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Effect of Residual Stresses on Threshold Value for Fatigue Crack Propagation†

Kohsuke HORIKAWA*, Atsushi SAKAKIBARA** and Takeshi MORI***

Abstract

The effect of welding tensile residual stresses on threshold value of stress intensity factor range for fatigue crack propagation was studied experimentally. Material used was steel of 800 MPa in tensile strength. Specimens were center-cracked-plates and consited of three kinds; base metal, welded joint with a longitudinal bead on center of specimen, and stress relieved welded joint.

Main results obtained are surmmarized as follows: Tensile residual stresses decreased the threshold value. The lower stress ratio was, the more remarkable the effect of tensile residual stresses on the threshold value was. When tensile residual stresses were large, the threshold value was unique and independent of stress ratio. Above results were closely related with fatigue crack closure phenomena.

KEY WORDS: (Fatigue Crack Propagation Rate) (Threshold Value) (Stress Intensity Factor) (Welding Tensile Residual Stress) (Stress Ratio) (Crack Closure Phenomena)

Nomenclature

ΔK	Stress intensity factor range, $MPa\sqrt{m}$
ΔKth	Threshold value of stress intensity factor range for fatigue crack propagation, $MPa\sqrt{m}$
da/dN	Fatigue crack propagation rate, mm/cycle
BM	Base metal specimen
WT	Welded joint specimen
SR	Stress relieved welded joint specimen
R	Stress ratio
ΔP	Load range, kN
Pmax	Maximum value of cyclic load, kN
Pmin	Minimum value of cyclic load, kN
Pop	Crack opening load, kN
U	Crack opening ratio
a_t	Crack length at the end of measurement, mm
C, m	Crack propagation constants in Eq. (2)
a	Crack length, mm
ΔKeff	Effective stress intensity factor range, $MPa\sqrt{m}$
(ΔKeff)th	Threshold value of ΔKeff, $MPa\sqrt{m}$
Kop	Crack opening stress intensity factor, $MPa\sqrt{m}$

1. Introduction

Some defects such as undercut and lack of penetration often exist in the welded joints of steel structures. When these joints are subject to repeated loads, fatigue cracks often initiate and propagate from the defect, and then the joints may deform. In this case, most of fatigue life is consumed in fatigue crack propagation process. Especially, crack propagation process when crack length is short and the range of stress intensity factor (ΔK) is small, occupies the greater part of fatigue life. From these standpoints, it is important to examine fatigue crack propagation behavior in the low rate of fatigue crack propagation for ensuring the safety against fatigue of welded joints. It is also important to measure threshold value of stress intensity factor range for fatigue crack propagation (ΔKth) because this value is relative to the endurance limit of fatigue strength.

Moreover, large tensile residual stresses exist in welded zone and its vicinity. It is known[1,2] that tensile residual stresses increase fatigue crack propagation rate (da/dN) and the effect of stress ratio on fatigue crack propagation is insignificant in the welded joints with large tensile residual stresses. The effect of welding residual stresses have been studied well in the middle da/dN region, where Paris's[3] rule holds good, but in the low da/dN region, there are a few studies about it. In this study, the effect

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of welding tensile residual stresses on da/dN in the low da/dN region and ΔKth-value has been examined experimentally. Moreover, the discussions were added to the results as based on the theory of fatigue crack closure phenomena[4].

2. Experiment

2.1 Material and specimens

The material used was 800 MPa lass quenched and tempered steel plate of 6 mm in thickness. The quenching temperature was 930°C, and tempering temperature was 625°C. The chemical composition and mechanical properties were shown in **Table 1**.

The preparation of specimens in this study was in proportion to the investigation of Watari et al[1]. The specimens were center-notched ones, whose configurations and dimensions were shown in **Fig. 1**. Three types of specimens were used; base metal (BM), welded joint (WT), stress relieved welded joint (SR). BM specimens were heat-treated (620°C, 1 hr) to relieve the residual stresses. WT specimens were prepared by micro-submarged-arc-welding process as beads-on-plate welds on an edge groove of 5.5 mm width and 2 mm depth. These specimens were used to observe the behavior of fatigue crack propagation in welding tensile residual stress field. The welding condition was shown in **Table 2**. SR specimens were done with postweld heat treatment (620°C, 1 hr). These specimens were used to observe the behavior of fatigue crack propagation in relieved welding tensile residual stress field.

Table 1 Mechanical properties and chemical composition of materials.

