Investigation of the Effect of the Roughness-Induced Crack Closure on the Fatigue Crack Propagation Behavior of Hot-Rolled Steels under Mixed-Mode Loading Conditions

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It is reasonable to apply crack closure concepts, i.e. roughness-induced crack closure, to understand the crack propagation behavior under mixed mode loading conditions. In this paper, the characteristics of fatigue crack propagation under mixed-mode loading is studied using the concept of roughness-induced crack closure, and a model of the variation of the crack opening ratio is proposed based on multi-variable statistics. In addition, fracture surfaces are examined by C-scan and classified into four stages to quantify the effect of crack closure. The roughness parameter based on the highest intensity reveals the effect of roughness-induced crack closure on the fatigue crack propagation.

Keywords: fatigue crack, crack opening ratio, roughness-induced crack closure, mixed-mode, C-scan

1. Introduction

Crack propagation behavior under mixed mode loading conditions is important to predict the lifetime of structures. For many years, there have been many researches and reviews of the fatigue crack propagation behavior under mixed-mode loading conditions.¹⁻⁵ There have been many discussions of the application of the crack closure concept to investigate the characteristics of fatigue crack propagation in mode I since Elber¹³ observed the closure between crack surfaces even during the application of tensile loads. In case of mode I fatigue cracks, it is known that the characteristics of the fatigue crack propagation can be analyzed by introducing the effective stress intensity factor range (ΔKeff) which is defined as the difference of the maximum stress intensity factor (Kmax) and the crack opening stress intensity factor (Kop).

Comparing with many works on the effect of the crack closure on the fatigue crack propagation behavior under the mode I loading condition, there are still limited amount of researches on the application of the crack closure concept to the fatigue crack propagation behavior in mixed mode I and II loading conditions. There have been several mechanisms of the fatigue crack closure, e.g. plasticity-induced crack closure, roughness-induced crack closure, early crack closure due to debris, etc., but, among them, the roughness-induced crack closure may be adequate to explain the effect of the mode mixity on the fatigue crack propagation behavior under mixed mode loading conditions. Carlson and Beevers¹⁴ studied the quantification of local mixed-mode crack closure characteristics using the roughness-induced crack closure model. Tschegg¹⁵ proposed the concept of sliding mode crack closure (SMCC) to specify the effect of reduction of nominal stress intensity factor due to the friction between crack surfaces for both of mode I and mode II loading conditions. Smith and Smith¹⁰ classified three root causes of the attenuation of fatigue crack propagation rate: (1) compressive residual stress ahead of the fatigue precrack, (2) interlocking of fracture surface asperities, and (3) gross plastic deformation of the interlocking asperities. Tong et al.¹⁷,¹⁸ modeled the sliding mode crack closure for pure mode II and mixed mode I and II loading conditions. They claimed that a small nominal mode I component tends to reduce the local wedging mode I stress intensity factor, and, it consequently reduces the attenuation of the friction between crack surfaces and increases the effective mode II stress intensity factor. Seo and Lee¹⁹ reported the effect of the roughness-induced crack closure on the fatigue crack propagation under mixed mode loading conditions for a single stress ratio (R = 0.5).

Roughness-induced crack closure can be useful to describe the variation of the fracture surface roughness under mixed-mode loading conditions. The fracture surface can be commonly observed by the scanning electron microscope (SEM) or transmission electron microscope (TEM), but the quantification of the fracture surface roughness is not easy. Atomic force microscope (AFM) and laser equipments are frequently used to quantify the surface roughness,²⁰,²¹ but these methods are not adequate for a large area such as fracture surface. Ultrasonic (C-scan) analyzer can be useful to map the quality of fracture surface quickly without any complicated specimen preparation.²²

In this paper, as an extension of our previous research, the characteristic of fatigue crack propagation under mixed-mode loading for two stress ratios is compared using the concept of roughness-induced crack closure considering the variation of the crack opening ratio experimentally. Empirical models of the variation of the crack opening ratio are proposed based on multi-variable statistics on key parameters such as the mode mixity, the stress ratio and the effect of crack length. In addition, fracture surfaces are examined by C-scan and classified into four stages to quantify and compare the effect of roughness-induced crack closure for two stress ratios and three load mixities. The roughness parameter, called as a contour area roughness parameter (CARP),¹⁹ defined by the normalization of the contour area of a specific C-scan peaks
by the examined area obtained from C-scan analysis reveals the effect of the roughness-induced crack closure on the fatigue crack propagation behavior under mixed-mode loading conditions.

