Title	An Experimental Study of Effect of Welding Residual Stress upon Fatigue Crack Propagation Based on Observation of Crack Opening and Closure(Welding Mechanics, Strength & Design)
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Citation	Transactions of JWRI. 8(2) P.265-P.271
Issue Date	1979-12
Text Version	publisher
URL	http://hdl.handle.net/11094/9471
DOI	
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An Experimental Study of Effect of Welding Residual Stress upon Fatigue Crack Propagation Based on Observation of Crack Opening and Closure†

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Abstract

The effect of welding residual stress on fatigue crack propagation was studied experimentally with chief attention paid to the crack opening-closure phenomenon. Two series of tests were carried out; one being made on longitudinally SAW-butt-welded specimens and the other on base metal specimens. Both series of tests used the same 80 kg/mm^2 high tensile strength steel center-notched specimens with the identical geometry and size. The observation of crack opening and closure was made by attaching extremely small wire strain gages at the points quite close to the crack line. It was found that the data of welded and base metal specimens with different stress ratios which scatter extensively on a da/dN - ΔK plot fall within a narrow band if they are replotted using ΔK_{eff}. This indicates that the effect of stress ratio and that of welding residual stress may be evaluated quantitatively on a systematic basis, if attention be paid to the crack opening and closing behavior and the crack tip stress intensity be evaluated by ΔK_{eff}.

KEY WORDS: (Fatigue Crack Propagation) (Welding Residual Stress) (Crack Opening and Closure)

1. Introduction

In spite of the recent considerable progress in fracture mechanics theories and applications, there seems to be few, if any, systematic investigations on the effect of welding residual stress on fatigue crack propagation. This paper constitutes a part of our research work program to clarify this problem.

In the past studies, a fatigue crack was regarded as a zero-width ideal sawcut and the behavior of a fatigue crack was discussed based on that of an ideal sawcut. But in the actual fatigue crack propagation, there exist such phenomena as the crack closure under cyclic tensile loading, which cannot be accounted for from the above standpoint. Elber[1)] pointed out that the crack opening and closing behavior of an ideal sawcut and that of a fatigue crack are different because in the case of a fatigue crack the cyclic plastic strain at the tip of a fatigue crack moves onto the crack surface with the extension of the crack, thereby causing the plastic deformation of the crack surface, and affects the opening and closing behavior. Since then, many researchers have confirmed that the phenomenon of crack opening and closure plays an important role in evaluating the behavior of fatigue crack propagation, so long as the behaviors of base metal specimens are concerned.

Although Elber paid attention only to the cyclic plastic strain, it is naturally expected that the residual plastic strain caused by welding heat input remaining on the crack surface may affect the crack opening and closing in the same manner. From this standpoint, this investigation studied the behavior of fatigue crack opening and closure in longitudinally butt-welded and base metal specimens, using extremely small wire strain gages and examined the effect of welding residual stress upon fatigue crack propagation based on these experimental observations.

2. Material and Test Procedures

The material used was 80 kg/mm^2 high tensile strength steel WT-80-C, and its chemical composition and mechanical properties are shown in Table 1 and 2 respectively.

Table 1 Chemical composition

C	Si	Mn	P	S	Cu	Cr	Mo	V	B	C_{eq}
0.12	0.26	0.88	0.017	0.005	0.23	0.89	0.31	0.04	0.0007	0.54

Table 2 Mechanical properties

Y.S. kg/mm^2	T.S. kg/mm^2	EL. %	Hv(10)
82	87	22	274

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† Received on October 6, 1979

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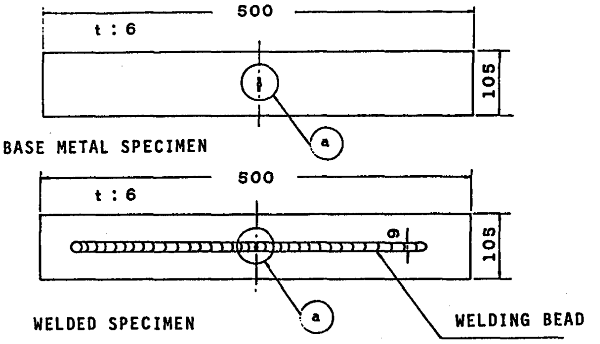
Transactions of JWRI is published by Welding Research Institute of Osaka University, Suita, Osaka, Japan

