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EFFECT OF STRESS RELIEF ON FATIGUE STRENGTH OF HIGH STRENGTH STEEL CORNER JOINT WITH BLOWHOLE

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The effect of low-temperature stress relieving was examined, using a partially penetrated groove weld with a blowhole. Box section specimens measuring 200 mm (W) × 250 mm (H), made of 15 mm thick 600 MPa class steel were tested.
The result proved that stress relief could reliably improve fatigue strength. Compared with the as-welded specimen, the 2 000 000-cycle strength of the treated weld increased by about 20 MPa.

1. INTRODUCTION

The partially penetrated groove weld is commonly used for the corner joints of box sectional members such as the truss chord. Some fatigue tests have been carried out on the partially penetrated joint of quenched and tempered high strength steel. These tests have proved that fatigue cracks originate from weld defects, such as blowholes at the root of the weld, and that the fatigue strength of the large size specimens considerably lower than that of the small specimens[1),2)]. The latter phenomena has been explained as being the effect of tensile residual stress[3)~6)]. On basis of these test results, the Honshu-Shikoku Bridge fatigue specifications classify a partially penetrated groove weld as being Category B[7)]; and disallow blowholes exceeding 1.5 mm in diameter[8)].

A blowhole over the tolerable size needs to be repaired. But it is feared that repair welding might lead to larger residual stresses and to other weld defects. A survey of the bridge in service shows that inadequate or defective weld repairs are a significant source of discontinuities[9)].

The authors prefered to reduce the tensile residual stress on the defective region rather than to repair it by welding. The technique for the reduction of local tensile residual stress at the corner joint was examined, and a low-temperature stress relieving method using an electric heater was developed[10)]. The effectiveness of this method was confirmed on a large-scale box member (1 000 mm×1 000 mm made of 40 mm thick 700 MPa class steel)[11)]. The characteristics of this method of stress relief is that it can be performed quickly, efficiently and economically on large box sectional chords.

This paper summarizes this method of fatigue strength improvement, as applied to a corner joint with blowholes. Box sectional specimens with 200 (W) ×250 (H) made of 15 mm thick 600 MPa class steel were

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tested for the three grades of the residual stress, namely : as-welded, reduced and more reduced.

2. SPECIMEN

(1) Specimen Fabrication

The specimen is a welded built-up box section of 15 mm thick 600 MPa class quenched and tempered steels. Fig. 1 shows the configuration and dimensions of the specimen. The chemical compositions and mechanical properies of this steel are shown in Table 1. The corner joints of this specimen consist of groove welds with partial penetration. Groove welds were placed with the submerged-arc process as shown in Fig. 2. In order to generate blowholes at the root, zinc-based paint was put on the root face.

(2) Residual Stress Relief

To reduce the residual stress of the corner joint, the low-temperature stress relieving method was applied. This stress relief is a process in which the weld is strained by the expansion force of heating parallel to and on both side of a corner joint. The devices for carrying out the treatment are schematically shown in Fig. 3. The center of each heater was positioned at a distance of 100 mm from the corner joint. Further, to assist the expansion force, a water cooler was set up on the corner joint. Treatment was conducted on the middle portion of the specimen, having divided the 1 500 mm length into four parts (as seen in Fig. 5).

At first, the treatment was done on two corner joints at the same time, as shown in Fig. 3(a) for Series B. In this case, the stress relief was found not to have enough effect. Therefore, the treatment in Series C was done on only one corner weld, as shown in Fig. 3(b).

(3) Residual Stress Measurement

The residual stress which was measured by the cutting method using strain gages, is shown in Fig. 4. The maximum residual stress in an as-welded specimen is from 400 MPa to 550 MPa on the welding bead.