Yield point	Tensile strength	Elongation
755 MPa	819 MPa	20.6 %

(%)

C	Si	Mn	P	S	Cu	Cr	Mo	V	B
0.16	0.06	1.13	0.016	0.006	0.29	0.76	0.21	0.03	0.015

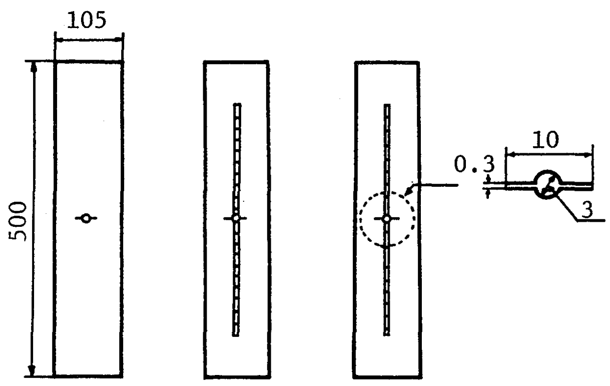

Fig. 1 Specimen configurations.

Table 2 Welding condition.

Wire	Y-CS ϕ1.6
Fused flux	NF-16
Welding position	Flat
Welding current	270 A
Arc voltage	30 V
Welding speed	52 cm/min.
Heat input	9.3 kJ/cm

2.2 Measurement of residual stresses

Residual stresses were measured from the changes of the outputs of strain gages, which were fixed in the sur-

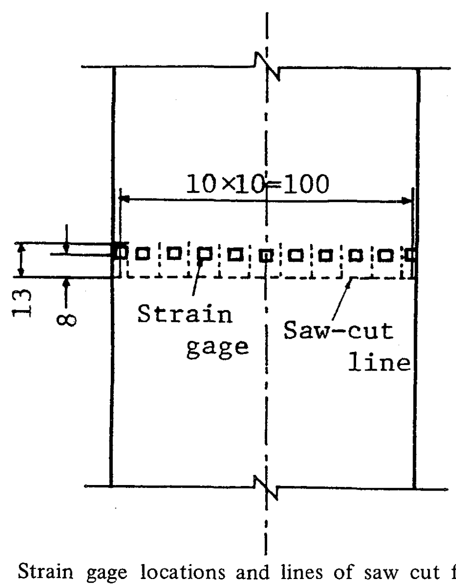

Fig. 2 Strain gage locations and lines of saw cut for measurement of residual stresses.

face and the back surface of the specimen as shown in **Fig. 2**, when the specimen was cut along the dash lines shown in this figure.

To investigate residual stress redistributions due to fatigue crack extension, the specimen was been cutting gradually from the center of it to right and left with a fretsaw of 0.2 mm in thickness. Whenever saw-cut cracks extended 10 mm, the outputs of the strain gages were obtained. And then the residual stress distributions at each length of saw-cut crack were obtained from the differences between the outputs at each length of it and the outputs after cutting the specimen completely.

To investigate residual stress redistributions due to cyclic loading, the changes of the outputs of the strain gages were observed after cyclic loading. The number of the cycles was 1 to 10^5. The cyclic loads applied were −35 to 35, 0 to 59, and 54 to 108 kN. These loads were equal to the initial loads in these fatigue crack propagation tests respectively.

2.3 Cyclic loading test

The cyclic loading tests were carried out by using an electro-hydraulic closed loop servo fatigue testing machine, whose dynamic capacity was 300 kN. The shape of the cyclic load was sine curve and its frequency was 10 to 30 Hz.

Testing conditions were shown in **Table 3**. To examine the effect of stress ratio (R), cyclic loads with two to four different R-ratios were applied to each type of specimens.

In welded joint specimens (WT) with R = 0 and stress relieved welded joint specimens (SR) with R = −1, ΔKth-values were measured at different crack lengths by using each two specimens to examine the effect of residual stress redistributions. And in WT-2b specimen (R = 0), ΔKth-values were measured twice at crack lengths of 14 and 33 mm.

Table 3 Testing conditions.

