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Fatigue Crack Growth in the Corner Weld of Box-Section Bridge Truss Chords

Propagation de fissures dues à la fatigue dans les soudures d'angle des membrures en caisson d'un pont à poutres en treillis

Analyse des Wachstums von Ermüdungsrissen an Ecknahtschweissungen von Trägergurten

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SUMMARY
Fracture mechanics concepts of fatigue crack growth are applied to investigate the effects of weld defects and residual stresses on the fatigue life of the corner welds in box-section members of a bridge truss.

RESUME
Les concepts de la mécanique de la rupture concernant la propagation de fissures dues à la fatigue, sont appliqués pour contrôler les effets des défauts de soudure et des contraintes résiduelles sur la durée de vie des soudures d'angle dans les membrures en caisson d'un pont à poutres en treillis.

ZUSAMMENFASSUNG
Konzepte der Bruchmechanik werden auf das Wachstum von Ermüdungsrissen angewandt. Dies erfolgt zur Untersuchung der Auswirkungen von Schweissnahtstellen und Restspannungen auf die Dauerfestigkeit von Ecknahtschweissungen an Kastenträgern.

1. INTRODUCTION

Recently in Japan, partially penetrated single-bevel-groove welding is usually employed for fabrication of box section truss member. For railway bridges in Japan [1], this joint is classified into Category A regardless of steels, which is the highest design fatigue allowable stress group in joint classification. (O - Tension : 150 MPa). The same value of allowable stress had been considered to be employed in Honshu-Shikoku Bridges which use up to 800 MPa class high tensile strength steel [2].

In the large-scale-model fatigue tests carried out by Honshu-Shikoku Bridge Authority in 1975 [3] and 1978, fatigue cracks occurred at corner weld of truss chord member after by far smaller number of repetitive loadings such as could hardly expected from the fatigue test results in the past. It was considered that these cracks were caused by such defects as bad penetration and blowholes at the root of corner weld, and extremely high tensile residual stress existed in the cracked zone.

The main objective of this paper is to clarify the properties of initiation and growth of fatigue cracks from the various weld defects at the root of corner welds. It is also examined that the influence of residual stress on fatigue crack growth rate. Furthermore, based on the results of these, fatigue crack growth life are predicted using fracture mechanics concept.

2. FATIGUE STRENGTH OF PARTIALLY PENETRATED LONGITUDINAL WELDS

2.1 Influence of Weld Residual Stress

Influence of residual stress was examined by comparing the fatigue strengths between joint specimens and small test pieces. Fig. 1 shows the configurations and dimensions of these specimens. Small test pieces were cut off from the weld zone of joint including weld root. Steel for testing was 800 MPa class high tensile strength steel. Both of joint specimen and small test piece were welded manually. The measured residual tensile stress in the direction of welded line was about 400 MPa in weld zone of joint specimen, while residual stress of small test piece was