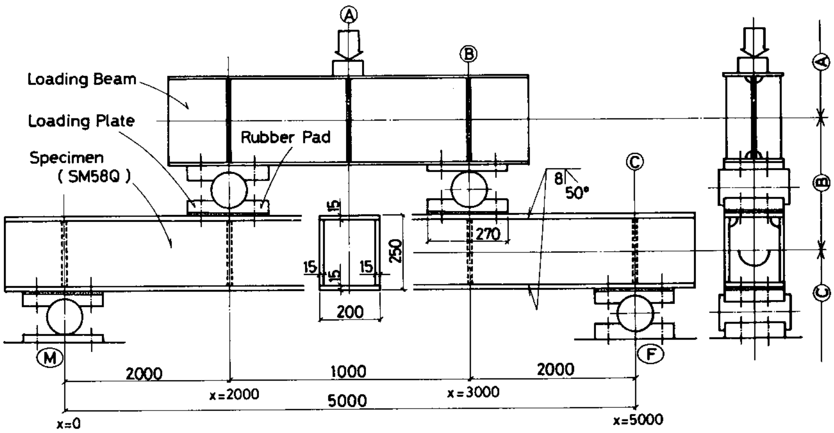

Fig. 1 Configuration and dimension of specimen.

Table 1 Chemical compositions and mechanical properties of steel.

	Chemical Compositions, %							Mechanical Properties		
	C	Si	Mn	P	S	Cu	Mo	Yield Strength MPa	Tensile Strength MPa	Elongation %
SM58Q t=15	0.13	0.23	1.38	0.011	0.003	—	—	550	650	38
US49 x MF38	0.10	0.03	1.63	0.013	0.011	0.11	0.54	490	600	—

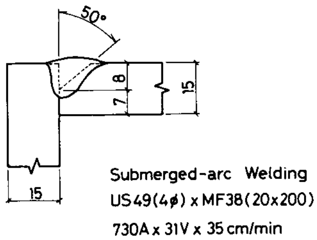

Fig. 2 Welding details.

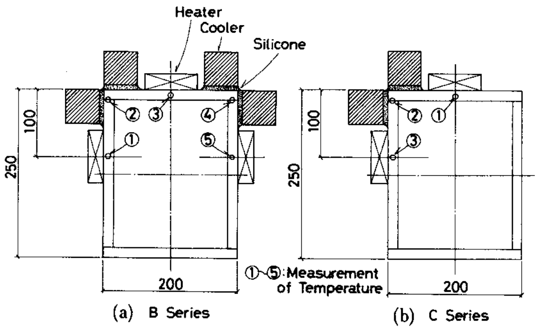

Fig. 3 Stress relief device.

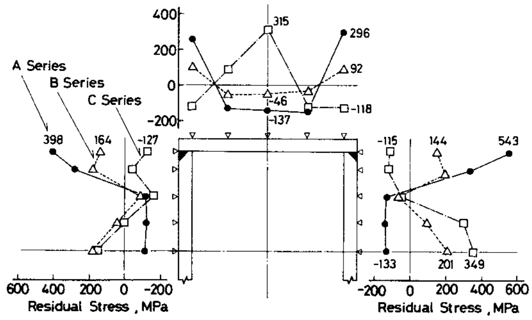

Fig. 4 Distribution of residual stress.

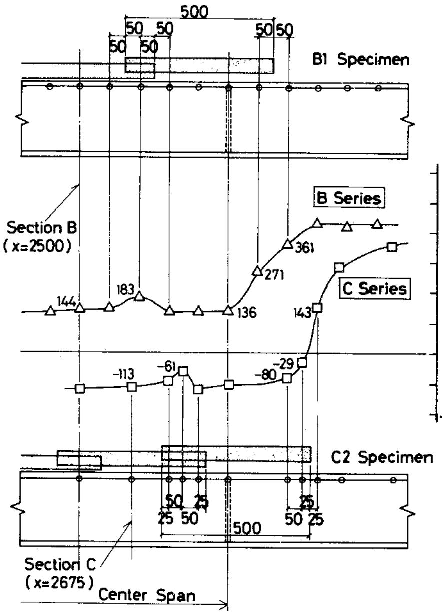

Fig. 5 Distribution of residual stress along corner joint.