No.	R	a_0 (mm)	ΔK_0 (MPa$\sqrt{m}$)
BM-1	-1	6.09	17.9
BM-2	0	9.13	13.8
BM-3	0.5	7.57	13.9
BM-4	0.7	7.45	15.1
WT-1	-1	7.23	13.2
WT-2a	0	7.15	13.1
WT-2b(14)	0	9.87	6.6
WT-2b(33)	0	29.54	6.9
WT-3	0.5	7.35	11.9
SR-1a	-1	7.77	17.6
SR-1b	-1	16.56	19.5
SR-2	0	7.79	14.9

BM: Base metal
WT: Welded joint
SR: Stress relieved welded joint
a_0: Fatigue crack length at the beginning of measurement
ΔK_0: ΔK at the beginning of measurement

2.4 Measurement of fatigue crack propagation rate

Fatigue crack lengths were measured with a traveling microscope whenever the fatigue cracks propagated more than 0.1 mm. At the operation for measuring crack lengths, the frequency of cyclic loads was dropped to 1 Hz in order to make the operation easy. In welded joint specimens (WT), the measurements were begun when the fatigue cracks propagated more than 7 mm from the centers of specimens, since the values of hardness dropped to that of base metal at the points of 7 mm away from the center of the bead. In other specimens, the measurements were also begun after crack lengths reached 7 mm. ΔKth-value was defined as the ΔK-value when da/dN was equal to 10^{-7} mm/cycle[5].

The load range (ΔP) was decreased less than 5% of the previous ΔP as steps, as shown in **Fig. 3**, till da/dN was dropped from about 3 x 10^{-5} mm/cycle to less than 1 x 10^{-7} mm/cycle. Crack lengths were measured two or more times in one load step. ΔP was decreased when the difference between the two sequent da/dN-values in one load step was less than 20%. But when the difference was more than 20%, the cracks were propagated and crack lengths were measured, that is, ΔP was not decreased till the difference became less than 20%. And then the

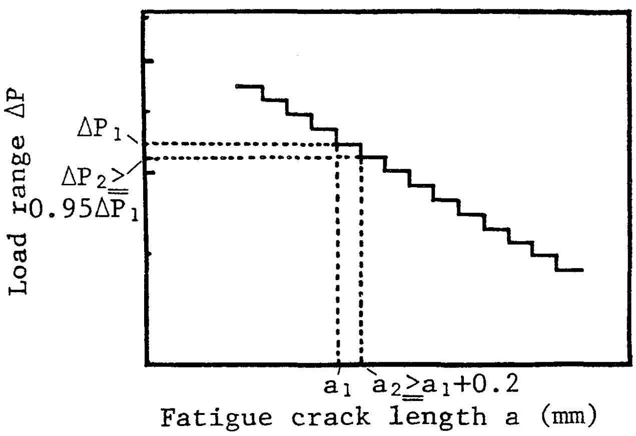

Fig. 3 Typical relationship between load range (ΔP) and crack length (a) in ΔK-decreasing test.

averages of the later two da/dN-values in one load step were used. In this way, the effect of fatigue crack growth retardation due to load interaction was taken away.

2.5 Measurement of crack opening ratio

To observe the behavior of crack opening and closure, strain gages (gage length 0.3 mm) were fixed along the expected fatigue crack extension line as shown in **Fig. 4**. **Figure 5** shows the relationship between a load cell output and an output of a strain gage near the crack tip. The crack opening point was defined as shown in this figure. The crack opening ratio (U) was calculated by

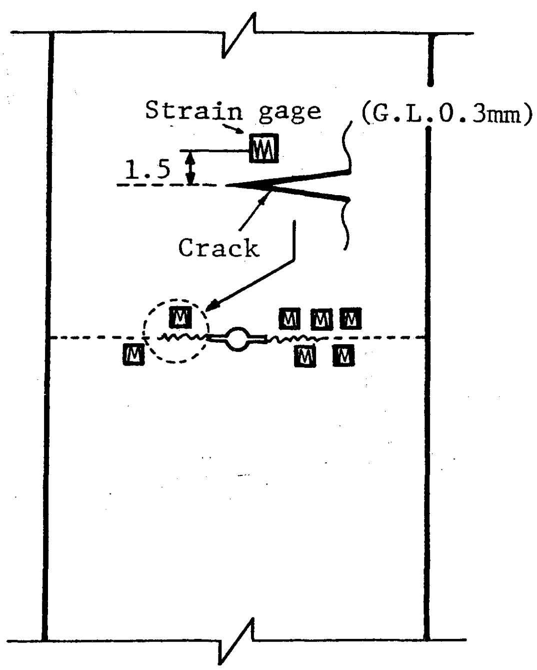

Fig. 4 Strain gage locations for measurement of crack opening ratio.