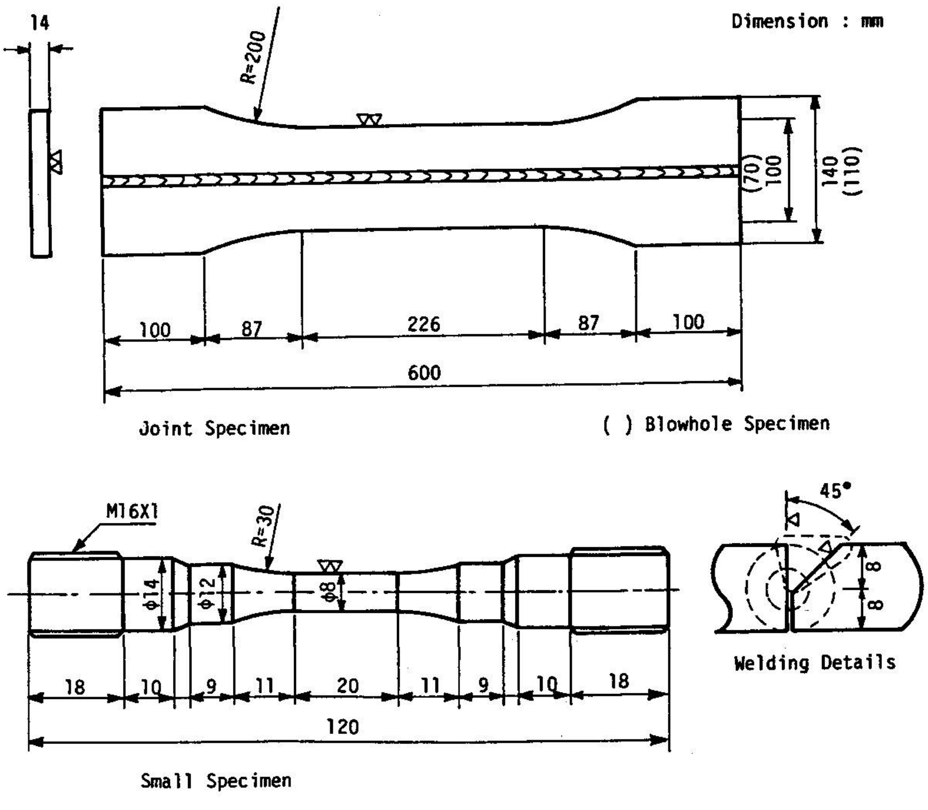

Fig. 1 Configurations and Dimensions of Specimens

completely released because this was extracted from weld zone of panel.

Fig. 2 shows the result of fatigue tests. The great difference is observed in fatigue strengths between joint specimens and small test pieces. Fatigue crack in both of joint specimen and small test pieces were initiated from root portion of weld. Considering the fact that in both type specimens the location of fatigue crack initiation are same and the cross sectional area is larger in joint specimen than that of small test piece, it is thought that the great difference of fatigue strength originated in residual stress.

2.2 Influence of Blowhole

Fig. 3 shows the results of fatigue tests of joint specimens containing blowholes in these root zone. Steel for specimen was 600 MPa class high tensile strength steel. The configuration and dimension of specimen are shown in Fig. 1. Submerged arc weld was employed for welding. Specimens were classified in accordance with the maximum width (w) of blowholes which was measured by radiographic examination. It was found that fatigue strength of no defect joint and small blowhole joint were almost same level, while fatigue strength remarkably decreased in proportion to blowhole getting larger. The occupation of blowholes in the cross sectional area was less than 0.7%, therefore area diminution by blowholes was negligible.

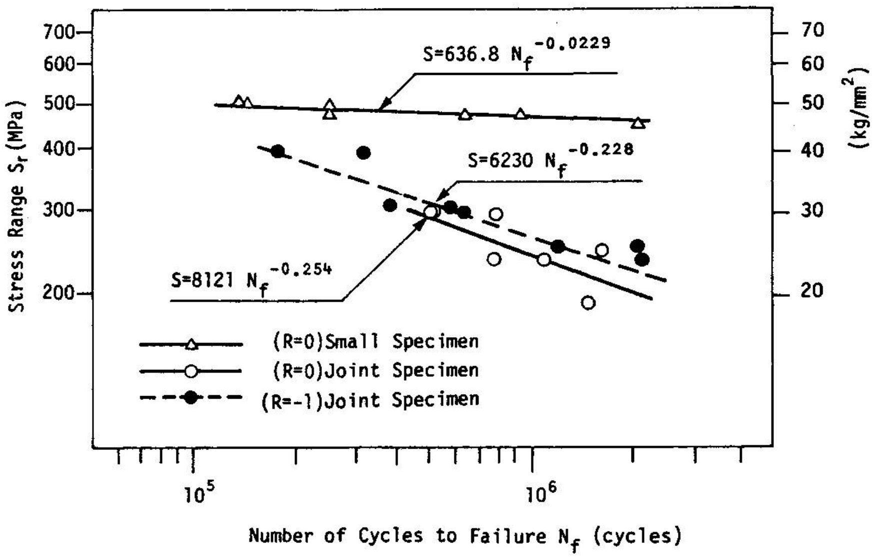

Fig. 2 Fatigue Test Results (Infruence of Residual Stress)

