGURATION ON FATIGUE CRACK GROWTH BEHAVIOR OF WELDED JOINTS

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Fatigue crack growth rates of butt-welded joints and base metals were measured using CT and CCT specimens, and the influence of specimen size, configuration and crack orientation on the growth rates were examined in connection with residual stress. The fatigue crack growth rates of the weld metal obtained by using CT specimens were decreased considerably as compared with those of CCT specimens, because the crack tips in the weld metal of CT specimens were always existence in a field of compressive residual stress. The fatigue crack growth rates in the weld metal with residual stress and in the base metal were correlated with ΔK_{eff} which were estimated by the crack closure experiment.

Introduction

It is known that fatigue life of a welded structure is primarily a fatigue crack growth problem. Since, fatigue crack growth tests for welded joints have been performed to determine inspection period or to predict service life of a welded structure. However, large scatter is found in the results because many variables such as residual stress, micro-structure, specimen size are involved. Among the variables, residual stress seems to play an important role in the fatigue crack growth rates in the welded joints. Despite of the importance of crack growth behavior to the integrity of a welded structure, the studies of welding residual stress on the fatigue crack growth rates have not intensively been performed so far(1)~(5). In this study, the influence of specimen size, configuration and crack orientation with respect to the weld axis on the fatigue crack growth rates of butt-welded joints were examined in connection with residual stress.

Specimens

The material used in this study is a mild steel plate (JIS SM50A) of 3050mm long, 1520mm wide and 16mm thick. Mechanical properties and chemical composition of the material used are given in Table 1 and 2, respectively. The plate was divided into eight stripes by fusion cutting across the rolling direction. A pair of the stripes with double-Vee groove were butt-welded with a manual metal-arc welding technique. The welding conditions are summarized in Table 3. Compact type (CT) specimens with different sizes (i.e. different widths) and center-cracked tension (CCT) specimens with a definite size were fabricated from the welded stripes. A notch in the CT specimen was located as the crack advances parallel to or perpendicular to the weld axis. In the CCT specimen, a notch was cut in the center line of the weld metal parallel to the weld axis. The size and configuration of the base metal specimens were the same as the welded specimens. The configuration and dimension for the welded specimens are shown in Fig. 1. Heat treatment was not performed for the all specimens.

Experimental procedure

The fatigue test of CT specimens was performed using a closed loop servo-controlled hydraulic testing machine at a frequency of 10Hz. The

test of CCT specimens was carried out on a Vibrophor fatigue machine at a frequency about 150Hz. The load was varied sinusoidally, and stress ratio, R(=Kmin/Kmax), was 0.05 for the CT specimens and 0 for the CCT specimens. The crack length at a certain number of cycles was measured using a traveling microscope with magnification x50 and a stroboscopic illumination. The crack growth rates were determined graphycally by taking the slopes of the crack growth curves at various crack length. The results were expressed in terms of stress intensity factor range, ΔK. Values of ΔK for the CT specimens were calculated using the result of Srawley(6) and for the CCT specimens were obtained from Feddersen's equation(7). Crack opening loads during the fatigue crack growth were measured using a strain gauge mounted on the back surface of the specimen. The residual stress distributions in the welded specimens were measured with a sectioning method using strain gauges.