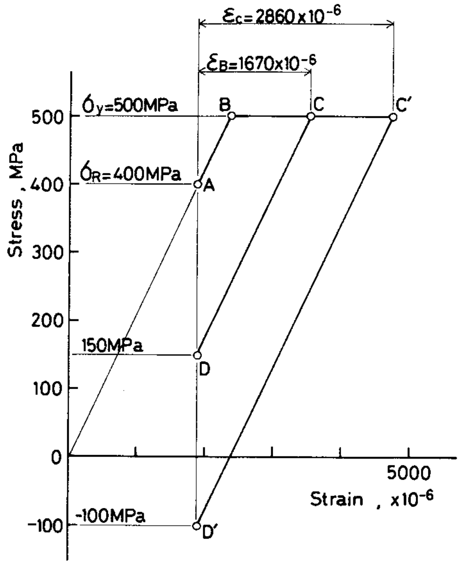

Fig. 6 Mechanism of stress relief.

The maximum residual stress of Series B, in which two corner welds are treated at the same time is 150 MPa, a reduction of about two-thirds of the initial residual stress. In Series C where each corner weld was treated separately, residual stress on the welding bead is about 100 MPa in compression.

Fig. 5 shows that the measured residual stress distributions along the corner joint are almost uniform at 150 MPa in Series B, and −100 MPa in Series C.

The mechanism of stress relief is explained in Fig. 6. The previous study has proved that the tensile strain caused in the weld by heating can be estimated from the temperature difference between the weld and the heated region. The temperature differencs ΔT were about 150°C in Series B and about 260°C in Series C, so the tensile strains caused in the welds were estimated to be $1\,670\times10^{-6}(=\alpha\cdot\Delta T_B)$ and $2\,860\times10^{-6}(=\alpha\cdot\Delta T_C)$, supposing the coeffecient of linear thermal expansion α to be 11×10^{-6}.

Assuming the stress-strain diagram of the weld as in Fig. 6 (yield strength : 500 MPa, initial residual stress : 400 MPa), the residual stresses of the weld are reduced to 150 MPa in Series B (A → B → C → D), and to −100 MPa in Series C (A → B → C′ → D′). These values agree well with the measured residual stresses.

3. FATIGUE TEST

Test series consisted of the three grades of residual stress : as-welded (Series A), reduced (Series B), and more reduced (Series C). Each series was tested at two levels of the stress range with reference to the allowable stress range in the fatigue design code[7]. In Series A, the stress ranges at the root of the corner weld in the constant moment region were 125 MPa and 150 MPa; and in Series B and C, these were 150 MPa and 175 MPa.

All specimens were tested on a 5 m span with two point loading using a testing machine with a 200 N dynamic capacity. The cyclic load wave form was sinusoidal, and the loading rate was 5 Hz. 200 000 cycles of halved stress range were inserted between every 500 000 cycles so that beachmarks would remain on the fatigue crack surface.

Table 2 Fatigue test results.

Specimen		Fatigue test results		
Series	No.	Stress range, MPa	Endurance cycles	Detail of failure
A Series σ_R=400MPa	A1	125	275x10^4	Crack propagation from compression corner weld at loading point
	A2	150	154x10^4	Crack propagation from tensile corner weld in constant moment region
B Series σ_R=150MPa	B1	150	230x10^4	Crack propagation from tensile corner weld in constant moment region
	B2	173	136x10^4	Crack propagation from tensile corner weld in constant moment region
C Series σ_R=-100MPa	C1	150	209x10^4	Crack propagation from artificial hole for measurement of temperature
	C2	173	150x10^4	Crack propagation from inside tack weld for assembly out of constant moment region

4. FATIGUE TEST RESULT

The results of the fatigue tests are shown in Table 2. Loading was discontinued when the largest crack penetrated to about a quater of the box section.

In the A1 specimen, a crack originated at the corner joint of the compression flange at the loading point. An exposed crack surface is shown in Photo. 1. The crack originated from a 1.5 mm wide and 1.7 mm high blowhole. In a later destractive test, a collective crack was discovered on both sides of this crack along the root. In other specimens, the same collective cracks were found at the loading points. It seems that these cracks are formed under secondary shear stress, which is peculiar to the loading point, in addition to normal stress[12].

