# EFFECT OF A SMALL BLIND HOLE ON THE FATIGUE STRENGTH OF HEAT-TREATED STEEL PLAIN SPECIMENS IN NACL SOLUTION

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In order to study the effect of defects on corrosion fatigue, rotating bending fatigue tests of smooth specimens having different sizes of a small blind hole (***d***=***t***=0.1 and 0.5 mm, ***d***: diameter of a hole and ***t***: depth of a hole) were carried out in 3 % NaCl solution and in air. Experimental results indicate that the decrease in corrosion fatigue strength due to such a small hole is negligible, whereas a dramatic decrease in fatigue strength in air is caused by drilling a small hole. The physical basis of the effect of a small hole on the corrosion fatigue damage was investigated through the successive observations of the specimen surface by the plastic replication technique.

## INTRODUCTION

Since fatigue strength is strongly influenced in general by small surface defects, many studies concerning the effect of surface defects on fatigue strength have been performed especially in laboratory air (1). For corrosive environments, however, few studies on the influence of defects have been carried out. Because the specimen surface is directly attacked with the corrosive environments, the corrosion fatigue data of specimens with surface defects is required for estimating the fatigue damage in corrosive environments.

In the present study, by using a heat-treated 0.45 % carbon steel, rotating bending fatigue tests of smooth specimens having different sizes of a small blind hole were carried out in 3 % NaCl solution and in air. Considering that the microscopic defects observed in the materials such as heat-treated steels, squeezed-cast alloys ect.

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are usually less than 0.5 mm, the effect of two levels of hole size (***d***=0.1 and 0.5 mm) on the fatigue behaviour of a plain specimen was studied. Successive observations of the surface were made by the plastic replication technique to clarify the physical basis of the effect of a small surface defect on the corrosion fatigue.

## EXPERIMENTAL PROCEDURES

The material was a 0.45 % carbon steel rolled bar about 18 mm diameter. Specimens were machined from the bar after normalizing for 30 min at 845°C, quenching for 30 min at 845°C and tempering for 60 min at 600°C. The chemical composition (wt%) is 0.45 C, 0.25 Si, 0.79 Mn, 0.01 P, 0.01 S, 0.09 Cu, 0.03 Ni, 0.18 Cr, remainder Fe and the mechanical properties are 750 MPa yield stress, 833 MPa ultimate tensile strength, 1510 MPa true breaking stress and 61.6 % reduction of area.

The round bar specimens, see Fig.1(a), were machined from the bars after heat treatment. Although the specimens have a circumferential notch ($\rho$ =17 mm), the strength reduction factor for this geometry close to unity, so that the specimens can be considered as plain specimens. Before testing, the specimens were electro-polished to remove about 20 μm from surface layer in order to facilitate the observations of changes in the surface state. In some specimens, a small blind hole, see Fig.1(b), was drilled at midsurface after electro-polishing. These are called drilled specimens in the following.

All the tests were carried out under constant stress amplitudes using a rotating bending fatigue machine with a capacity of 100 Nm operating at 60 Hz. The environment for corrosion fatigue tests was a NaCl solution with a concentration of 3 % at room temperature (25±1°C). The solution was dripped continuously onto the midsurface of a specimen during the tests and was circulated between a test chamber and a large reservoir bottle at a ratio of about 1,000 $cm^3$/min. The solution was renewed for each test.

The observation of fatigue damage on the surface and the measurements of crack length were made via plastic replicas using an optical microscope at a magnification of x400. The value of stress, $\sigma_a$, means the nominal stress amplitude at the minimum cross section.

## EXPERIMENTAL RESULTS AND DISCUSSION

Figure 2 shows the S-N curves in air and in NaCl solution for plain and drilled specimens. In air, distinct fatigue limits exist and dramatic decreases in fatigue strength due to a hole are observed (for example, fatigue limit, $\sigma_w$, of drilled specimen with ***d***=0.5 mm is about 55 % of the plain specimen, see Fig.(a)). On the other hand, in NaCl solution, fatigue limits for all of the specimens disappear and the difference in fatigue strength between the plain and drilled specimens is negligible, whereas its difference tends to increase slightly with an increase in stress amplitude. Thus, the corrosion fatigue strength of specimen with small surface defects less than 0.5 mm can be approximately estimated from the results of a specimen without defects.

In what follows, the physical basis of the effect of defects on corrosion fatigue is studied based on the results obtained from the successive observations of the surface.

Figure 3 shows the crack initiation behaviour of drilled specimen in NaCl solution ($\sigma_a$=250 MPa). At extremely early stages of cycling, a corrosion pit is generated at the edge of a hole. At $N=10^4$ cycles, a fatigue crack initiated from the pit is observed. Namely, in NaCl solution, the number of cycles to fatigue crack initiation is very small when compared to the total fatigue life.