Fig. 1 shows the center-notched plate specimen. The welded specimen was prepared by submerged-arc-welding under "bead on plate" condition after making an edge preparation of 5.5 mm width and 2 mm depth to obtain a uniform distribution of welding residual stress across the thickness. The welding condition is shown in Table 3. The initial center notch (Fig. 2) was introduced after welding and its length was determined by taking into account the hardness distribution in the vicinity of the bead (Fig. 3). It can be observed from Fig. 3 that at the point 1 mm away from the HAZ, the value of hardness drops to that of base metal. Therefore, the half length of the initial center notch was chosen as 5.5 mm and the observation of fatigue crack propagation was started from



DETAILS OF A IS SHOWN IN FIG.2

Fig. 1 Geometry and size of specimen

Table 3 Welding condition

CURRENT	270 A
VOLTAGE	30 V
SPEED	52 cm/min
PREHEATING	NO
POSITION	FLAT
BACKING	COPPER PLATE
WIRE	Y-CS 1.6 dia.
FLUX	NF-16

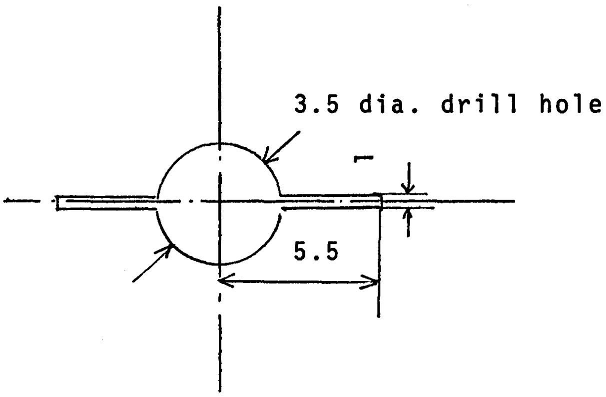


Fig. 2 Initial center notch

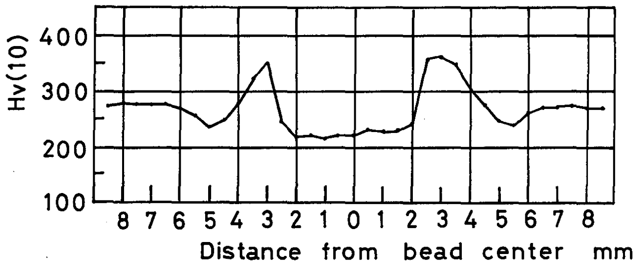


Fig. 3 Hardness distribution in the vicinity of weld bead

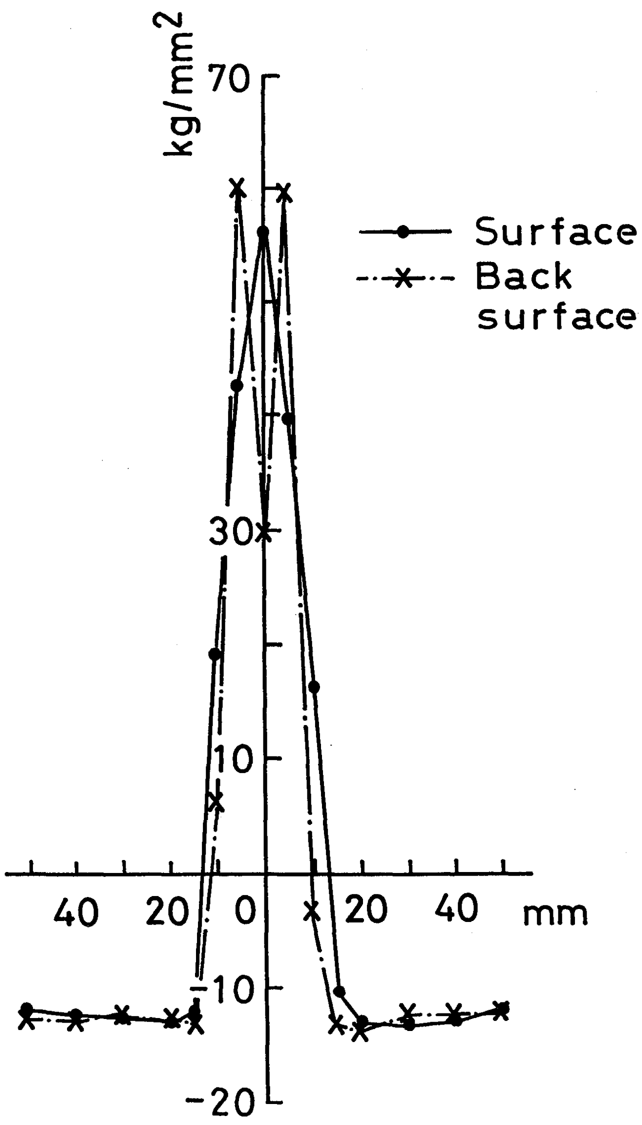


Fig. 4 Initial welding residual stress distribution before a notch is introduced

the point 1.5 mm away from the end of the initial notch. It is expected, therefore, that the dominant controlling factor in fatigue crack propagation may be more of mechanical nature, and that the effect of microstructure might be small. The initial notch of the identical size was introduced in the base metal specimen to compare with the results of welded specimens. An example of the initial welding residual stress distribution before the notch is introduced is shown in Fig. 4.

Tests were conducted by using an electrohydraulic closed loop servo fatigue testing machine under the conditions of Table 4. The testing frequency was 10 Hz. It was dropped, however, to 0.1 Hz or 1.0 Hz when observing a crack opening or closure.

Table 4 Test condition

	SPECIMEN NUMBER	STRESS RANGE $\Delta\sigma$ kg/mm^2	STRESS RATIO $R = \sigma_{min}/\sigma_{max}$
BASE METAL SPECIMEN	HB1	8.55	0.5
	HB2	8.51	0.2
	HB3	8.55	0
	HB4	11.51	-0.5
	HB5	11.94	-1.0
WELDED SPECIMEN	HW1	8.53	0.5
	HW2	6.42	0.5
	HW3	8.57	0.2
	HW4	8.55	0
	HW5	6.84	0
	HW6	8.55	-0.5
	HW7	8.55	-1.0
	HW8	8.54	$-\infty$

Crack length was measured by using a crack gage and the observation of crack opening and closure was made by attaching extremely small wire strain gages of 0.3 mm gage length at the points quite close to the expected fatigue crack extension line, and by observing these output signals on an oscilloscope (Fig. 5). As the output of the wire strain gage near the fatigue crack tip changes remarkably when the crack opens or closes, a deflection point is observed on an oscilloscope as can be seen in Fig. 6. Therefore, the timing or the stress at which the crack opens or closes can be determined by comparing the output signal of the wire strain gage near the crack tip with that of the load cell. But these observations on time axis are not so accurate. Therefore, in this investigation, the crack opening or closure was determined from a deflection point in a hysteresis curve between a load cell output (Y-axis) and an output of a wire strain gage near the crack tip (X-axis), as is illustrated in Fig. 7.