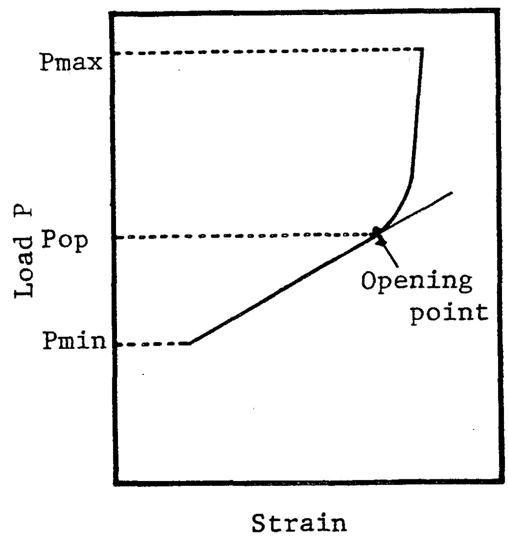

Fig. 5 Definition of crack opening point.

$$U = \frac{Pmax - Pop}{Pmax - Pmin} \quad (1)$$

where Pmax: maximum load, Pmin: miniumu load,
Pop: the load when the crack begins to open.

3. Results and Discussions

3.1 Residual stress distributions

Figure 6 shows residual stress distributions in all types of specimens. In base metal specimen (BM), the residual stresses were very small (–6.9 to 16 MPa). In welded joint specimen (WT), the residual stress at the center of the specimen was very large (290 MPa). In stress relieved welded joint specimen (SR), the residual stress at the center of it was dropped to 35 MPa by postweld heat treatment.

Figures 7 and 8 show redistributions of residual stresses due to extension of saw-cut crack in WT and SR specimens, respectively. The residual stresses were always maximum values near the crack tips, and these stresses were always tensile. It can be cosidered that redistributions of residual stresses due to fatigue crack extension are similar to that of saw-cut crack extension.

Besides residual stress distribution scarcely changed due to the three kinds of cyclic loading in WT specimens.

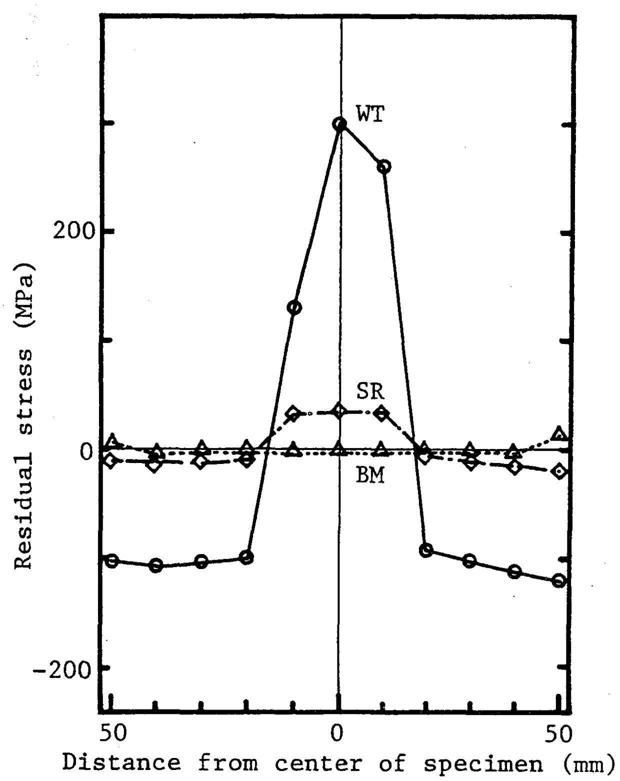

Fig. 6 Residual stress distributions.