2. Experiment

2.1 Materials and test setup

In Tables 1 and 2, chemical compositions and mechanical properties of the test material, SAPH440, are shown. SAPH440 is a commercial-grade hot-rolled steel plate, which is popularly used for automotive chasses and frames. A modified compact tension shear (MCTS) specimen was selected to create various mixed-mode loading conditions for this study. The original geometry of the compact tension shear (CTS) specimen was proposed by Richard and Benitz, and MCTS specimen had some modifications for the efficient test procedure. In Figs. 1(a) and 1(b), the MCTS specimen with a MCTS loading device is shown, and some key terminologies for this study are defined. The width (W) of the MCTS specimen was 40 mm and the thickness (t) of the MCTS specimen was 2 mm. CTS specimen had a 19 mm-long notch (the normalized initial crack length by the width of MCTS specimen (a/W): 0.475) which was machined, and a 0.5 mm-long pre-crack was made prior to the actual test. Local coordinates are defined at the crack tip to evaluate the fatigue crack propagation under mixed-mode loading conditions [Fig. 1(b)]. The mode-mixity was defined through various values of the loading angle (β), i.e., mode I corresponded to β = 0°, mode II to β = 90°, and mixed-mode I+II to β = 30° and 60°. The mode-mixity increased as the various loading angles increased.

Two stress ratios (R), which is defined as the ratio of the maximum stress and the minimum stress, were selected as 0.50 and 0.33 to investigate the effect of the stress amplitude on the roughness-induced crack closure, and fatigue tests were executed for three load angles for each stress ratio (β = 0° (C0), β = 45° (C45) and β = 60° (C60) for R = 0.33 and β = 0° (C0), β = 30° (C30) and β = 60° (C60) for R = 0.50). A sinusoidal wave was selected for fatigue loads with the maximum loads of 3.6 kN, and the frequency of fatigue loads was at 10 Hz. Stress intensity factors (SIFs: \(K_I\) and \(K_{II}\)) of the MCTS specimen were calculated on the basis of equations suggested by Richards as follows,

\[
K_I = \frac{P \sqrt{\pi a}}{Wt} \left( \frac{0.26 + 2.65 \frac{a}{W} - 0.55 \frac{a}{W} - 0.08 \left( \frac{a}{W} - \frac{a}{W} \right)^2}{1 + 0.67 \frac{a}{W} - 2.08 \left( \frac{a}{W} - \frac{a}{W} \right)^2} \right)
\]

(1)

\[
K_{II} = \frac{P \sqrt{\pi a}}{Wt} \left( \frac{-0.23 + 1.40 \frac{a}{W} - \frac{a}{W}}{1 - 0.67 \frac{a}{W} + 2.08 \left( \frac{a}{W} - \frac{a}{W} \right)^2} \right)
\]

(2)

The effective stress intensity factor was calculated through Tanaka’s equation as follows,

\[
K_{eff} = \left[ K_I^4 + 8K_{II}^4 \right]^{1/4}.
\]

(3)

The length and direction of the fatigue crack propagation were measured through an image-analyzing system without detaching the specimen during the test. The interval of fatigue crack measurements (Δ\(a_t\)) was 0.1 mm, and the crack was

| Table 1 Chemical compositions of the test material, SAPH440. |
|-----------------|---|---|---|---|---|
| C (mass%)      | 0.168 | 0.020 | 0.810 | 0.012 | 0.008 |
| Si (mass%)     |      |      |      |      |      |
| Mn (mass%)     |      |      |      |      |      |
| P (mass%)      |      |      |      |      |      |
| S (mass%)      |      |      |      |      |      |

| Table 2 Mechanical properties of the test material, SAPH440. |
|-----------------|---|---|---|---|---|
| Yield strength (MPa) | 302 | 440 | 214 | 44 | 201 |
| Ultimate strength (MPa) |      |      |      |      |      |
| Vicker’s hardness (HV) |      |      |      |      |      |
| Elongation to break (%) |      |      |      |      |      |
| Young’s modulus (GPa) |      |      |      |      |      |
| Poisson’s ratio |      |      |      |      |      |
measured up to 5 mm from the pre-crack tip. The rate of propagation of the fatigue crack was calculated by the 7-point polynomial method, following ASTM E647.