Figure 4 shows the crack growth curves in NaCl solution and in air. At $\sigma_a$=500 MPa, no effect of environment on the growth curve is observed. When the stress is less than 400 MPa, however, the growth rate in NaCl is smaller than that in air especially in the range of a large crack. With regard to the crack initiation in NaCl solution, the number of cycles required for crack initiation, $N_i$, is very small (for example, $N_i/N_f$=0.008 at $\sigma_a$=250 MPa). In such a case, the shape of ln$\boldsymbol{l}$ versus $N$ relation is convex upward. It means that the fatigue life in NaCl is mainly controlled by the growth life of a large crack. The main reason for the decreasing growth rate in NaCl solution is probably the wedge action caused by the corrosion products (3).

In Fig.5, crack growth curves of the specimens with different hole sizes are compared at the same stress amplitudes. Figures 5(a) and (b) show the crack growth curves at $\sigma_a$=400 and 300 MPa in NaCl solution, respectively. No significant difference in the growth curves (growth rates) of comparatively large cracks ($\boldsymbol{l}$ >1 mm) is recognized.

Figure 6 shows the $\boldsymbol{dl/dN}$ versus $\boldsymbol{l}$ relation in NaCl solution for plain specimens and drilled specimens. For the case of $\sigma_a$=500 MPa, no influence of hole size on the relation is observed. The relation in air is also shown by a dotted line, which is nearly equal to the relation in NaCl solution. Thus, it can be said that the effect of corrosive environments on crack growth behaviour is negligible at high stress amplitude. For the case of low stress amplitudes ($\sigma_a$=400 and 300 MPa), also, no significant difference in the relation due to the variation of hole sizes is recognized, whereas the comparatively large scatter in the relation is exhibited. At $\sigma_a$=400 MPa, $\boldsymbol{dl/dN}$ is nearly constant when the crack length is less than 2 mm, followed by gradual increase in $\boldsymbol{dl/dN}$ with further growth of a crack. On the other hand, $\boldsymbol{dl/dN}$ at 300 MPa is nearly constant in a whole range of crack length. Moreover, the relation at $\sigma_a$=200 MPa was examined for a drilled specimen with $d$=0.5 mm. The growth rate at $\sigma_a$=200 MPa decreases sharply with an increase in crack length (see Fig.6). In this case, the crack from a hole stopped to propagate up to $N$=2.0x$10^6$ cycles, and the specimen was broken at $N$=1.01x$10^7$ cycles by the coalescence of multiple large cracks.

A large drop of fatigue strength in laboratory air is caused by drilling a hole. Conversely, the fatigue strength in NaCl solution is hardly affected by a small blind hole less than 0.5 mm, see Fig.2. This may results from the following reasons; (a) Because of very short life for crack initiation, the ratio of initiation life to the fatigue life is negligible independent of the difference in hole size, and (b) The growth life of a large crack (e.g. crack in excess of $l$=0.5 mm) principally controls the fatigue life in NaCl solution and the growth behaviour of such a large crack is almost independent of hole sizes, including the case of a plain specimen.

## CONCLUSIONS

In order to clarify the effect of small defects on the fatigue strength in NaCl solution, rotating bending fatigue tests of heat-treated steel plain specimens having different sizes of a small blind hole ($d$=0.1 and 0.5 mm) were carried out in 3 % NaCl solution and in air. The successive observations of the specimen surface were performed to study the physical basis of corrosion fatigue damage. Results show that the negligible decrease in fatigue strength in NaCl solution due to a hole is recognized, whereas the drilling a hole drops dramatically the fatigue strength in air. In NaCl solution, crack initiation life is very small in dependent of stress levels and the crack growth curve (ln$l$ versus $N$ relation) is convex upward. It means that the corrosion fatigue life is mainly dominated by the growth life of a large crack. The $dl/dN$ versus $l$ relation suggests that there are no effects of hole sizes on the $dl/dN$ for such a large crack. Consequently, when the defect size is less than 0.5 mm, the decrease in corrosion fatigue strength due to a defect can be negligible (fatigue strength can be estimated approximately from the results of a plain specimen).

## REFERENCES

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(3) G.E.Nordmark and W.G.Frocke, Fatigue crack arrest at low stress intensities in a corrosion environment, J. Test. Eval. **6**, (1978) p.301-303.

