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# A study of fatigue cracking behavior dependent on the distance between two hole defects

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## ABSTRACT
The fatigue crack initiation and propagation behavior have been studied considering the distance between two hole defects in this work. The location of two hole defects is defined by an angle and the distance between two holes. The stress distribution around two holes is calculated by finite element method. The fatigue crack initiation is changed with the distance and the relative location of two holes. A parameter is introduced to predict the fatigue crack initiation life. This parameter contains the plastic deformation area and strain at stress concentrations.

## KEY WORDS
Hole-defect, Crack initiation, Stress, Strain, Finite element method

## INTRODUCTION
The life time of engineering materials can be associated with the size, the shape and the relative location of defects contained in the components. Thus, it is important to understand the fatigue crack initiation and propagation behavior in the vicinity of the defects under the complex stress field caused by those defects. When defects are located close to each other, the fatigue crack initiation life of material is very different from that of the material with sparsely distributed defects. The knowledge of fatigue crack initiation mechanisms from such interacting defects becomes a main concern of engineers engaged in fatigue life assessment. Song et al. [1] have studied the stress distribution and interaction around closely located two circular inclusions by the finite element method and experiments. The results indicate that interaction effect between two holes occurs at $s/r<2.2$. In other works, the interaction effects between flaws aligned perpendicular to the loading direction have been studied [2-3]. However it is hard to find the studies which deal with the fatigue crack initiation life at arbitrarily located defects. The life of crack initiation at simple notch has been predicted from the simple parameters such as stress concentration factor and local strain, but it is not fully understood that the parameters can always be applicable. In this study, the relative location of two hole defects with respect to the loading direction and the distance between hole defects are varied, and the fatigue

crack initiation life is investigated. A parameter based on the plastic deformation area and strain is proposed to predict the number of cycles to crack initiation.

## EXPERIMENTAL PROCEDURE

The fatigue test was performed using a commercial bending testing machine (Model TB10). The crack was observed using an optical microscope. The material used in the test was ASTM Al-5086. The mechanical properties and chemical compositions of this material are shown in Tables 1 and 2. The geometries of specimen are illustrated in figure 1. The maximum applied stress was 90MPa and the stress ratio was $R(\sigma_{min}/\ \sigma_{max})=-1$. The stress waveform was sinusoidal. Hole defects were machined by using a 0.5 mm drill. The depth of defect was 0.5 mm. The relative location of two holes is shown in figure 2. For examining crack initiation life, the angle between the line connecting two centers of holes and x-axis were chosen as $\theta=0°$, 30°, 45°, 60° and 90°, and the distance between two centers of holes was chosen as l=3,4 and 5. Here, l=L/r. The stresses and the strains were analyzed by a commercial finite-element package [4].

Table 1 Mechanical properties of Al-5086

| Yield stress (MPa) | Ultimate stress (MPa) | Elongation (%) | Elasticity modulus (GPa) | Poisson's ratio |
|---|---|---|---|---|
| 190 | 260 | 22 | 62.4 | 0.32 |

Table 2 Chemical properties of Al-5086 (wt %)

| Al | Mn | Mg | Cr |
|---|---|---|---|
| 95.4 | 0.1 | 4.0 | 0.15 |

## RESULTS AND DISCUSSION

When two hole defects are located close together, the crack initiation lives are affecte by the distance and relative locations of them. The stress concentration is varied with the distance of defects. The angle between the line connecting two centers of holes and x-axis was varied with $\theta=0°$, 30°, 45°, 60° and 90°. Figure 3 shows the stress concentration factor($K_t$) when the distances of two hole are l=3 and l=5. The stress concentration factors were calculated by two-dimensional finite element method. $K_t$ is defined as the ratio of the y-direction maximum stress $\sigma_{max}$ to the nominal stress $\sigma_{nom}$.

$$K_t = \frac{\sigma_{\max}}{\sigma_{nom}} \qquad (1)$$

$K_t$ is maximum at $\theta=30°$, and minimum at $\theta=90°$. $K_t$ when l=3 is much larger than those when l=5 because the interacting effect of two holes are promoted by the adjacent hole. The crack initiation lives obtained experimentally are shown in figure 4. As seen from the figure 4, the crack initiation life strongly depends on the distance and the angle between two centers. Here, the fatigue crack initiation life is defined as the cumulative cycles up to crack length a=0.1 mm on the surface, because it is difficult to observe the crack initiation smaller than a=0.1 mm