In the A2, B1, and B2 specimens, cracks were found at the corner joint of the tension flange in the constant moment regions. Each crack originated from a blowhole at the root. The

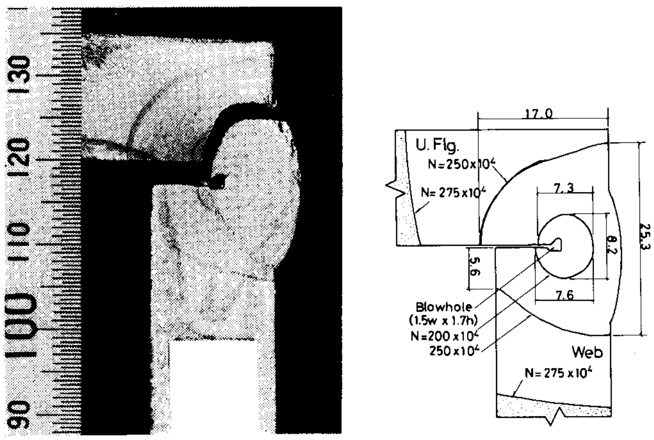

Photo. 1 Fracture surface of crack (A1)

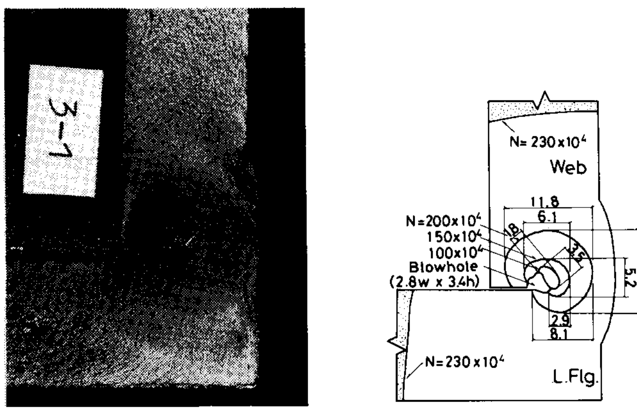

Photo. 2 Fracture surface of crack (B1).

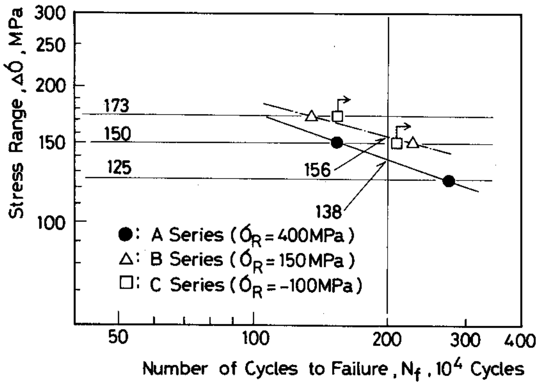

Fig. 7 Relation between failure life and stress range.

Table 3 Probability of cracking.

(number of crack / number of blowhole)

Specimen	Testing Condition		Tension side (Lower flange)			Compression side (Upper flange)		
	Stress range, MPa	Endurance cycles	$1.5 \geq W$	$3 \geq W > 1.5$	$W > 3$	$1.5 \geq W$	$3 \geq W > 1.5$	$W > 3$
A 1	125	275×10^4	1/32	8/22	1/2	0/42	4/34	1/1
A 2	150	154×10^4	5/31	11/23	0/1	0/39	5/18	1/1
B 1	150	230×10^4	4/37	9/23	2/2	0/15	0/25	0/1
B 2	173	136×10^4	11/91	12/21	0/2	0/37	0/12	0/5
C 1	150	209×10^4	0/62	0/25	1/4	0/25	0/12	0/1
C 2	173	150×10^4	0/106	8/54	0/0	0/8	0/9	0/0

facture surface of the crack in B1 is shown in Photo. 2.

In the C1 and C2 specimens, no crack propagated through the full thickness of the corner joint, but failure occured from other discontinuity, as seen in Table 2.

Fig. 7 shows the relation between the failure life N and the stress range $\Delta\sigma$ of the corner joint in the constant moment region. In comparison with as-welded Series A, the 2 000 000-cycle strength of Series B with the residual stress of 150 MPa increases by about 20 MPa. For Series C with the residual stress of −100 MPa, the fatigue strength of the corner weld joint is expected to be the same or longer compared with Series B.