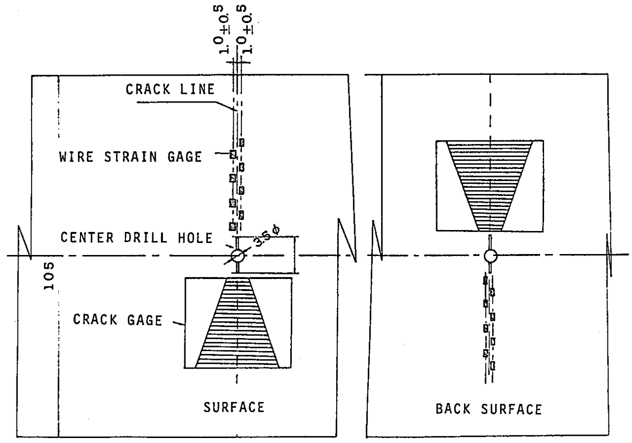


Fig. 5 Crack gage and wire strain gage location

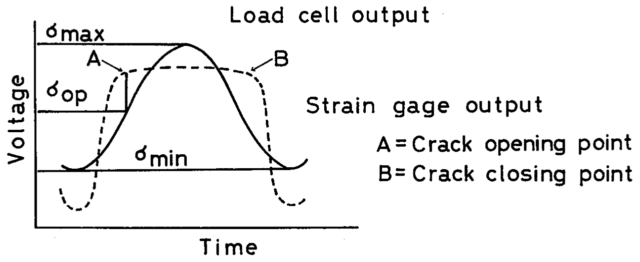


Fig. 6 Observation of crack opening and closure on time axis

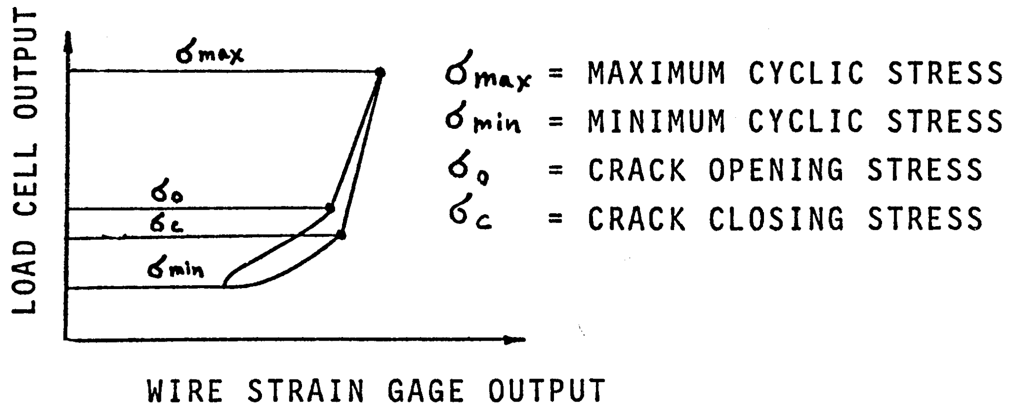


Fig. 7 Observation of crack opening and closure on X – Y axes

3. Test Results and Discussion

3.1 Fatigue crack propagation in welded and base metal specimens

Fig. 8 shows the relationship between fatigue crack propagation rate da/dN - Δ K for base metal specimens. Secant formula was used in evaluating Δ K. It can be seen that da/dN decreases with the decrease of stress ratio R, if the value of Δ K is the same.

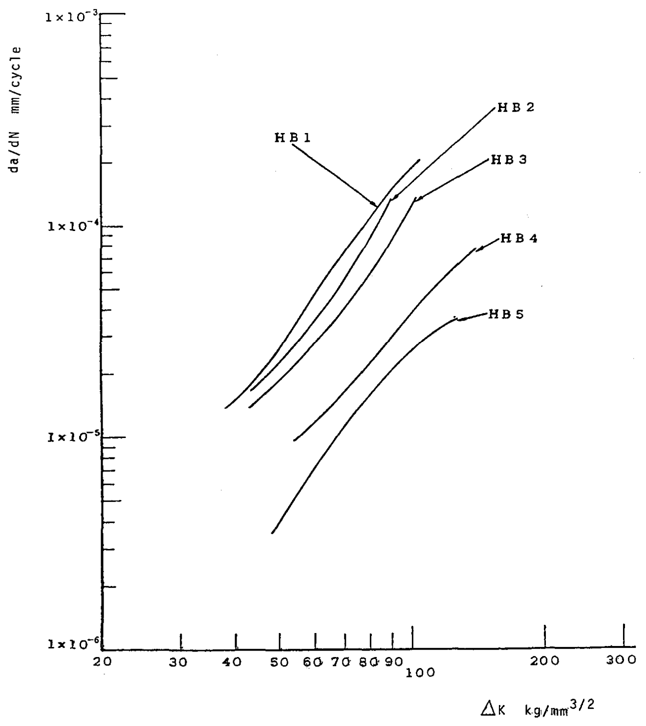


Fig. 8 da/dN – Δ K relation for base metal specimens

Fig. 9 shows the da/dN – Δ K relation for welded specimens. The stress ratio R shown in Fig. 9 represents the value which is evaluated only with respect to cyclic stresses. The data of welded specimens in small Δ K region or more precisely in small crack length region fall within a narrow band no matter what value the stress ratio may be, which is quite different from the case of base metal specimens. The data of HW8 which was obtained under repeated compression loading ($R=-\infty$) show that da/dN decreases quite rapidly after exceeding approximately Δ k=60 kg/mm$^{3/2}$. Unlike other cases, the right hand side data and the left hand side data of HW8 are quite different so each result is shown in the figure as HW8-A and HW8-B. But in either case of A or B, a crack is found to propagate even under repeated compression loading, where a crack is considered never to propagate if the welding residual stress is not present and the remarkable effect of welding residual stress can be observed.