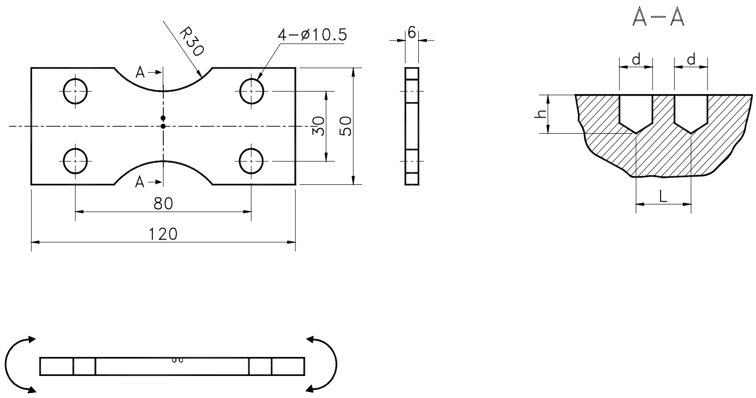


Figure 1: Geometries of test specimen

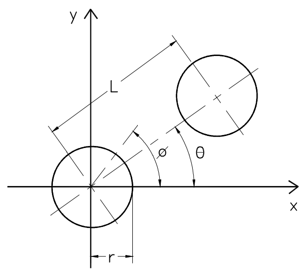


Figure 2: Position of two holes (l=L/r)

$K_t$ is explicitly one of the main factor affecting crack initiation when the material behavior is supposed to be elastic. The relation of $K_t$ and crack initiation life are drawn in figure 5. It shows the relation when l=3. The stress concentration factors and fatigue crack initiation lives is not correlated. Although the stress concentration factor at θ=30° was the largest, the crack at θ=0° was detected sooner. And the crack at θ =60° was detected sooner than the crack at θ=45°. This is attributed to the local stress that exceeds the yield stress as well as the difference of the stress gradient. Because of the rapid decrease of stress concentration with increasing distance from the defect and the existence of complex states of stress at a small distance from the defect, it is difficult to predict crack initiation life by using stress concentration factors. Strain-life concepts may be useful to estimate the crack initiation life when plasticity is dominant. The relation of post yield strain and crack initiation life is investigated. The equivalent strain is calculated by finite element method. The two-dimensional eight node plane stress element and full Newton-Raphson iterative scheme were used. The strain hardening of materials in finite element method was considered as elastic-piecewise linear, which was obtained from the tensile test. The yield criterion is Von-Mises. The relation of strain and crack initiation life has the same tendency of $K_t$. Because there is no correlation between local strains and crack initiation lives like the case of stress, it needs more precise parameter to find correlation.

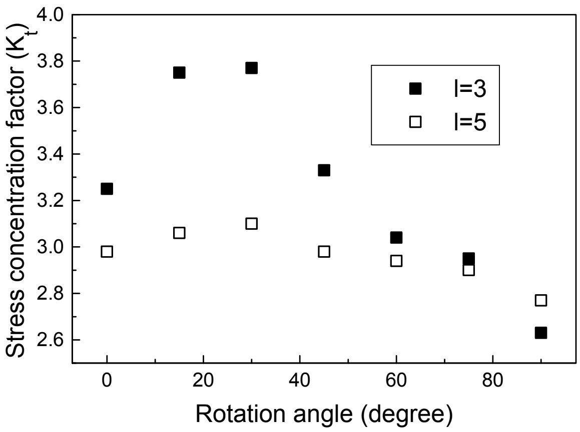


Figure 3: Stress concentration factor when l=3,5

The plastic strain area was also calculated to investigate the relation of crack initiation lives and stress distributions. In the experiment of this study, the plastic deformation area strongly played a role in the crack initiation life. A parameter is introduced to predict the fatigue crack initiation life. This parameter contains local strain magnitude and plastic deformation area as follows:

