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Behavioral Characteristics of Fatigue Cracks in Small Hole Defects Located on Opposite Sides of the Shaft Cross Section

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ABSTRACT

The shaft with the circular cross section has symmetric structural combination parts to keep the rotating balance. Hence the crack usually initiates from symmetric combination parts due to the stress concentration of these parts. In this study to estimate the fatigue behavior of symmetric cracks, the fatigue test was performed by using a rotary bending tester and the specimen with symmetric defects in circular cross section. The characteristics of crack initiation and propagation on the symmetric surface cracks in circular cross section were examined. We also observed the internal crack using the oxidation coloring method and investigated the fatigue behavior using the relationship between the surface crack and the internal crack. As a result, the fatigue life of symmetric cracks was reduced by 35% compared to that of a single crack. We examined the characteristics of fatigue behavior of elements with symmetric cracks using internal crack propagation rate and maximum stress intensity factor range that were obtained from an approximation method.

Key Words : Fatigue life, Fatigue crack propagation rate(da/dN), Small hole defects, Stress intensity factor range (ΔK), Surface and Internal cracks, Symmetric fatigue cracks

1. Introduction

Mechanical elements including universal joint, turbine shafts, and engineering structures have initial defects such as natural defects or artificial defects. Such initial defects can be the main cause for initiation of fatigue cracks because they sometimes act as a stress concentration source[1-3].

Fatigue cracks mainly appear in external initial defects rather than internal initial defects even though the defects are the same in their sizes or shapes. The reason is that the resistance for plastic deformation at the surface is smaller than at the internal region, and the stress reaches its maximum level in the surface of the specimen. It has been reported that the initiation and propagation behavior of fatigue cracks are different according to size, shape and distribution aspects of initial defects even if the surface initial cracks are equal[4-7]. However, since recurrence of experiments for natural defects is difficult, many researchers have examined the behavior of fatigue crack initiated and propagated at small artificial defects using artificial defects[8,9].

Song[10,11] reported that when initial artificial defects are in the shape of a small hole, fatigue cracks initiate at both ends of the small hole surface. However, if the internal length of fatigue crack grows to exceed the depth of the initial defects, the shape of internal crack becomes in semi-elliptical.

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Table 1 Chemical composition of SNCM220

Compositions (wt.%)					
C	Si	Mn	Ni	Cr	Mo
0.29	0.23	0.60	0.57	0.66	0.20

Table 2 Mechanical properties of SNCM220

Yield Stress (MPa)	Ultimate Strength (MPa)	Hardness (Hv)
385.4	536.4	149

Also Smith and Lin[12] examined the behavior of two cracks using FEM when these two cracks, with 60° phase difference in cross section of a round bar, are under cyclic tensile loading. They reported that if the two cracks draw very near as the cracks propagate, cracks propagate faster in the interior than on the surface.

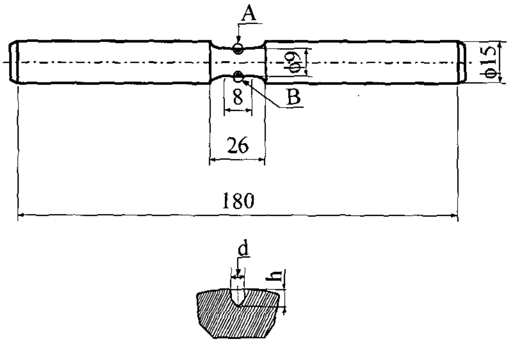
Fonte and Freitas[13] utilized FEM to obtain the behavior and stress intensity factor(SIF) for semi-elliptical surface cracks of a round bar subjected to bending and tensile loading at the same time. Hence there is no common opinion up to now about the research[14] on behavior of cracks initiated in the shaft cross section of a rotating structure. Therefore the reports on the behavior of cracks initiated on opposite sides of the shaft cross section were not available.

In this study the fatigue behavior of defects located on opposite sides of the shaft cross section was examined. That is, we machined small holes on opposite sides of the shaft cross section then investigated the characteristics of the fatigue cracks that initiate on opposite sides of the shaft cross section and others that move toward the interior. Also, the propagation rate and the fracture life of fatigue crack were investigated.

2. Experimental method

The material used in the experiments was Ni-Cr-Mo Alloy which is commonly used for mechanical structure (KS3709). This material is mainly used for shafts, gears etc. The chemical components and mechanical properties of the experimental material are given in Tables 1 and 2.

To remove residual stress and homogenize the structure, the specimen was annealed for 50 minutes at 850℃ in a furnace. Then the specimen was machined as shown in Fig. 1.