Fig. 10 shows the results of base metal specimens (Fig. 8) and the results of welded specimens (Fig. 9) plotted together.

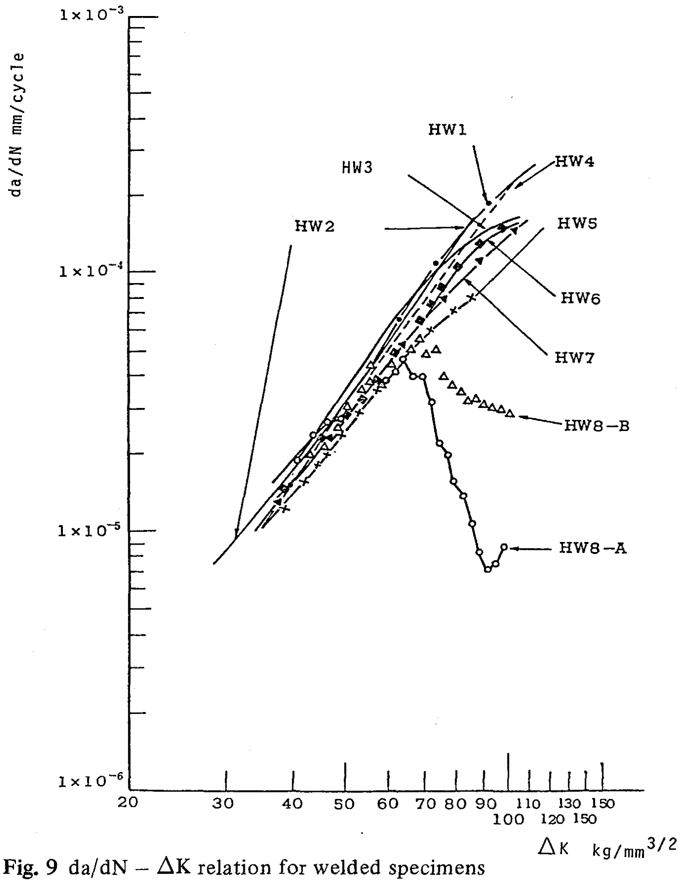


Fig. 9 da/dN – ΔK relation for welded specimens

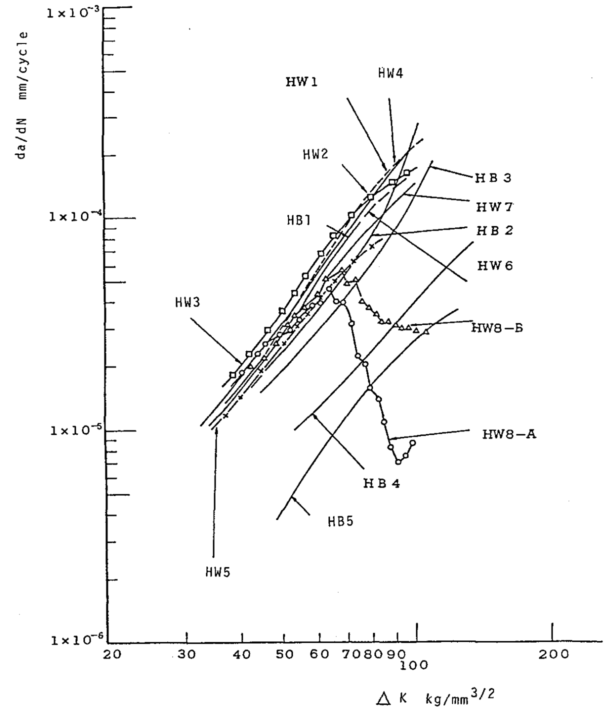


Fig. 10 da/dN – Δ K relation for base metal specimens and welded specimens

3.2 Observations of crack opening and closure

The results of observations of crack opening and closure in base metal specimens are shown in Fig. 11, using the crack opening ratio U. The crack opening ratio U is defined by the following equation;