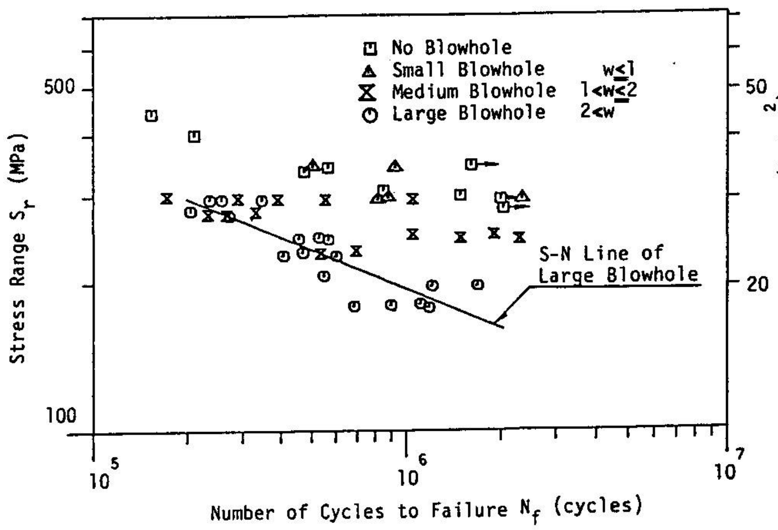

Fig. 3 Fatigue Tests Results (Influence of Blowhole)

3. INITIATION AND GROWTH OF FATIGUE CRACK

When stress condition is changed after a fatigue crack has initiated, the striae called beach mark is left on the fracture surface. In order to clarify the initiation and growth properties of fatigue crack, beach marks were intentionally left on the fracture surface by reducing stress range to half (Beach mark test).

Fig. 4 shows the result of beach mark test on manually welded joint specimen. This specimen was failed out during the ninth halving of stress range and eight beach marks were left on the fracture surface. It is clear that the most inner beach mark was formed by the first halving of stress range. If crack initiation life (Nc) is defined as the number of cycles until formation of the most inner beach mark, Nc/Nf equals to 0.11. (Nf : failure life, Nc, Nf : not including the number of cycles in the period of stress range halving.) Therefore, most of the fatigue life was spent to the growth of fatigue crack. The initial fatigue crack was combined with the second crack which initiated shortly late, and the combined crack grew in the whole part of non weld zone while becoming circular. It was immediately before failure that this fatigue crack appeared at the surface of the specimen.