Results and discussion

Fatigue crack growth behavior

Figure 1 shows the fatigue crack growth rates of the base metal specimens and of the parallel specimens in which cracks grow in the weld metal to the direction parallel to the weld axis with different sizes. The slashed data in the figure do not meet the criterion proposed by ASTM(8) as a recomendation to indicate the valid range for the growth rates of the CT specimen. No significant size effects are found for the base metal with specimens ranging from 51 to 260mm widths. In the parallel specimens, however, the growth rates of the specimen with 51mm width are higher than the other specimens with larger widths. Moreover, the resistance of crack growth in the weld metal is greater than that of the base metal, particulary in the low growth region. Figure 3 shows the crack growth rates of the transverse specimens with different sizes in which cracks grow perpendicular to the weld axis. The growth rates of the base metal specimens shown in Fig. 2 are also given by a straight line in the same figure for comparison. In the figure, white arrows indicate the values of ΔK corresponding to the positions that the growing cracks reach the weld axes, and black arrows show ΔK at the positions that the growing cracks intersect the weld axes. Below the values of ΔK at which cracks reach the weld axes, the crack growth rates are considerably reduced as compared with those of the base metal specimens, and the size effects also can be seen in this range of ΔK. Above the values of ΔK, however, the growth rates of the transverse specimens are about the same or slightly higher than those of the base metal specimens because of relief of the residual stress at crack tips in the specimens. Figure 4 shows a comparison of the growth rates between the parallel and the transverse specimens with 260mm width. In addition, the growth rates of the weld metal in the CCT specimens are superimposed on the same figure for the sake of comparison. It can be seen that the growth rates of the parallel and the transverse specimens are roughly the same regardless of the difference of the crack orientation to the weld axis. The growth rates of the welded CT (the parallel and the transverse specimens) and the CCT specimens do not match over any appreciable range of ΔK. At the low growth region, the CT specimens are found to have a greater resistance for the fatigue crack growth. The discrepancy of the growth rates in the two types specimens may be dependent on the difference of the residual stress distributions between the CT and the CCT specimens.

Residual stress distributions

In order to explore a cause of the difference of the crack growth behavior in the weld metals between the CT and the CCT specimens, residual stress distributions of the both specimens were measured. Figure 5 shows an example of the residual stress distributions along X axis (crack growth direction) of the parallel specimen with 260mm width. As seen in the figure, the longitudinal residual stress, σ_y, which is located to the direction of the external applied load, is compressive near the tip of notch and the end of the specimen, while the tensile stress exists near the middle part of the specimen. The transverse residual stress, σ_x, which is located to the direction of parallel to the X axis, is tensile stress independent of the positions on the X axis. The longitudinal residual stress in the transverse specimen takes the lowest value at the position between the notch and the weld metal, and increases at the center in the weld metal and then decreases again toward the end of the specimen, as shown in Fig. 6. The most significant residual stress components in the welded CT specimens are the longitudinal residual stress, and the summation of the longitudinal residual stress and the applied stress is supposed to play a dominate role in the fatigue crack growth rates. On the other hand, the transverse residual stress may have little influence on the crack growth rates. As the result of the distributions of the longitudinal residual stress, the crack tips in the welded CT specimens may always be located in the field of compressive residual stress. Accordingly, the growth rates of the parallel or the transverse specimens were found to be lower than those of the base metal specimens. In the CCT specimens, however, the tensile residual stress exists in the vicinity of the notch sides of the middle part of the specimen, as seen in Fig. 7. Hence, the resistance of the crack growth in the weld metal of the CCT specimens may be lower than that of the CT specimens. Then, if the test results obtained by using CT specimens were used to evaluate the life of a welded structure, it might be difficult to insure the safety of the structure.

Estimation of crack opening load

It is suggested by Elber(9) that the influence of stress ratio on the fatigue crack growth rates is evaluated using the concept of effective stress intensity factor range, (ΔK_{eff}), which is based on the assumption that propagation occurs only when crack tip completly open. The residual stress influence on the growth rates may also be related to the crack opening phenomenon. For example, compressive residual stress perpendicular to the plane of crack counteracts the applied crack opening load, and thereby decreases the ΔK value calculated from the external applied stress. In this study, the crack opening loads, Pop, were measured by unloading elastic compliance method(5), and effective load ratios $U=\Delta K_{eff}/\Delta K$, were determined from the values of Pop. The curves in Fig. 9 show some examples of the relationship between the load, P, and the displacement, δ'. The displacement, δ', on the abscissa is expressed as $\delta'=\delta-\alpha P$, where δ is the crack opening displacement and α is the adjustable coefficient of the subtractive circuit. The vertical lines of the P-δ' curves in Fig. 9 mean that cracks are completly open, while the deviated parts from the vertical lines mean that crack are closed along the parts. As seen in Fig. 8, the crack opening loads decrease with increasing the crack length. Figure 9 shows the relationship between the effective load ratios, U, and crack length ratios, a/w, for some of the parallel, transverse and base metal specimens. The values of U in the parallel and the transverse specimens increase with increasing a/w, whereas the U values for the base metal specimens are approximately the same regardless of a/w. The crack growth rates of the specimens in which the values of U were measured, were reportted against $\Delta K_{eff}=U\Delta K$ instead of ΔK. As seen in Fig. 10, the growth rates of all the specimens fall within a narrow scatter band regardless of residual stress, specimen size and crack orientation with respect to the weld axis.