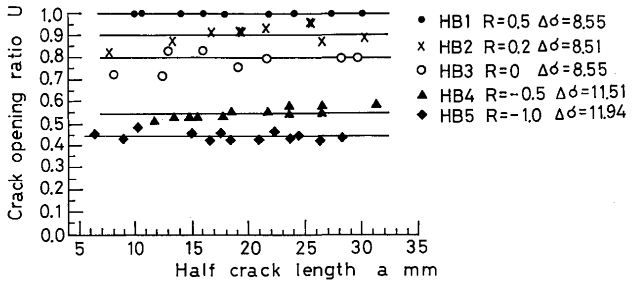


Fig. 11 U – a relation for base metal specimens

$$U=\frac{\sigma_{max}-\sigma_c}{\sigma_{max}-\sigma_c}=\frac{\sigma_{max}-\sigma_c}{\Delta\sigma} \qquad (1)$$

where σ_{max}=maximum cyclic stress, σ_{min}=minimum cyclic stress, $\Delta\sigma$=stress range, σ_c=stress at which a crack closes. The value of U denotes the ratio of the effective stress range which substantially contributes to fatigue crack propagation to the stress range $\Delta\sigma$ of external loading. Therefore, the effective stress intensity factor range ΔK_{eff} at a certain crack length can be evaluated by multiplying the corresponding "apparent" stress intensity factor range ΔK by the value of U at that crack length;

$$\Delta K_{eff}=U \times \Delta K \qquad (2)$$

Consider, for example, the case of R=0 in Fig. 11. If a fatigue crack can be regarded as an ideal zero-width sawcut, then it follows that the value of U is unity, because the plastic strain is zero on the crack surface in this case even if there is plastic strain at the crack tip. But the experimental result indicates that the value of U is 0.8. This difference in the value of U, i.e., the reduction of the amount of crack opening is Elber's effect, and it is caused by the plastic deformation of the crack surface which is induced by the crack tip cyclic plastic strain remaining on the crack surface after fatigue crack extension. In the case of base metal specimens, the value of U is almost constant regardless of the crack length and it decreases with the decrease of stress ratio R. This implies from Eq. (2) that ΔK_{eff} decreases, therefore da/dN decreases with the decrease of stress ratio R even if ΔK is the same and it supports the results of Fig. 8.

Fig. 12 shows the results of welded specimens. In the case of welded specimens, all values of U are unity regardless of the stress ratio R in the region where half crack length a is smaller than 14 mm. It should be noted that even in the case of repeated compression loading where a crack is expected never to open if it is regarded as an ideal zero-width sawcut the value of U is unity in this small crack length region. These results indicate that the effect of welding residual stress is quite remarkable especially in this region. The reason why all values of U are unity regardless of the stress ratio in this region is assumed to be because the crack closure is prevented by the large plastic strain on the crack surface which is produced by the welding heat input. Experimental results show that when a crack becomes longer, the crack closure takes place and the value of U decreases. This may probably be attributed to the fact that the plastic strain on the crack surface produced by welding decreases with crack extension. The value of U of HW1 and HW2 for R=0.5 are, however, unity for all crack length and crack closure was not observed.