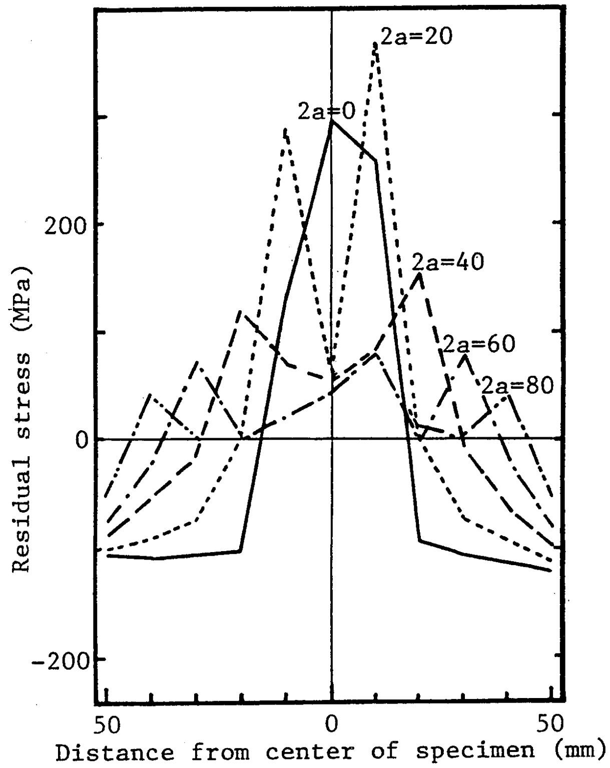

Fig. 7 Residual stress redistributions due to extension of saw-cut crack in welded joint specimen.

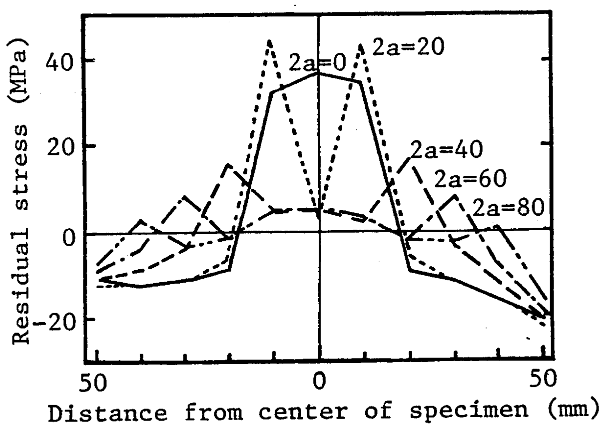

Fig. 8 Residual stress redistributions due to extension of saw-cut crack in stress relieved welded joint specimen.

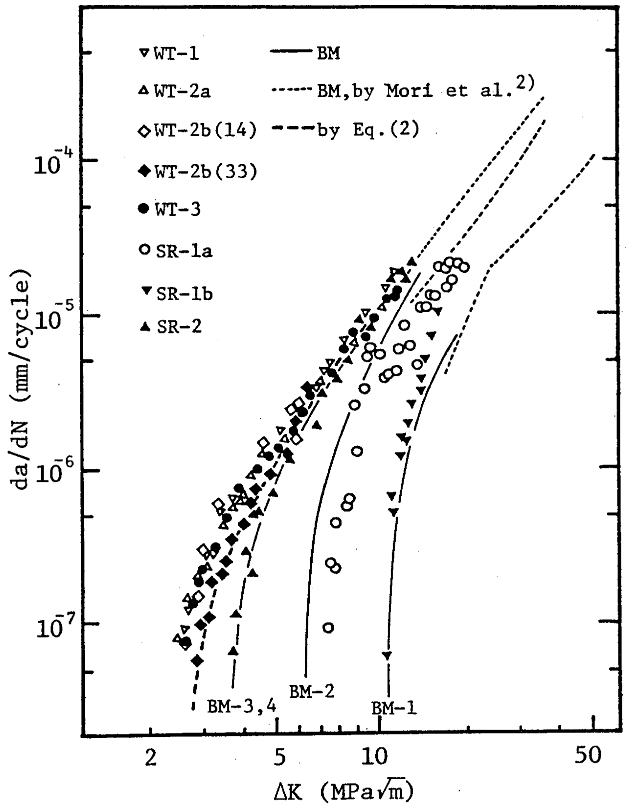

Fig. 9 Relations between fatigue crack propagation rate (da/dN) and stress intensity factor range (ΔK).

Table 4 Crack length at the end of measurement (a_t) and threshold value for fatigue crack propagation (ΔKth).

No.	a_t (mm)	ΔKth (MPa√m)
BM-1	8.33	11.8
BM-2	18.88	6.1
BM-3	18.29	4.0
BM-4	24.17	3.9
WT-1	19.54	2.7
WT-2a	24.66	2.7
WT-2b(14)	14.04	2.8
WT-2b(33)	33.30	3.0
WT-3	17.52	2.8
SR-1a	19.64	7.4
SR-1b	23.01	11.9
SR-2	17.01	3.9

3.2 Fatigue crack propagation rate

Figure 9 shows da/dN-ΔK relations in all specimens. **Table 4** shows ΔKth-values and the crack lengths at the end of measurements (a_t). ΔKth-values were measured at the crack lengths of a_t's.