Detail of A, B

Fig. 1 Geometry of specimen (dimensions in mm)

The shape of the small hole defect machined at the surface of specimen has a diameter(d) of 0.5 mm and a depth(h) of 0.5 mm. In the case of one small hole defect, it was machined at "A" part as shown in Fig. 1, in the case of two small hole defects, they were machined at "A" and "B" parts which were located on opposite sides of the shaft cross section as shown in Fig. 1. The test machine used was the Ono type rotary bending fatigue tester with 98 N·m maximum bending moment. The rotational speed was 3600 rpm, and stress ration R was set to -1.

3. Experimental results and Discussion

3.1 a-N curves of symmetric fatigue cracks in shaft cross section

Symmetric fatigue cracks described in this study refer to fatigue cracks that form on opposite sides of the shaft cross section and form a symmetry as shown in the diagram. The behavior of the single fatigue crack and the two fatigue cracks that appear on opposite sides of the cross section was compared by using the relationship between the fatigue crack length, a, and the number of cycle, N, in each case.

The a-N curves in the case of single crack and the case of main crack and sub-crack of symmetric fatigue cracks are shown in Fig. 2. The division of main crack and sub-crack among symmetric fatigue cracks are described below.

In Fig. 4, the fatigue fractured area centered at the upper small hole is big, while the fractured area centered at the lower small hole is relatively small. Hence, the fatigue crack initiated at the upper part is called as the

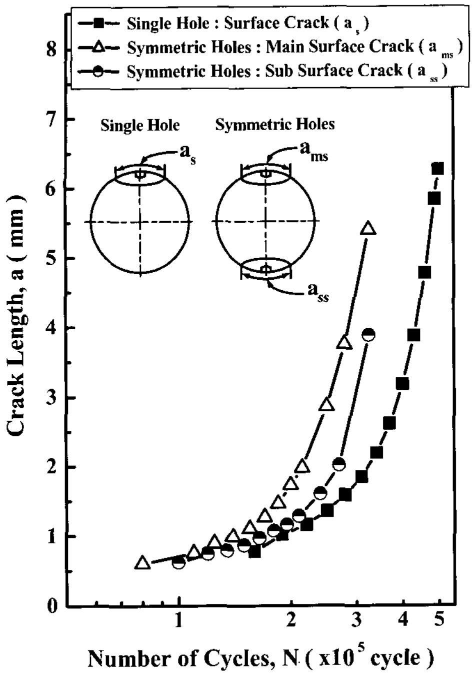


Fig. 2 The relationship between number of cycle and surface crack length

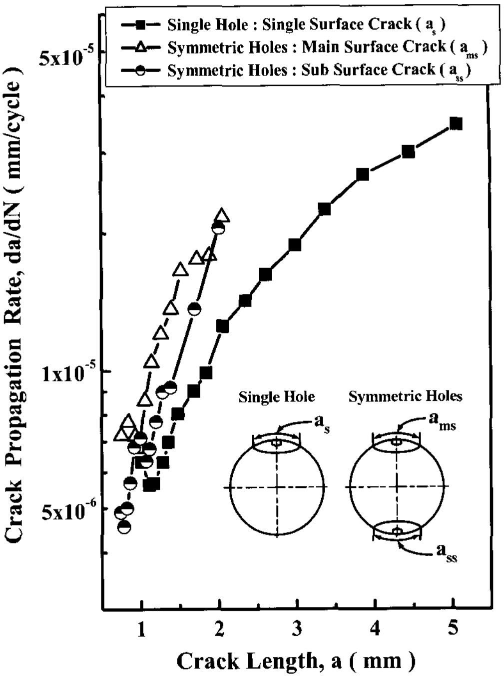


Fig. 3 The relationship between surface crack length and surface crack propagation rate

main crack because it initiated and propagated rapidly compared to the crack at the lower part. The fatigue crack initiated at the lower part was called as the sub-crack.

Initiation aspects of the main and sub-cracks in symmetric fatigue cracks were similar to a single fatigue crack at the early initiation stage. However, as the number of cycle increased, crack propagation length of the main crack increased more rapidly than the sub-crack and the increment was large compared to that of the sub-crack(Fig. 2).