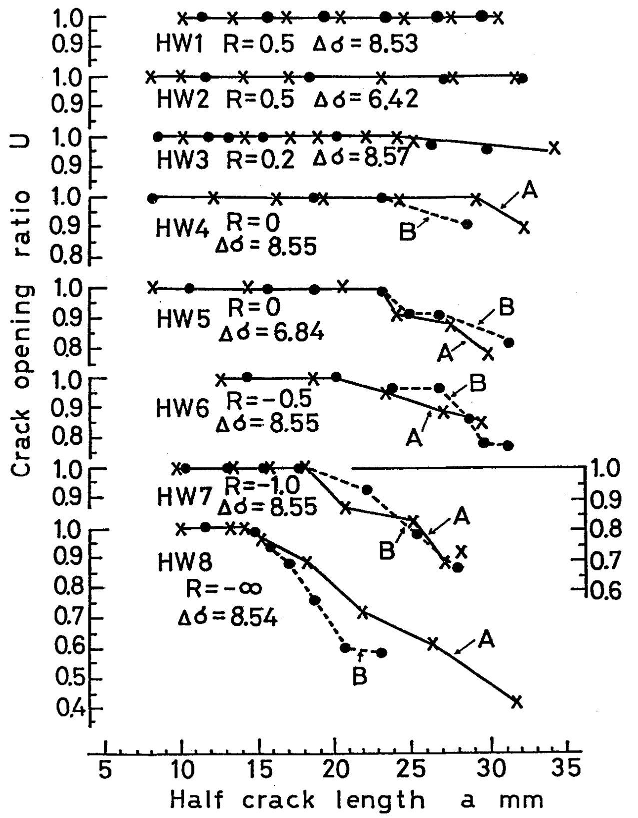


Fig. 12 U – a relation for welded specimens

3.3 Analysis by effective stress intensity factor range ΔK_{eff}

Fig. 13, Fig. 14 and Fig. 15 are the replots of the results of Fig. 8, Fig. 9 and Fig. 10 respectively, using ΔK_{eff} which is evaluated by Eq. (2) based on experimental-