In base metal specimens (BM), da/dN increased and ΔKth-value decreased with increase in stress ratio (R) in the range of $R \leq 0.5$. In the range of $R \geq 0.5$, da/dN-ΔK relations were almost the same and independent of R-ratio.

In welded joint specimens (WT), da/dN was high and ΔKth-value was small as compared with BM specimens. The da/dN-ΔK relations of three R-ratios (−1, 0, 0.5) were identical to one another, and those ΔKth-values were about 2.8 $MPa\sqrt{m}$. These relations were almost same to those in BM specimens with $R \geqq 0.5$ except around ΔKth-values. Moreover, these relations were the upper limit one obtained in this experiments. And these could be expressed by

$$da/dN = C(\Delta K^m - \Delta Kth^m) \qquad (2)$$

where C, m: constants.

When using mm/cycle for da/dN, and $MPa\sqrt{m}$ for ΔK and ΔKth, the value of C was 1.64×10^{-8}. The value of m was 2.72. And the ΔKth-value was 2.8 $MPa\sqrt{m}$. The dashed line in Fig. 9 was depicted by Eq. (2).

Besides in WT-2a specimen (a_t = 24.66 mm) and WT-2b specimen (a_t = 14.04, 33.03 mm), da/dN-ΔK relations around ΔKth-values were almost the same and independent of a_t. Tensile residual stresses near the crack tip decrease with the crack extending as shown in Fig. 7. Therefore, it can be considered that the effect of tensile residual stresses near the crack tip on da/dN-ΔK relation around ΔKth-value is saturated at the crack length of $a \leqq 33$ mm, in R = 0. Moreover, as R-ratio or ΔK-value became low or small, the effect of tensile residual stresses on da/dN-ΔK relation became remarkable. Particularly, the lower R-ratio was, the more remarkable the effect of tensile residual stresses on ΔKth-value was.

In stress relieved welded joint specimen (SR), the effect of R-ratio in the range of $R \leqq 0$ was observed. In R = −1, da/dN-ΔK relation around ΔKth-value in SR-1a specimen (a_t = 19.64 mm) was near to that in BM-2 specimen with R = 0, but that in SR-1b specimen (a_t = 23.01 mm) was almost same to that in BM-1 specimen with R = −1. That is, in R = −1, tensile residual stresses near the crack tip with the crack length of a ≑ 20 mm changed the da/dN-ΔK relation around ΔKth-value to that in the base metal specimen (BM) with R = 0. And it seems that the residual stresses at the crack length of $a \geqq 23$ mm hardly affect da/dN-ΔK relation around ΔKth-value. In R = 0, da/dN-ΔK relation in SR-2 specimen (a_t = 17.01 mm) was almost same to that in base metal specimens (BM) with $R \geqq 0.5$ and in welded joint specimens (WT) except around ΔKth-values. And ΔKth-value in SR-2 specimen was slightly larger that in WT specimens. That is, in R = 0, tensile residual stresses near the crack tip with the crack length of $a \leqq 17$ mm change da/dN-ΔK relation around ΔKth-value to that in WT specimens.

3.3 Crack opening ratio

Figure 10 shows relations between crack opening ratio (U) and stress intensity factor range (ΔK).

In base metal specimens (BM), crack opening ratio (U) increased as R-ratio became high in the range of $R \leqq 0.5$.

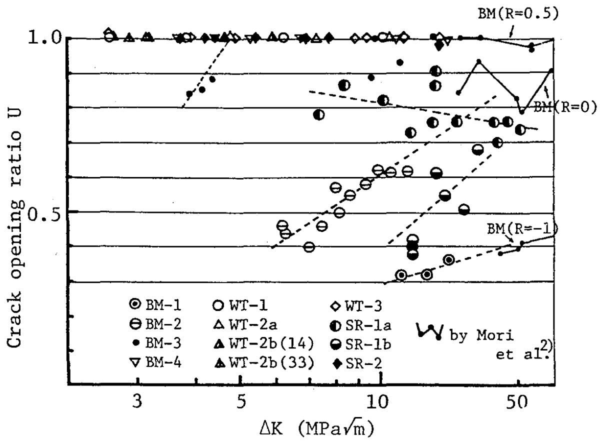

Fig. 10 Relations between crack opening ratio (U) and stress intensity factor range (ΔK).