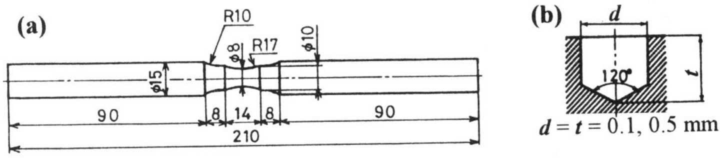


Figure 1 Details of the specimen; (a) the plain specimen, (b) the small blind hole which is drilled on the midsurface of some plain specimens

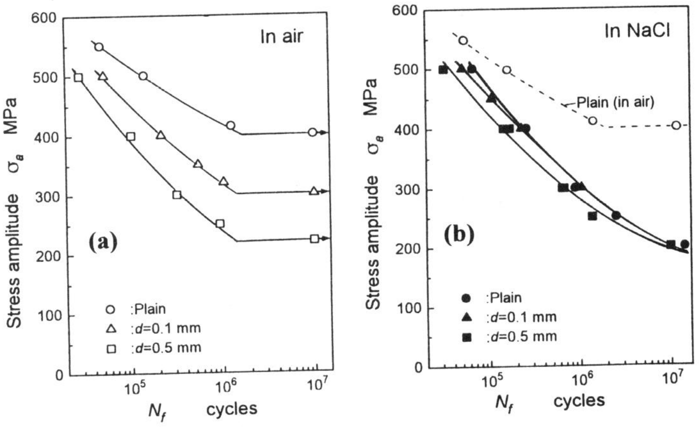
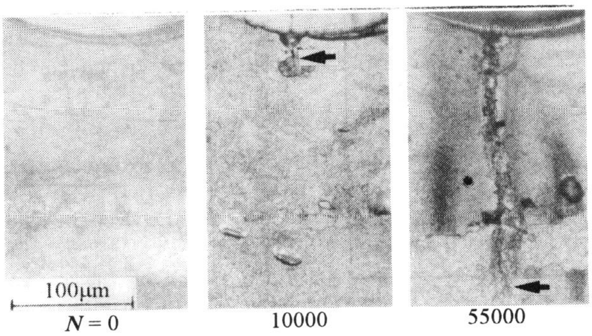


Figure 2 S-N curves; (a) in air, (b) in NaCl solution



$N = 0$ 10000 55000

In NaCl solution, $\sigma_a$=250 MPa, $N_f$=1.28 × $10^6$, ◀ :Crack tip

Figure 3 Crack initiation behaviour from a hole ($d$=0.5 mm) in NaCl solution

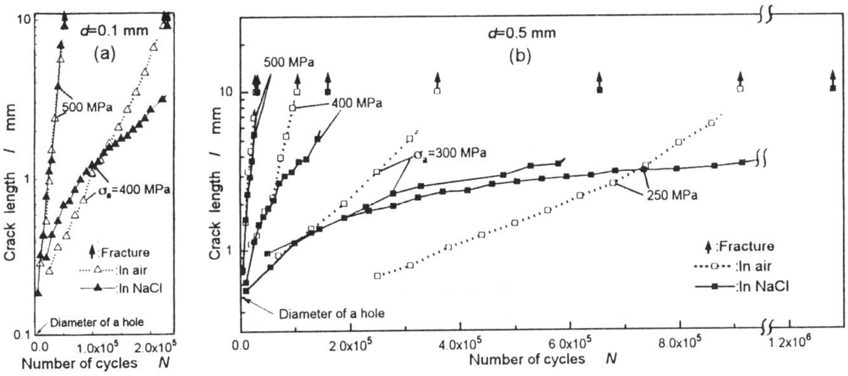


Figure 4 Comparison of crack growth curves of drilled specimens in air and in NaCl solution; (a) *d*=0.1 mm, (b) *d*=0.5 mm

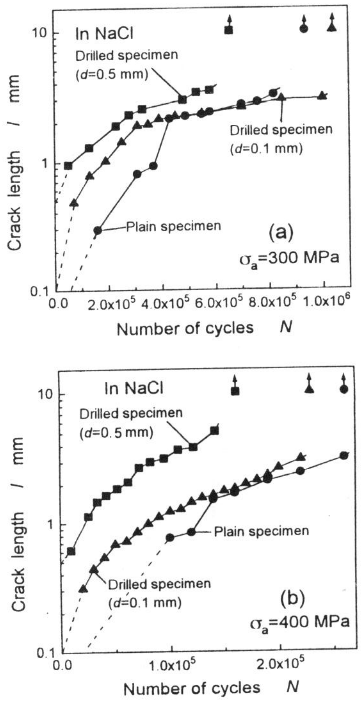


Figure 5 Effect of hole size on crack growth curve; (a) $\sigma_a$= 300 MPa, (b) $\sigma_a$= 400 MPa

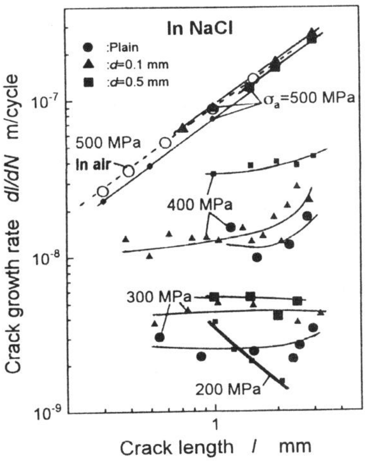


Figure 6 *dl/dN* vs *l* relation in NaCl solution for plain and drilled specimens