(1) Crack from Blowhole

From the previous study, it is presumed that a large number of concealed fatigue cracks originated from the blowholes beside the cracks grown enough to propagate through the full thickness. So, the partially penetrated weld was destroyed along the weld root to expose weld defects and fatigue cracks. In this observation, the blowhole size was measured by width w and height h, and a blowhole over 1 mm in either width or height was defined as a weld defect.

There were a lot of blowholes and fatigue cracks in all of the specimens. Table 3 shows the probability of cracking in the constant moment region, where the blowholes are classified into three groups according to the size : small blowhole ($w \leqq 1.5$ mm), middle blowhole (1.5 mm $< w \leqq 3.0$ mm) and large blowhole (3.0 mm $< w$). In this table, the cracks which originated near the loading points are omitted.

In any specimen, the probability of cracking depends on the size of the blowhole. As the size grows, the probability gets larger. As for the probability of cracking in the tension side of specimen A2, B1 and C1, which were tested under the same stress range of 150 MPa, there is no difference between A2 and B1 ; but in C1, the probability is extremely reduced. There is the same tendency in B2 and C2 under a higher stress range of 173 MPa.

These results can not lead to a fair estimation about the effect of stress relief, because each test was not finished at the same cycle, and because the cracks were of various sizes. Photo. 3 shows the appearance of typical cracks of almost the same size. The smallest beachmarks of B1 and C1 appeared at 1 000 000 cycles, while on two crack surfaces of A2, beachmarks were left at 500 000 cycles. And all of the smallest beachmarks are almost the same size. Consequently, crack initiation life is presumed to get longer by the reduction of residual stress.

In Series A, the cracks originated in the corner joint under the compression stress. This is due to a tensile residual stress large enough to cause a tensile stress amplitude under the applied compression stress. No cracks were found in the compressive corner joint of Series B and Series C, where the effective tensile stress on the weld was small, or did not exist.

(2) Estimating Fitigue Life

There were many fatigue cracks which originated from blowholes at the root of the partially penetrated groove weld. These cracks were various in size. To compare the effect of the residual stress relief, the fatigue life, in which any crack grows to a defined size $2a_f$, is required. The fatigue life of each crack is estimated on the basis of the following assumption using fracture mechanics:

a) Fig. 8 shows three steps in the process of crack growth. As most of the cracks were observed to be type (ii) or (iii) in this test, the shape of the fatigue crack was defined to be circular with a diameter of $2a^*$ $(=a+b)$.

b) The stress intensity factor of the circular crack is given by the following equation:

$$K=\Delta\sigma\sqrt{\pi a}\cdot\frac{2}{\pi}\cdot\sqrt{\sec\frac{\pi a}{t}} \quad \cdots\cdots (1)$$

c) After the crack tip arrives near to the surface, a crack grows rapidly to propagate through the full thickness[13]. So, the final crack size $2a_f$ is assumed to be 80% of the thickness.