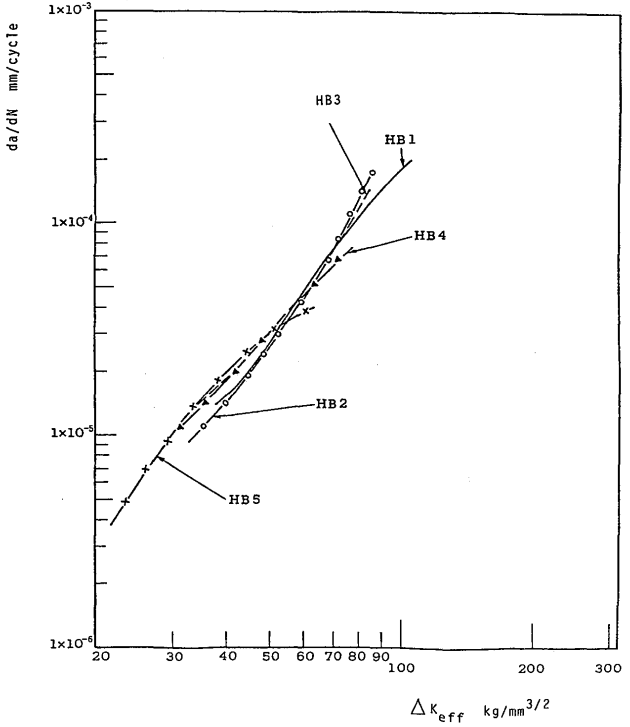


Fig. 13 da/dN – ΔK_{eff} relation for base metal specimens

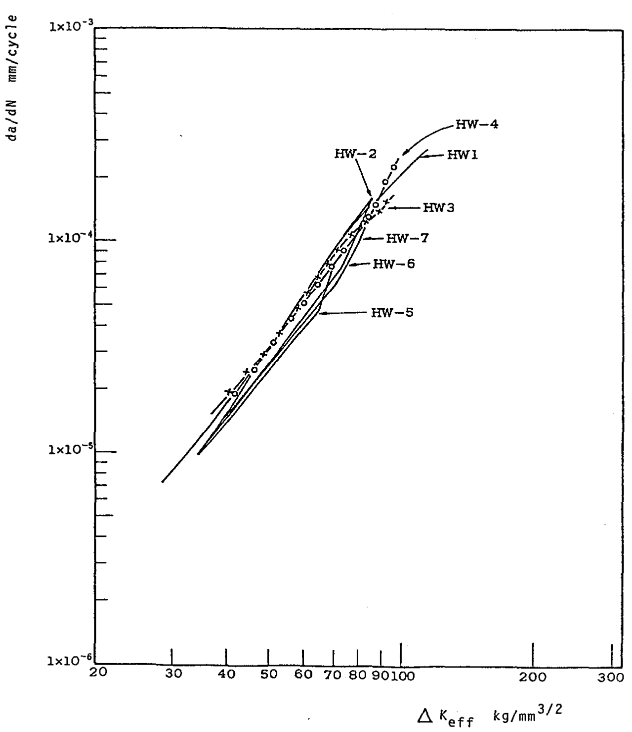


Fig. 14 da/dN – ΔK_{eff} relation for welded specimens

ly obtained U value. It is generally observed by comparing Fig. 8 – Fig. 10 with Fig. 13 – Fig. 15 that experimental results which scatter quite widely on da/dN – ΔK plots fall within a narrow band if they are replotted using ΔK_{eff}. Thus, it is easily understood that the behavior of crack opening and closure plays quite an important role in evaluating the effect of stress ratio R in base metal specimens (Fig. 8 and Fig. 13) and in evaluating the effect of welding residual stress in welded specimens (Fig. 9 and Fig. 14). Especially it should be noted that even the HW8 data of repeated compression loading which are quite far off in Fig. 9 fall within the same narrow band if they are replotted by ΔK_{eff}. By comparing Fig. 10 and Fig. 15 which show the results of all base metal specimens and all welded specimens respectively, it is known that the effect of stress ratio R in base metal specimens and the effect of welding residual stress in welded specimens can be treated quantitatively on the identical basis if attention is paid to the crack opening and closure phenomenon and effective stress intensity factor range ΔK_{eff} is used.

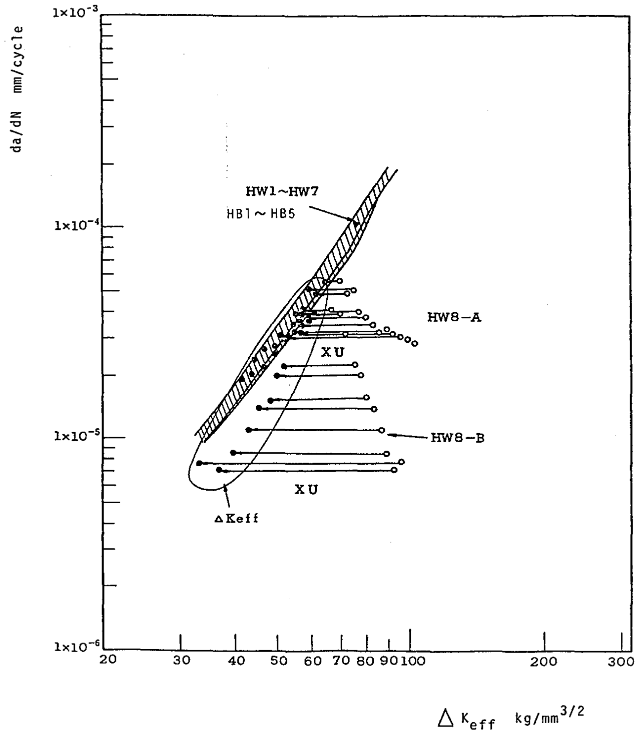


Fig. 15 da/dN – ΔK_{eff} relation for base metal specimens and welded specimens

4. Conclusions

The effect of welding residual stress upon fatigue crack propagation was studied experimentally using 80 kg/mm^2 high tensile strength steel specimens with chief attention paid to the phenomenon of crack opening and closure.

The major conclusions obtained are as follows:

(1) Although the lines of da/dN – ΔK differ for different stress ratios in the case of base metal specimens, the data of da/dN – ΔK for small crack lengths fall within a narrow band in the case of welded specimens, even though their stress ratios are different.

And in the presence of welding residual stress, fatigue cracks are found to propagate even under fully repeated compression loading.

(2) The crack opening ratio U's of welded and base metal specimens are evaluated based on experimental observations; in the case of base metal specimens, U's are almost constants irrespective of crack lengths and they decrease with the decrease of stress ratio R, but in the case of welded specimens, U's within the region of $a < 14$ mm were all obtained as unity, including even the case of fully repeated compression loading. This implies that within this region the crack is fully open and it shows the marked effect of welding residual stress.

(3) All data of welded specimens and base metal specimens which scatter quite extensively on $da/dN - \Delta K$ plots fall within a narrow band if they are replotted by ΔK_{eff}. This indicates the validity of the present approach and it implies that the effect of stress ratio in the case of base metal specimens and the effect of welding residual stress in the case of welded specimens may be evaluated quantitatively on the identical basis if attention is paid to the crack opening and closing behavior and effective stress intensity factor range is used.

Acknowledgements

The authors would like to thank Prof. Yoshiaki Arata, Director of Welding Research Institute, Osaka University for his encouragements.

Reference

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