In the range of $R \geqq 0.5$, U-ratio was almost equal to the upper limit of 1, except around ΔKth-value in BM-3 specimen with R = 0.5. Besides, around ΔKth-values, U-ratio decreased with decrease in ΔK-value, and the ratio was minimum when ΔK-value was equal to ΔKth-value in the range of $R \leqq 0.5$. Generally, it is known[2] that U-ratio in base metal specimen is constant independent of ΔK-value in the middle da/dN region. In the study by Mori et al.[2], where the same specimens and measurement method of U-ratio as this study were used, U-ratios for various R-ratios were equal to 0.4 (R = −1), 0.85 (R = 0), and 1 (R = 0.49). Therefore, U-ratio in BM specimen is constant independent of ΔK-value, but around ΔKth-value U-ratio decreases with decrease in ΔK-value.

In welded joint specimens (WT), U-ratio was higher than that in BM specimens, and it was always equal to the upper limit of 1 independent of ΔK-value. Besides U-ratio in WT-2a specimen (a_t = 24.66 mm) and WT-2b specimen (a_t = 14.04, 33.30 mm) was always equal to 1. Therefore it can be considered that the effect of tensile residual stresses near the crack tip on U-ratio is saturated at the crack length of $a \leqq 33$ mm, in R = 0. Moreover, the smaller ΔK-value was or the lower R-ratio was, the more remarkable the effect of tesile residual stresses on U-ratio was.

In stress relieved welded joint specimens (SR), the effect of R-ratio on U-ratio was observed. In R = −1, U-ratio in SR-1a specimen (a_t = 19.64 mm) increased gradually with decrease in ΔK-value. But U-ratio in SR-1b specimen (a_t = 23.01 mm) decreased largely with decrease in ΔK-value, and the U-ratio was almost equal to that in BM-1 specimen when ΔK-value was equal to ΔKth-value. That is, the effect of residual stresses on U-ratio around ΔKth-value is slight at the crack length of a ≧ 23 mm.

It seems that the difference in U-ratio of these specimen was caused by the following phenomena. That is, in SR-1a specimen, the phenomena that the effect of residual stresses increased with decrease in ΔK-value was remarkable, and in SR-1b specimen, the phenomena that tensile residual stresses near the crack tip decreased with the crack extending was remarkable. In R = 0, U-ratio in SR-2 specimen (a_t = 17 mm) was always equal to 1 and independent of ΔK-value. Therefore it can be said that tensile residual stresses near the crack tip with the crack length of a ≦ 17 mm change U-ratio around ΔKth-value to the upper limit of 1.

3.4 Discussions as based on theory of crack closure phenemena

Above results are discussed as based on the theory of crack closure phenomena. The theory is that the only range of stress intensity factor (ΔK) while a crack is opening affects fatigue crack propagation. And the ΔK-value is called effective stress intensity factor range (ΔKeff). ΔKeff-value is calcurated by

$$\Delta Keff = U \cdot \Delta K \quad (3)$$

where U: crack opening ratio.

Figure 11 shows the relations between fatigue propagation rate (da/dN) and effective stress intensity factor range (ΔKeff) in all specimens. da/dN-ΔKeff relations existed in narrow region rather than da/dN-ΔK relation. Similarly, threshold values of effective stress intensity factor range for fatigue crack propagation, (ΔKeff)th, were almost same to one another.

In BM-4, SR-2 and WT specimens, crack opening ratios (U) were always equal to the upper limit of 1 as shown in Fig. 10, and da/dN-ΔK relations were almost identical to one another as shown in Fig. 9. Therefore, it can be said that da/dN-ΔK relations in these specimens are equal to da/dN-ΔKeff relation. Namely, these relations are the upper limit of ones obtained from these types of specimens, and these ΔKth-values are the lower limit of ones obtained from them.

In base metal specimens (BM), U-ratio increased with increase in stress ratio (R). When R-ratio increased more, U-ratio became equal to 1 and it didn't increased more than 1 as result of definition of U-ratio. Therefore, as R-ratio becomes high, da/dN-ΔK relation gets near to da/dN-ΔKeff relation and ΔKth-value gets near to