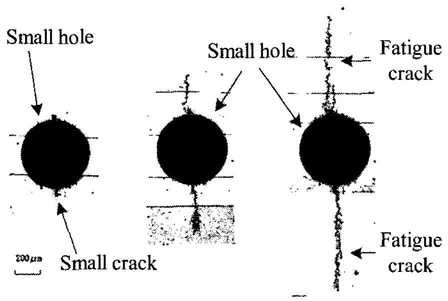
Cracks initiated respectively on opposite sides of the cross section could not be observed as main crack and sub-crack at the early initiation stage. However, as the number of cycle increased, one crack length rapidly increased compared to another due to the difference of structure state at the crack tip and stress concentration. As this crack grows to a main crack we could distinguish the sub-crack from the main crack. In addition, the early propagation process of the main crack was similar to the single crack, but as the number of cycle increased, we could observe that the main crack length was longer than the single crack.

Schijve and Partl[15] reported on the life evaluation for three damage(MSD: Multi Site Damage) cracks of Al 2024-T3. In this case, they reported that early cracks initiated and propagated similarly without any interaction, and the lives of these cracks decreased by about 20% from that of a single crack.

This experimental result was similar to the result reported by Schijve and Partl[15], but the number of initiation cycle for main and sub-crack of symmetric fatigue cracks were 50% more rapid and the total life decreased by about 35% compared to the single crack.

3.2 The propagation rate of symmetric fatigue cracks in shaft cross section

The propagation rates of fatigue crack initiated from a single hole and symmetric fatigue cracks located on opposite sides of the shaft cross section were compared in Fig. 3. The crack propagation rate of a single fatigue crack increased at a regular speed. On the other hand, the crack propagation rate for a main crack and a sub-crack of symmetric fatigue cracks gradually increased, repeating the pattern of increase and decrease. It is regarded that such results can be attributed to fatigue crack driving force applied both on the main and sub-cracks. That is, main cracks and sub-cracks have



(a) N=8×10^4 (b) N=15×10^4 (c) N=25×10^4

Fig. 4 Photograph of fatigue crack initiation from one small hole

respective characteristics of propagation according to stress concentration near the crack tip, the phase of structure and loading states. As the crack propagation rates of symmetric fatigue cracks were also quicker than that of a single fatigue crack, fatigue life decreased.

3.3 Surface crack and internal fatigue crack on opposite sides of the shaft cross section

Each fatigue crack initiated from two small holes located on opposite sides of the shaft cross section, different from fatigue crack that initiated and propagated at a single small hole on the shaft surface(Fig. 5), did not initiate and propagate simultaneously. When fatigue fractured section area of upper and lower parts were compared with each other as observed in Fig. 5, the initiation and propagation behavior of two fatigue cracks were not the same. It is thought that such difference is caused because the initiation and propagation type of a main crack differ from that of a sub-crack according to the structure or stress concentration near the small hole defects machined at the specimen surface. At the same time, we could observe that as the number of cycle increased, initiated symmetric cracks propagated continuously, and their propagation rates were different. Related to such results, Murakami and Tsuru[16] proposed the dimensionless equation which shows the relationship between the surface crack length and the internal crack length through the rotating bending fatigue tests using large or small specimens:

$$\frac{a_i}{D} = A\left(\frac{a_s}{\pi D}\right)^B \qquad (1)$$

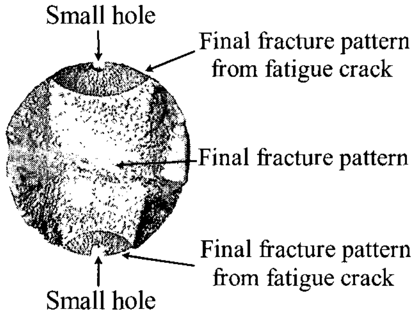


Fig. 5 Photograph of final fracture from two small holes

where a_i is the internal crack length, a_s is the surface crack length and D represents the diameter of the parallel part. A and B are dimensionless proportional constants. This equation was not affected by the different levels of stress, diameter of specimen and kind of steel. Hence the relationship between surface and internal crack length of symmetric fatigue cracks were arranged by using Eq. (1).

Fig. 6 represents the relationship between the normalized surface and the internal crack length for single and symmetric fatigue cracks. To compare the propagation aspect of surface crack, internal cracks were observed by using the oxidation coloring method which makes beach marks by cyclic loading with high and low amplitude(Fig. 5). The constants calculated by Eq. (1) based on the obtained experimental results are shown in Table 3. Using the constants in Eq. (1) and in turn using the equation and the surface crack length measured at each position, the internal crack length for single and symmetric cracks could be calculated. The results show that there was little difference between the constants A and B for single fatigue crack and main crack among the symmetric fatigue cracks, and this fact represents that there is similarity between the surface and internal cracks. It also indicates that in the case of main crack among symmetric cracks, the behavior of internal crack to surface crack is similar to that of a single crack. Meanwhile, in the case of a sub-crack, internal crack behaves differently from the single or main crack due to the effect of main crack.