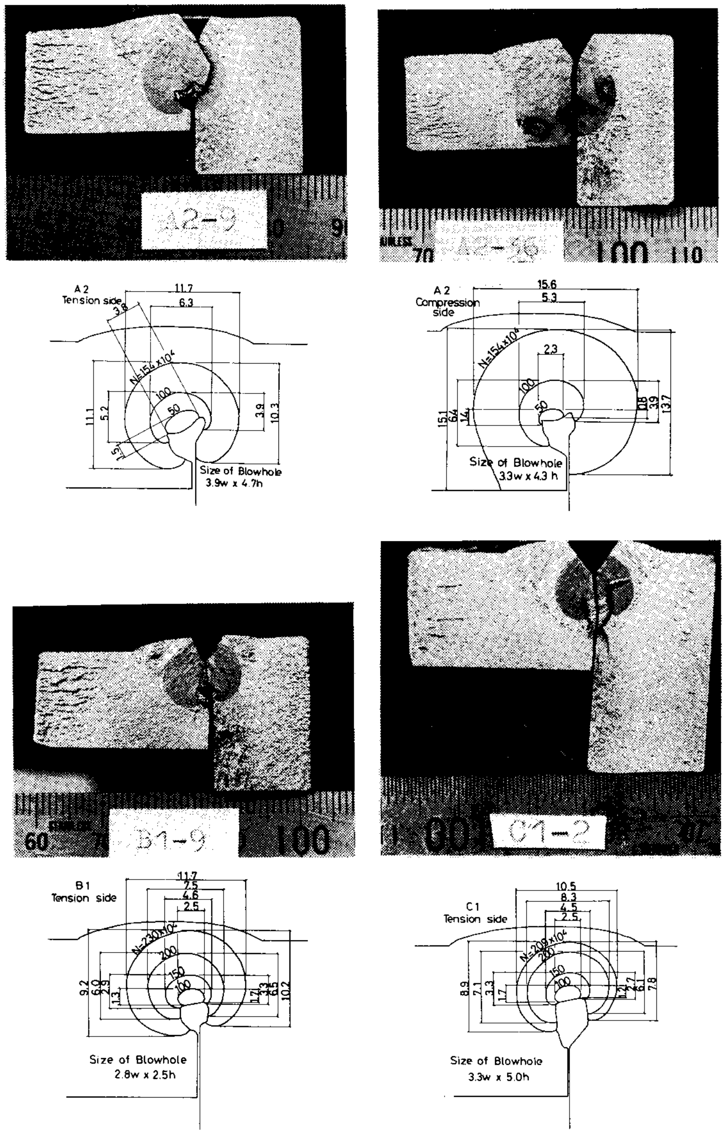

Photo 3 Appearance of typical cracks (A2, B1, C1).

d) Equation (2) is used for calculating the fatigue life by using the relation of the fatigue crack growth rate da/dN (mm/cycles) to the stress intensity factor range ΔK (MPa$\sqrt{m}$).

$$da/dN=C(\Delta K)^m \quad \cdots\cdots (2)$$

where C and m are constant.

The propagation life ΔN_p to develop from $2a^*$ to $2a_f$ is obtained by equation (3).

$$\Delta N_p=\frac{1}{C}\int_{a^*}^{a_f}\frac{1}{(\Delta K)^m}da \quad \cdots\cdots (3)$$

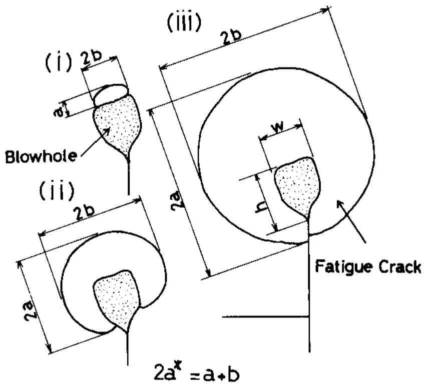

Fig. 8 Dimension of crack.

(3) Fatigue Crack Growth Rate

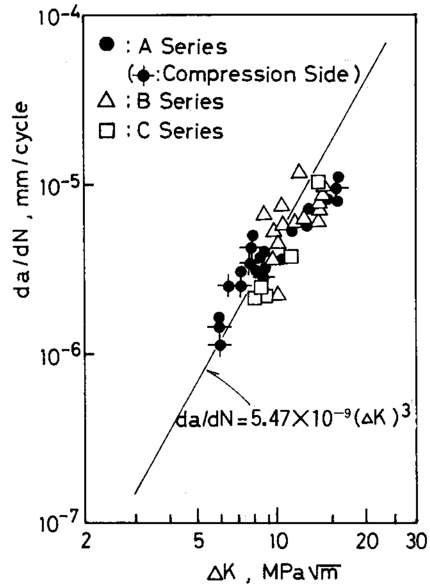

Fig. 9 Relationship between da/dN and ΔK.