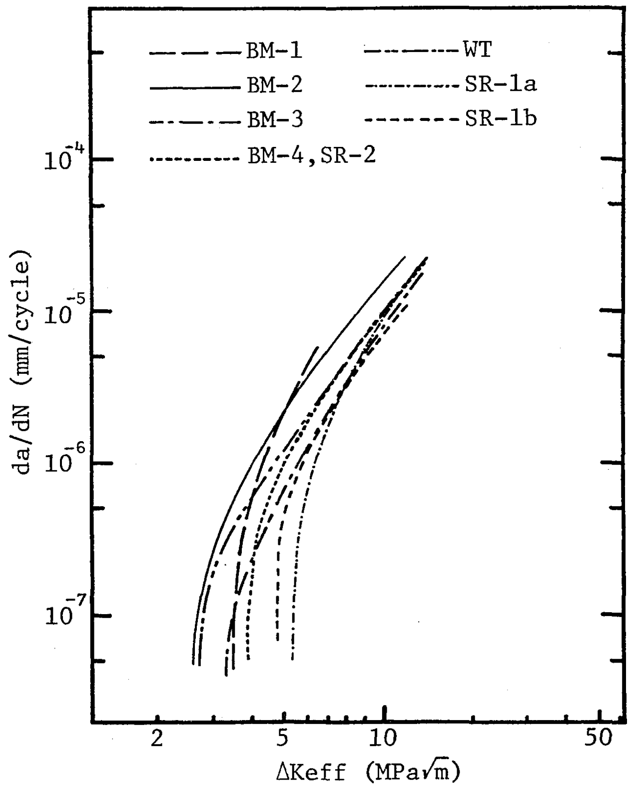

Fig. 11 Relations between fatigue crack propagation rate (da/dN) and effective stress intensity factor range (ΔKeff).

(ΔKeff)th, that is, da/dN increases and ΔKth-value decreases. If R-ratio increases more, da/dN-ΔK relation is equal to da/dN-ΔKeff relation of the upper limit and the effect of R-ratio is saturated.

In welded joint specimens (WT) and stress relieved welded joint specimens (SR), it seems that tensile residual stresses near the crack tip decrease crack opening stress intensity factor (Kop). Therefore, U-ratio increases with increase in tensile residual stresses. If tensile residual stresses increase more, U-ratio becomes equal to 1, and it doesn't increase more than 1. Namely, in the same as the effect of R-ratio, da/dN increases and ΔKth-value decrease with increase in tensile residual stresses. And it seems that if the tensile residual stresses increase more, the effect of the residual stresses is saturated. Moreover, if da/dN-ΔK relations for various R-ratios get equal to da/dN-ΔKeff relation, there is no effect of R-ratio. Besides, U-ratio is calculated by Eq. (1). Consequently, assuming that the change of crack opening K-value (Kop) by tensile residual stresses near the crack tip is independent of ΔK-value and R-ratio, the smaller ΔK-value is or the lower the U-ratio before the change of Kop due to the residual stresses is, the larger the change of U-ratio is. That is, as ΔK-value or R-ratio becomes small or low, the effect of tensile residual stresses becomes remarkable.

4. Conclusions

Based on the experimental results and subsequent discussions about the effect of welding tensile residual stresses and stress ratio on the relations between fatigue crack propagation rate and stress intensity factor range around the threshold value, the following conclusions have been drawn:

1) In base metal and stress relieved welded joint specimens, stress ratio (R) increased fatigue crack propagation rate (da/dN) and decreased threshold value of stress intensity factor range for fatigue crack propagation (ΔKth).
2) In base metal specimens, crack opening ratios were constant independent of stress intensity factor range (ΔK) in the middle da/dN region, but they decreased with decrease in ΔK-value in the low da/dN region and in the range of $R \leq 0.5$.
3) In welded joint and stress relieved welded joint specimens, tensile residual stresses increased da/dN and decreased ΔKth-value.
4) The smaller ΔK-value was or the lower R-ratio was, the more remarkable the effect of tensile residual stresses on da/dN-ΔK relation was. In particular, the lower R-ratio was, the more remarkable that on ΔKth-value was.
5) In welded joint specimens, there was no effect of R-ratio on da/dN-ΔK relation, and namely, ΔKth-value was independent of R-ratio. At this, crack opening ratio was always equal to 1. Therefore, it seems that this da/dN-ΔK relation is the upper limit and this ΔKth-value is the lower limit. If tensile residual stresses are larger than that of welded joint specimens, da/dN-ΔK relation and ΔKth-value are not changed.
6) All data of base metal, welded joint, and stress relieved welded joint specimens scattered quite extensively on da/dN-ΔK plots and ΔKth, but the data fell within a narrow band if they were replotted by effective stress intensity factor range (ΔKeff).
7) It is generally recognized that it is possible to explain the behavior of fatigue crack propagation with fatigue crack closure phenomena in the middle da/dN region where Paris's rule holds good. In the same way, it was also possible in the low da/dN region around ΔKth-value.

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