3.4 Fracture life of symmetric fatigue cracks

Fig. 7 shows the relationship between the length of single or symmetric surface cracks and the cycle ratio. This represents the characteristics of propagation for

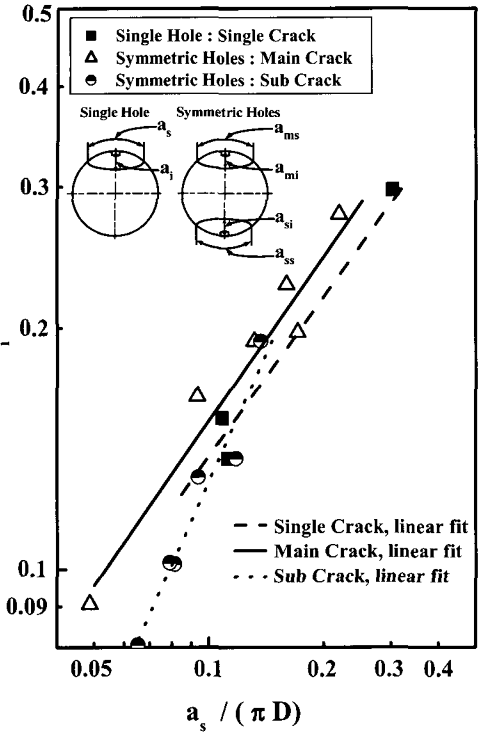


Fig. 6 The relationship between surface crack length and internal crack length

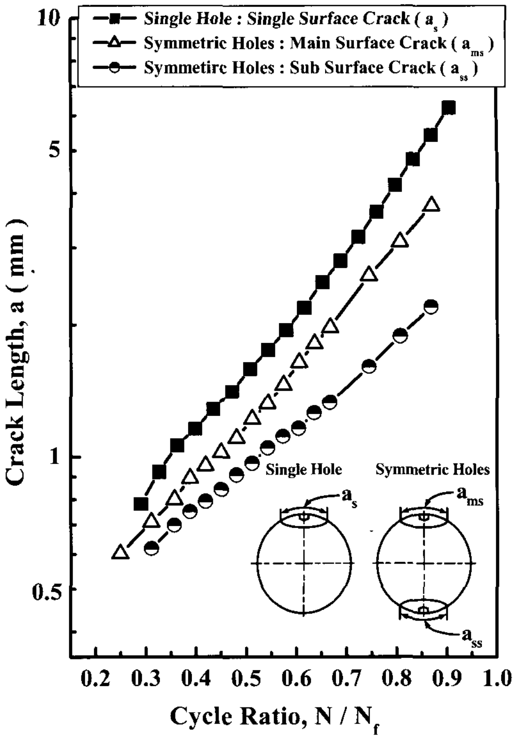


Fig. 7 The relationship between surface crack length and cycle ratio

Table 3 Material constant A, B obtained from Eq. (1)

	Single Hole	Symmetric Holes	
	Crack	Main Crack	Sub Crack
A	0.69	0.78	1.36
B	0.71	0.70	1.02

Table 4 Material constant α, β obtained from Eq. (2)

	Single Hole	Symmetric Holes	
	Crack	Main Crack	Sub Crack
α	-0.509	-0.568	-0.508
β	1.411	1.302	0.968

fatigue cracks without regard to stress level, and we could learn from the Fig. 7, that there is a proportional relationship between a_s-N/N_f.

Nishitani and Takenori[17] proposed such a relationship as follows:

$$\log(a_s) = \alpha + \beta\left(\frac{N}{N_f}\right) \qquad (2)$$

where a_s is the surface crack length, α is the constant given according to the size of small hole, β is the proportional constant. N and N_f are number of cycle and fatigue life, respectively.

Table 4 represents the constants α and β obtained from Eq. (2) in this test. In Table 4, the values of α were almost the same in all cases, while the values of β in the case of single crack and main crack among the symmetric cracks were similar. But, the value of β for a sub-crack among the symmetric cracks was different from any other value.

Such results mean that the propagation pattern of fatigue crack for a single crack and symmetric cracks are alike. It is necessary to consider the behavior of sub-crack because the total surface crack length is shorter than two cracks and the ratio of increase for the crack length to number of cycle is small.