Conclusions

1. The fatigue crack growth rates of the welded CT specimens (the parallel and the transverse specimens) having widths of 100 and 260mm were roughly the same regardless of crack orientation with respect to the weld axis, while the growth rates in the CT specimens with width less than 100mm were faster than the larger width specimens. In the base metal specimens, the specimen size had no appreciable effect on the crack growth rates.

2. The fatigue crack growth rates of the welded CT specimens were markedly reduced as compared with those of the CCT specimens or of the base metal in the CT specimens, because the crack tips in the welded CT specimens are always located in the field of compressive residual stress which was induced by welding.

3. The fatigue crack growth rates of the welded CT specimens with residual stress and of the base metal specimens were well correlated with ΔK_{eff} estimated based on the crack opening load measurement.

References

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Table 1 Mechanical properties of the material used.

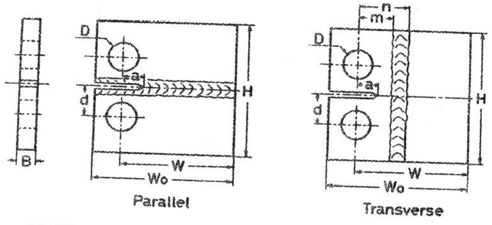
Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)
382	520	26

Table 2 Chemical composition of the material used. (wt.%)

C	Si	Mn	P	S
0.16	0.23	1.10	0.023	0.006

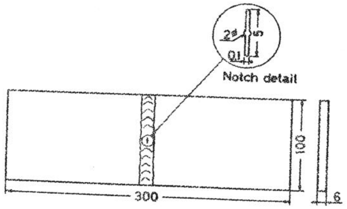
Table 3 Welding conditions

Groove	Double V
Electrode	JIS D5016
Dia. of electrode	4, 5, 6mm
Welding current	180~290 amps
Welding speed	250 mm/min.
Arc voltage	35 volts
Heat imput	15.1 24.4 KJ/cm
No. of runs	6



W	Wo	H	d	D	m	n	a	B
51	63.5	61	14	12.7	20	32	10	12.7
100	125	120	27.5	25	32	44	20	14
260	325	312	71.5	65	140	152	52	12

(a) CT specimens



(b) CCT specimen

Fig. 1 Dimensions and configurations of the welded specimens

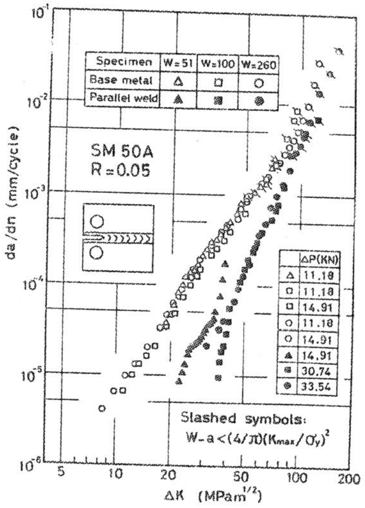


Fig. 2 Fatigue crack growth rates of the parallel and the base metal specimens with different sizes.

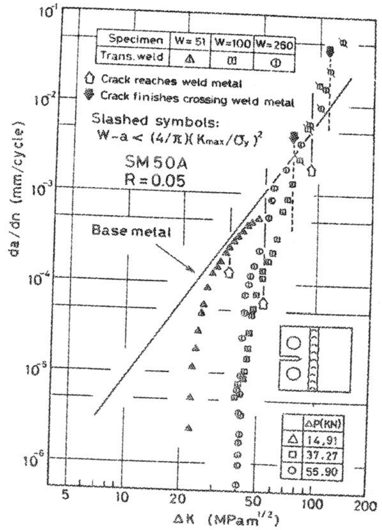


Fig. 3 Fatigue crack growth rates of the transverse specimens with different sizes.