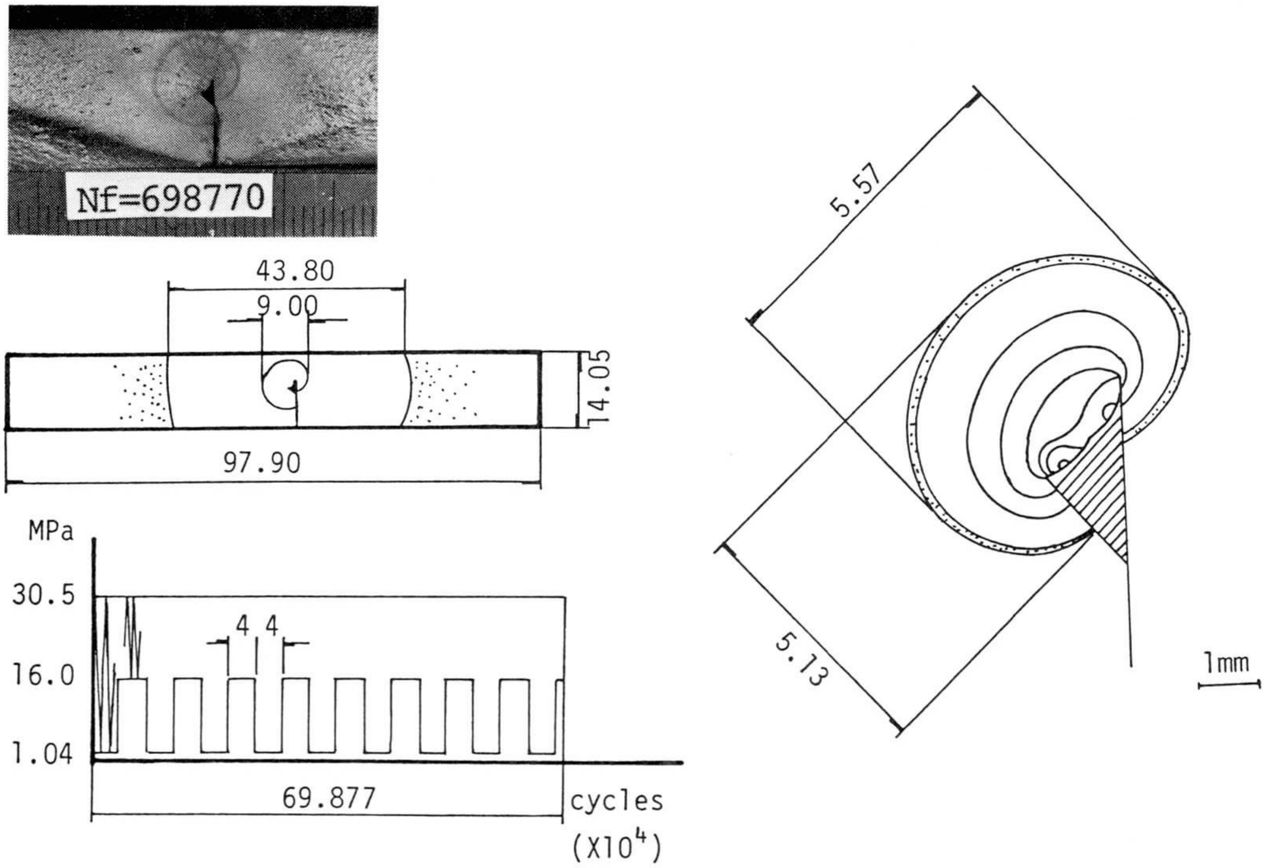

Fig. 4 Result of Beach Mark Test (Manually Welded Joint)

Fig. 5 shows the results of beach mark tests performed to submerge arc welded joint specimens. By radiographic examination given before test, specimen No. 2 was classified into no defect, No. 45 to medium blowhole, and B16 into large blowhole. In the specimen No. 2, fatigue crack was initiated from microscopic blowhole which existed in root zone, and grew into orbicular shape. In No. 45, fatigue crack was initiated from several points of the wall of tubular blowholes at the almost same time and grew into semi-circular shape. In B16, fatigue crack was initiated in the bottom face which contained semi-spindle shape blowholes and grew into semi-circular shape. The dimensions (width x depth) of beach marks at the most inner side of each specimen No. 2, No. 45 and B16 are 0.5 x 0.3 mm, 0.6 x 0.2 mm, and 1.3 x 1.6 mm respectively. Nc/Nf was 0.76, 0.44 and 0.24 respectively.