3.5 The relationship between propagation rates of symmetric fatigue cracks and ΔK

Actually exact stress intensity factor(SIF) for surface

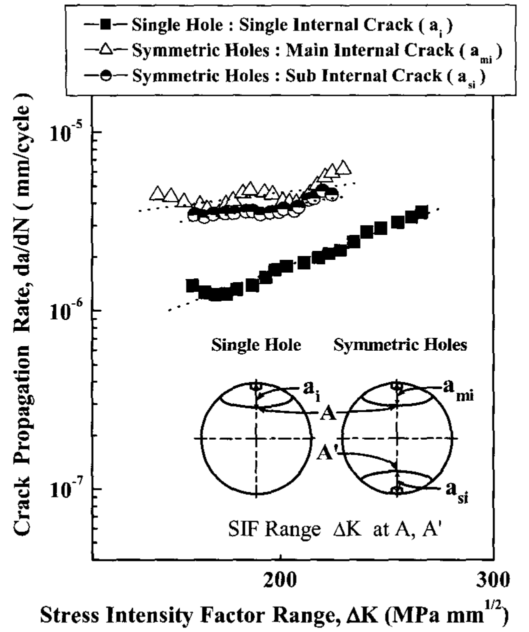


Fig. 8 The relationship between the maximum stress intensity factor range(ΔK) and internal crack propagation rate

crack of round material was not defined because its shape is three dimensional and the stress states of internal and external are different. However the maximum SIF of semi-elliptical crack was calculated at the most lower part of the internal crack when the direction of bending and bisected perpendicular planes coincide[16,18]. The calculation result was the same as the SIF that was calculated at the most lower part of the internal crack when only a simple bending load was applied. Hence, in this study the propagation rate of the internal crack initiated and propagated from single or symmetric defects were compared using the maximum SIF under three dimensional bending which was calculated by the approximation analysis method proposed by Murakami and Tsuru[16]. Fig. 8 shows the propagation rate of the internal crack for single and symmetric cracks using the maximum SIF range.

This test result showed that the propagation rate of symmetric internal cracks, which is same as the result of fatigue life, was quicker than that of a single internal crack. Also, the propagation rate of internal cracks for main and sub-crack of symmetric cracks have little difference that noticeable reduction of fatigue life caused by the symmetric defect was detected. In addition, this result is similar to the characteristics of the propagation rate of a surface crack for single and symmetric cracks shown in Fig. 3. From the above facts, the propagation behavior of single and symmetric fatigue cracks could be compared and evaluated by using the maximum SIF range for the internal crack length.

4. Conclusions

In this study fatigue behavior of symmetric cracks initiated and propagated from small hole defects located on opposite sides of the shaft cross section was examined under a rotating bending stress. The conclusion from the test results are as follows.

(1) The life of total fatigue crack initiated and propagated from opposite sides of the shaft cross section decreased by about 35% from the life of fatigue crack initiated and propagated from a single defect at the shaft surface.

(2) The propagation rate of a single fatigue crack at the shaft surface increased regularly, but the propagation rate of symmetric surface fatigue cracks divided into the rate of main and sub-cracks respectively, and they gradually increased with repeating pattern of increase and decrease.

(3) The relationship between the surface fatigue crack and the internal fatigue crack located on opposite sides of the shaft cross section could be arranged as follows by using the equation proposed by Murakami and Tsuru[16] and the proportional constants could be obtained:

$$\frac{a_i}{D} = A\left(\frac{a_s}{\pi D}\right)^B$$

where a_i is the internal crack length, a_s is the surface crack length and D represents the diameter of the parallel part.

From the above facts, the internal crack behavior of a main crack among symmetric fatigue cracks was similar to the behavior of a single fatigue crack, while the internal crack of sub-crack behaved differently.

(4) The relationship between the length of symmetric fatigue cracks and the ratio of fracture life could be arranged by obtaining the proportional constants using the equation proposed by Nishitani and

Takenori[17]:

$$\log(a_s) = \alpha + \beta\left(\frac{N}{N_f}\right)$$

where a_s is the surface crack length, α is the constant given according to the size of small hole, β is the proportional constant. N and N_f are number of cycle and fatigue life, respectively.

The propagation pattern of the main crack among the symmetric fatigue cracks is similar to a single fatigue crack, while, in the case of a sub-crack, the rate of increase of the crack length to the ratio of life was small.

(5) The propagation rates of symmetric internal cracks were more rapid than a single internal crack, and the propagation rate of a main crack among the symmetric crack was somewhat quicker than the sub-internal crack.

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