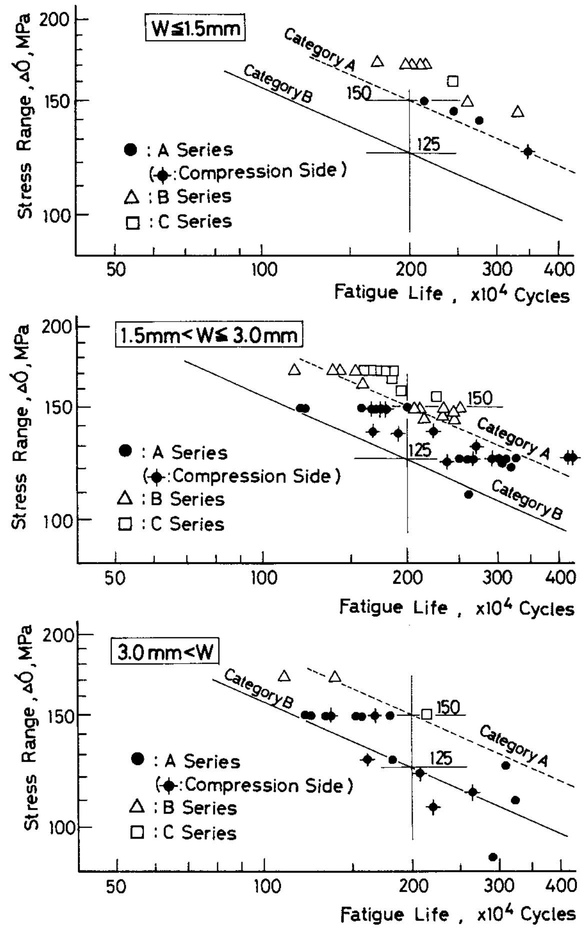

Fig. 10 Estimated fatigue life.

Fig. 9 shows the da/dN versus ΔK relationship where da/dN was calculated from the spacings between beachmarks. The behavior of crack growth in the early stage, where ΔK is below 7 MPa$\sqrt{m}$, is not presented in this figure. In the region of $\Delta K > 7$ MPa$\sqrt{m}$, the test data does not show any appreciable difference, so that the residual stress relief is supposed to have no effect on the crack growth rate. When ΔK is over 7 MPa$\sqrt{m}$, 2 a^* is 4 mm under the stress range of 125 MPa, which is the allowable fatigue strength for a corner joint. This suggests that the stress relief of a corner joint with a crack over 4 mm in diameter has no effect on fatigue strength improvement.

The line in Fig. 9 was given from the studies on the weld joint of the quenched and temprered high strength steel by Dr. Okumura and others[14]. As all the plots are distributed around this line, so the value of m and C in equation(2) can be assumed to be 3.0 and 5.47×10^{-9}.

(4) Fatigue Strength

The relation between the estimated fatigue life and the stress range is shown in Fig. 10. Test results are classified and plotted in accordance with the blowhole size. In Fig. 10, the design curves for Category A and B in the fatigue design code[7] are shown for comparison.

The amount of data is not enough to derive the apparent relation, but it shows that plots of Series B and C are generally distributed on the safety side, compared with Series A.

Fig. 11 shows the 2 000 000-cycle strength of each group, which is estimated from the data in Fig. 10 by the least squares method. In every series, as the size of the blowhole grows, the 2 000 000-cycle strength decreases. Those of Series B and C are larger by about 20 MPa than those of Series A, regardless of the class of the blowhole size.

The 95 % lower confidence limits for the middle blowholes, which is over the tolerable size in the fabrication specifications, are as follows.

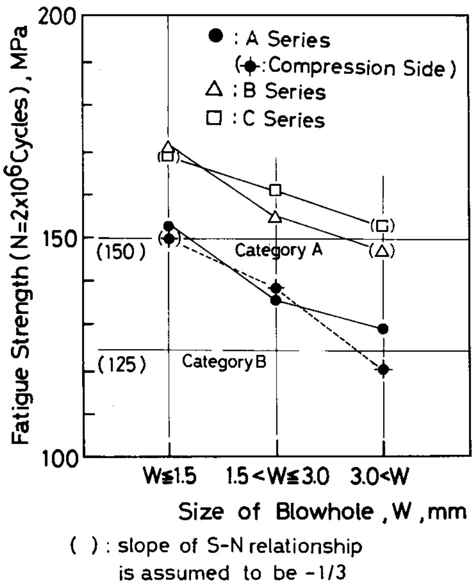

Fig. 11 2 000 000-cycle fatigue strength.