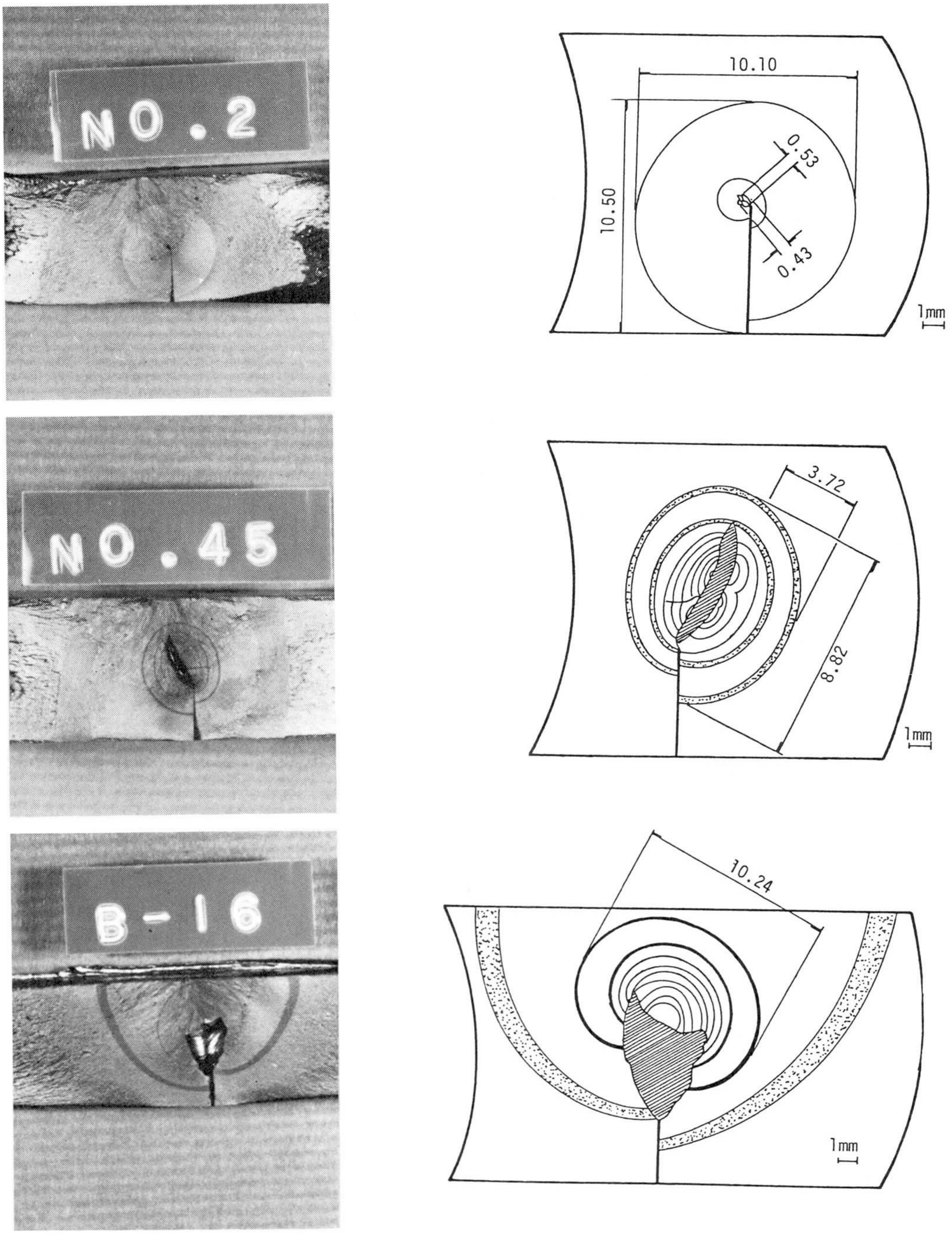

Fig. 5 Results of Beach Mark Tests (Blowhole Specimens)

4. INFLUENCE OF RESIDUAL STRESS ON FATIGUE CRACK GROWTH RATE

Fatigue crack growth tests were performed using center-crack-specimens shown in Fig. 6. Steel for testing was 800 MPa class high tensile strength steel. Weld residual stress was introduced by placing one longitudinal weld bead on the specimen. After measuring weld residual stress, it was found that 400 - 500 MPa of axial tensile residual stress existed in B-I and B-II type specimen. In A-II type specimen, 100 MPa of tensile residual stress also existed.

Fig. 7 shows the relation between fatigue crack growth rate (da/dN) and stress intensity factor range (Δk). In the region where Δk exceeds 16 MPa$\sqrt{m}$, any difference was not observed in da/dN - Δk relations in four types of specimens. However, in A-1 type specimen, fatigue crack growth rate rapidly decreases in the region where Δk is under 9.5 MPa $\sqrt{m}$ and threshold stress intensity factor range (Δk_{th}) is 9.0 Mpa $\sqrt{m}$. In other three types of specimen, Δk_{th} is 2.5 MPa $\sqrt{m}$. From this observation, it can be said that influence of residual stress is distinguished in the low Δk region.

The following equation is employed for obtaining relation among da/dN - Δk and Δk [4].

$$da/dN = c(\Delta k)^m - c(\Delta k_{th})^m \quad (1)$$

c, m maintains 5.47 x 10 and 3 respectively for quench and tempered steels by adjusting much of data. The two curves in Fig. 7 shows the result of calculation under which c, m and Δk_{th} = 9.0, 2.5 was put into the eq. (1). Both of two curves show good coincidence with the experimental values.