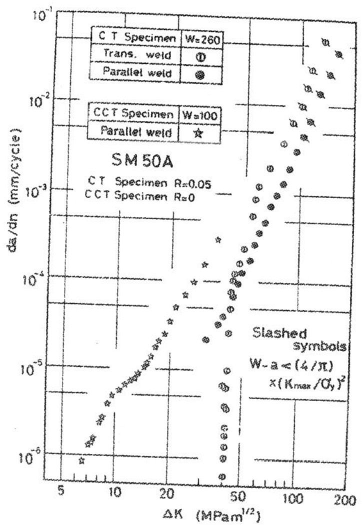


Fig. 4 Comparison of fatigue crack growth rates in the parallel and the transverse specimens.

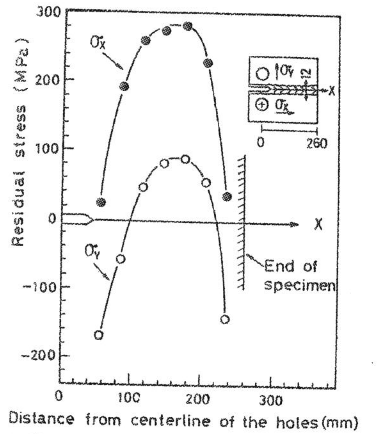


Fig. 5 Residual stress distribution of the parallel specimen.

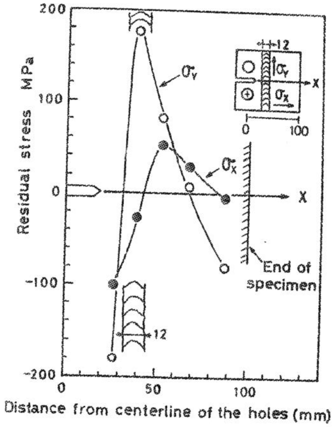


Fig. 6 Residual stress distribution of the transverse specimen.

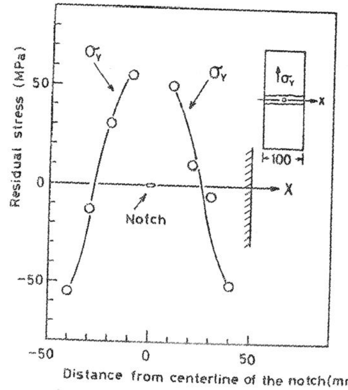


Fig. 7 Residual stress distribution of the welded CCT specimen.

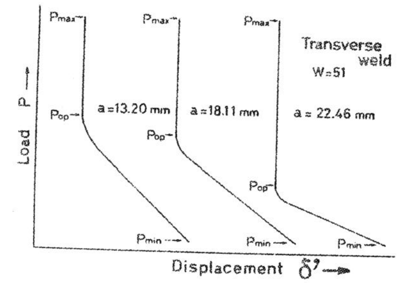


Fig. 8 Relationship between load and displacement.

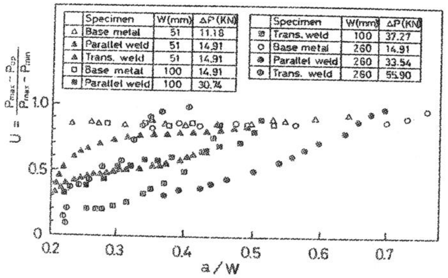


Fig. 9 Relationship between U and a/w.

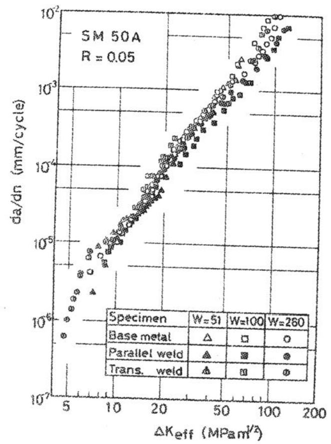


Fig. 10 Fatigue crack growth rates as a function of ΔKeff.