$$A_{p\varepsilon} = \varepsilon_l \times A^3 \qquad (2)$$

$$A = \frac{A_l}{A_1} \qquad (3)$$

$\varepsilon_l$ : equivalent local strain obtained by F.E.M.
$A_l$ : the area of plastic deformation occurred at each specimen
$A_1$ : the area of plastic deformation occurred at one hole notched specimen
At θ=0°, even though the magnitude of local strain is small, the plastic deformation area is so large that consequently the value of $A_{p\varepsilon}$ becomes large. At θ=0° and 45°, stress concentration factor is large but the plastic strain area is small, so that $A_{p\varepsilon}$ becomes small. Therefore crack initiation lives and $A_{p\varepsilon}$ for Al-5086 are fitted by the following equation:

$$N_i = \left( \frac{A_{p\varepsilon}}{9.0 \times 10^4} \right)^{-0.76} \qquad (4)$$

$N_i$ : crack initiation life
The results are shown in log-log plot of Fig.8. If we find $A_{p\varepsilon}$, we can predict crack initiation life of the material used in this study.

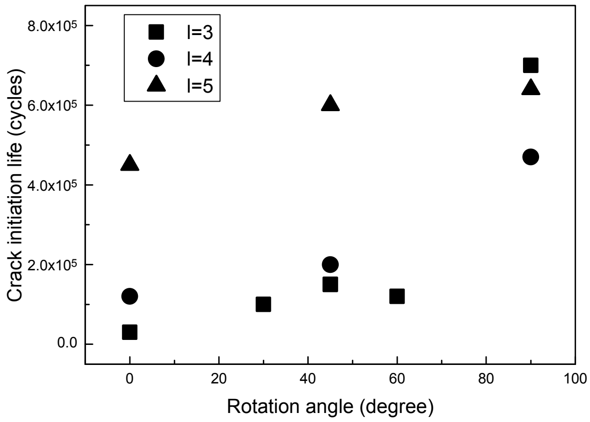


Figure 4: Relation between crack initiation life and relative location

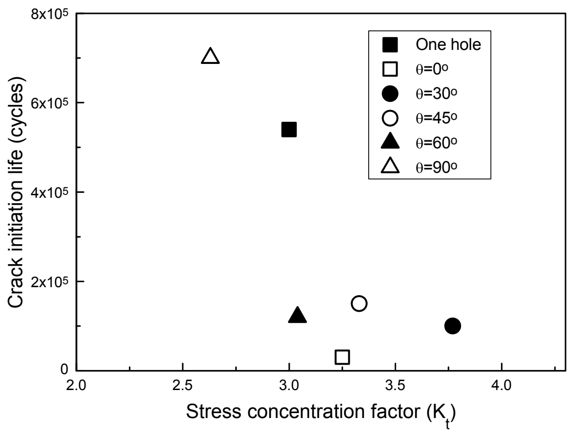


Figure 5: Relation between crack initiation life and stress concentration factor

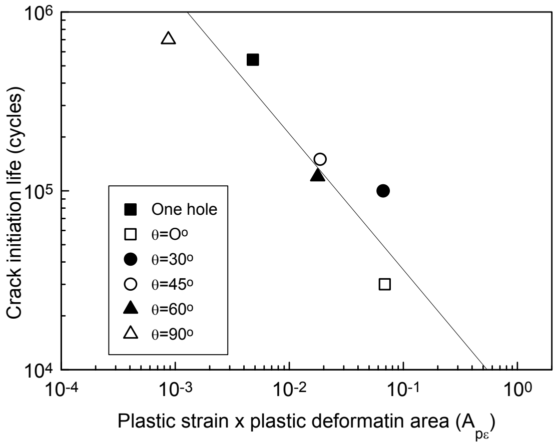


Figure 6: Relation between local strain and crack initiation life

## CONCLUSIONS

In this study, the fatigue crack initiation and propagation behavior of Al-5086 with two interacting hole defects were investigated experimentally. The obtained results are as follows.

1. The relative location of two hole defects, the distance and angles, affects the crack initiation life.
2. When the defects are located close to each other, the fatigue crack initiation lives vary with the relative location of two hole defects. A new parameter is proposed for the prediction of fatigue crack initiation life. It contains an equivalent local strain magnitude and a plastic deformation area as follows.

$$A_{p\varepsilon} = \varepsilon_l \times A^3$$

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