5. PREDICTION OF FATIGUE CRACK GROWTH LIFE

Fatigue crack growth life (Np) was predicted based on the following

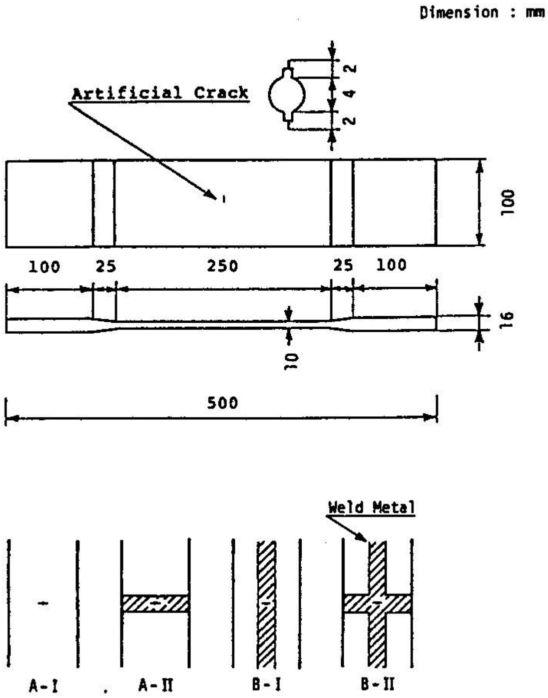

Fig. 6 Specimen for Crack Growth Tests

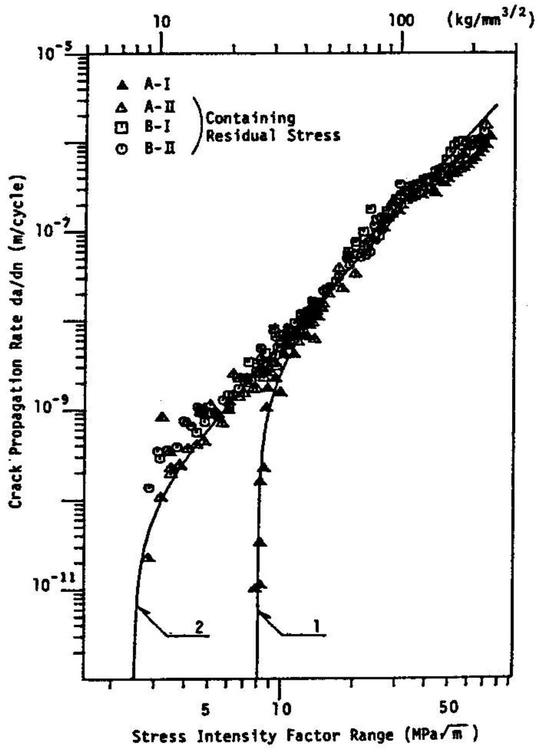

Fig. 7 Fatigue Crack Growth Rate

assumptions.

(i) The initial defect is regarded as a penny-shape crack. Fatigue crack grows keeping penny shape. Consequently stress intensity factor against this crack is calculated by the Eq. (2).

$$\Delta K = S_r\sqrt{\frac{\pi a}{Q}\sec(\pi a/t)}\,(1 - 0.025\lambda^2 + 0.06\lambda^4)$$
$$Q = \{E(h)\}^2 - 0.212\,(\sigma/\sigma_Y)^2 \qquad (2)$$

where
ΔK : Range of stress intensity factor
S_r : Stress range
a : Radius of a crack
Q : A parameter of defect form
E(h): Complete elliptic integral of the second kind, equal here to $\pi/2$
λ : 2a/t
t : Plate thickness

(ii) The final crack size (af) is supposed to be 90% of the distance from the point of crack initiation to the plate surface.

(iii) Regarding to the relation of da/dN - Δk, the curve 1 in Fig. 7 is employed for the case that fatigue crack grows in the field where weld residual stress does not exist, and the curve 2 in Fig. 7 for the growth in tensile residual stress field.