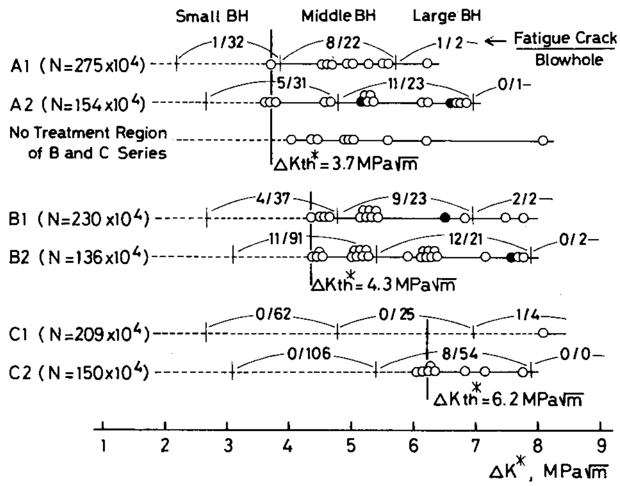

Fig. 12 Apparent stress intensity factor.

Series A 123 MPa
Series B 146 MPa
Series C 152 MPa

Though the confidence limit of Series A is a little below the allowable stress range of 125 MPa for the corner joint, those of Series B and C are over that value. Especially, the fatigue strength of Series C is expected to become allowable even in one higher design category. It is clear that stress relief can reliably improve the fatigue strength of a corner joint.

In Series A, no difference in the estimated fatigue life was observed between the tension zone and the compression zone. When the crack in the compression side extends to the region of small tensile or of comprissive residual stress, it is interesting to note how it behaves. Such behavior must be deeply investigated in future studies.

(5) Threshold of Crack Initiation

Fig. 12 shows the apparent stress intensity factor ΔK^* of the blowhole from which the fatigue crack originated, assuming the blowhole to be a circular plane with a radius of its inscribed-circle. ΔK^* was calculated from equation (1).

The least final cycle in this test, 136×10^4 in the B2 specimen, is enough to produce all possible cracks. The smallest ΔK^* of the blowhole with any fatigue crack can be considered to be the threshold stress intensity factor range ΔK^*_{th}. Each in three series is as follows.

Series A $\Delta K^*_{th}=3.7$ MPa$\sqrt{m}$
Series B $=4.3$ MPa$\sqrt{m}$
Series C $=6.2$ MPa$\sqrt{m}$

These results prove that ΔK^*_{th} increases, especially in Series C due to the stress relieving treatment.

5. CONCLUSION

The effect of low-temperature stress relief on the fatigue strength of partially penetrated groove weld with root blowholes was examined. Box section specimens made of 600 MPa class steel were tested with the three grades of residual stress : as-welded (Series A), 150 MPa (Series B), and −100 MPa (Series C). The results of this test are summarized as follows.

(1) Low-temperature stress relief can reliably improve the fatigue strength of a corner joint under applied tensile stress. In comparison with as-welded Series A, the 2 000 000-cycle fatigue strength of Series B with the residual stress of 150 MPa increases by 20 MPa. For Series C with the residual stress of −100 MPa, it is expected to be the same or longer compared with Series B.

(2) As for the fatigue life, assuming the diameter of a final crack to be equal to 80 % of the thickness, the 95 % lower confidence limits for the blowhole over the tolerable size in the fabrication specifications are as follows :

Series A 123 MPa
Series B 146 MPa
Series C 152 MPa

(3) This fatigue strength improvement may result from the following two phenomena :

a. The crack initiation life gets longer by the reduction of residual stress ; and
b. The threshold for the crack initiation (apparent stress intensity factor K_{th}^{*}) increases due to stress relief.

(4) Stress relief has a significant effect on the crack inintiation and growth under applied compressive stress. In Series B and C, no crack was observed though cracks originated in the corner joint of Series A.

(5) Among the three levels of residual stress, there is no significant difference of fatigue crack growth rate in the region of $\Delta K > 7$ MPa$\sqrt{m}$.

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