Fig. 8 shows the result of prediction of fatigue crack growth life corresponding to the results of experiment shown in Fig. 2. The initial crack size (ai) was supposed to be 0.2mm. A radius of inscribed circle to non weld metal zone which remained in the root zone was 0.3 - 0.5 mm, therefore ai was a little bit smaller than that. The predicted Sr - Np life curve in both of joint specimen and small test piece showed a good coincidence with that of experimental results. (Sr - Nf). Accordingly it is clear that the big difference of fatigue strength between joint specimen and small test piece is caused by the acceleration of fatigue crack growth rate by residual tensile stress especially in the low Δk region.

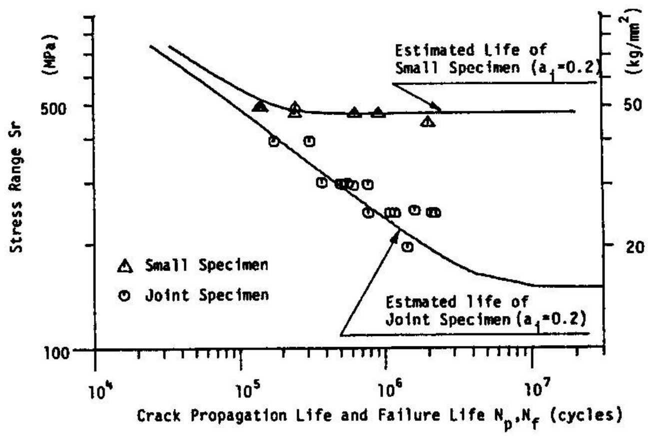

Fig. 8 Predicted S-Np Curves and Test Results (Manually Welded Joints)

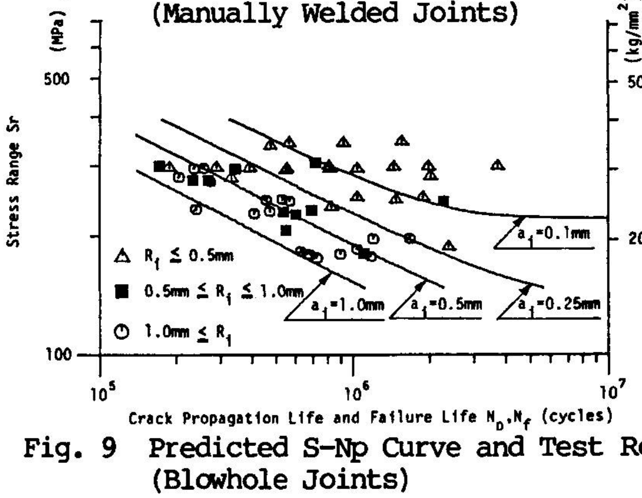

Fig. 9 Predicted S-Np Curve and Test Results (Blowhole Joints)

Fig. 9 shows predicted fatigue crack growth life corresponding to that of experiments shown in Fig. 3. The initial crack size (ai) was supposed to be 0.1, 0.25, 0.5, 1.0 and 2.0 mm. The test value (Sr - Nf) were classified and plotted in accordance with a radius of inscribe circle of blowhole. The test results which were classified into Ri = 0.5 varies in wide range, however, predicted Sr -Np curve based on assumption of ai = 0.5 is positioned at rather long life side. This is due to the fact that a pretty lot of stress repetition was needed until the occurrence of fatigue crack. The test results which were classified into 0.5 Ri 1 were plotted between predicted Sr -Np curves of ai = 0.5 and ai = 1.0. Most of the test results which were classified into 1 Ri were plotted at the longer life side than predicted Sr - Np curve of ai = 1.0. Replacement of blowhole to the initial crack of inscribed circle dimension means prediction of life of lower bound [5], while this estimation had a good coincidence with test results, and never gave risk side predicted results.

6. CONCLUSIONS

The principal results obtained in this study are as follows.

(1) In partially penetrated longitudinal weld, the reduction in fatigue strenth due to welding residual tensile stress is very substantial. As the blowholes in weld root become larger, the fatigue strength decreases.

(2) Fatigue crack is initiated and begin to propagate at extremely early stage of stress repetitions. Fatigue crack propagate while becoming circular.

(3) The influence of residual tensile stress on fatigue crack growth rate is distinguished in the low Δk region.

(4) The predicted Sr - Np curves obtained based on the results above are very close to the experimental results in various kinds of longitudinal welds.

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