2.2 Measurement of the crack tip opening load

There are some techniques available to measure the fatigue crack closure behavior, such as mechanical compliance measurements, physical compliance curves, indirect measurements, direct measurements, etc. Among them, direct measurements\(^{(26)}\) of the crack closure can be useful in our case because these measurements are relatively convenient and accurate for the crack propagation under mixed-mode loading conditions. As shown in Fig. 1(b), microindentors are applied above and below the crack wake and the crack tip, and the variation of microindentors’ positions (the vertical displacement, \(\delta_v\), and the horizontal displacement, \(\delta_h\), can be decomposed by measuring the actual displacement, \(\delta_{I,\Pi}\)) is recorded by an image analyzer with a high resolution CCD camera. The crack tip opening load (\(P_{op}\)) can be determined by the load-displacement curve using the parabola-line method proposed by Kujawski and Stoychev.\(^{(27)}\)

2.3 Determination of contour area roughness parameter (CARP)

Contour area roughness parameter (CARP) is measured by the ultrasonic C-scan system, Mi-scope from Hitachi. Pulse-eco mode was used with a probe of 25 MHz of the frequency, 8.0 mm in diameter and 17 mm in focus length. The scan size is 6 mm by 4 mm, and the pixel size is 0.015 mm. C-scan is one of ultrasonic non-destructive testing methods, and this technique refers to a method for displaying the relative attenuation of ultrasonic waves across the surface of a component. The ultrasonic transducers scan the surface of a material, and the received wave signals are electronically conditioned and measured to determine relative energy losses of the wave as it progresses through the material at each particular location on the specimen.\(^{(28)}\)

This method was implemented to analyze the fracture surface of the fatigue crack for a single stress ratio under the mixed-mode loading condition by Seo and Lee,\(^{(19)}\) and, in this paper, the obtained CARP for two levels of stress ratios and three levels of load mixity is compared to expand and validate the proposed concept from Seo and Lee.\(^{(19)}\) In Fig. 2, an example of 3-dimensional C-scan spectrum of the fracture surface at \(R = 0.50\) and \(\beta = 0^\circ\) is shown. As shown in Fig. 3(a), the roughness of two fracture surfaces, i.e. pre-crack \((S_{FC})\) and fatigue crack \((S_{FC})\), can be measured by C-scan, and the obtained spectrum is mapped as 2-dimensional signal intensity in order to evaluate the variation of the roughness of fracture surfaces [Fig. 3(b)]. The recorded spectrum of the fracture surfaces can be classified into four stages \((V_1, V_{II}, V_{III}, V_{IV})\) and the upper limit of the intensity for each stage is set as 25 mV for \(V_1\), 75 mV for \(V_{II}\), 150 mV for \(V_{III}\) and 250 mV for \(V_{IV}\) in this study. The fracture surface is divided into six regions \((S_{FC}, S_{FC-I}, S_{FC-II}, S_{FC-III}, S_{FC-IV} and S_{FC-V})\) for the convenient comparison of test data. CARP \((R_{CA})\) can be defined as a ratio between the contour area for a specific stage (e.g. \(V_{IV}\)) and the examined area for a specific region (e.g. \(S_{FC-III}\)), for example, CARP for stage IV can be calculated as,

\[
R_{CA-[IV]} = \frac{\text{Contour area of } V_{IV}}{\text{Examined area}}. \quad (4)
\]

CARP for other stages, \(I, II\) and \(III\), can be determined similarly (i.e. \(R_{CA-[I]}\) for stage \(I\), \(R_{CA-[II]}\) for stage \(II\) and \(R_{CA-[III]}\) for stage \(III\)).

3. Fatigue Crack Propagation Behavior Considering the Roughness-Induced Crack Closure

3.1 Fatigue crack behavior under mixed-mode loading conditions

The fatigue crack propagation rate at \(R = 0.33\) is faster than that at \(R = 0.50\) due to the difference of the stress amplitude for the normalized crack length \((a/W)\). But, the effect of stress amplitude might be eliminated if the effective stress intensity factor \((\Delta K_{eff})\) is introduced as shown in eq. (3). Fig. 4, the relation between the fatigue crack propagation rate \((da/dN)\) and the effective stress intensity factor \((\Delta K_{eff})\) is shown. Though the effective stress intensity factor is introduced to evaluate the fatigue crack tip under
mixed-mode loading conditions, the effect of stress ratio and load mixity is still observed, which can be explained by roughness-induced crack closure.\(^{19,29}\) The quantification of the magnitude of the fatigue crack closure can be achieved by introducing the crack opening ratio \((U)\),

\[
U = \frac{\Delta K_{\text{eff,cl}}}{\Delta K_{\text{eff}}} = \frac{K_{\text{eff,max}} - K_{\text{eff,op}}}{K_{\text{eff,max}} - K_{\text{eff,min}}},
\]

where, the subscript \(\text{cl}\) and \(\text{op}\) mean the crack closure and the crack opening respectively.

The Paris’ equation for the fatigue crack propagation under mixed-mode loading conditions can be modified by using the crack opening ratio as,

\[
\frac{da}{dN} = C(U \cdot \Delta K_{\text{eff}})^m = C(\Delta K_{\text{eff,cl}})^m,
\]

where, \(C\) and \(m\) are material constants.

The variation of measured crack opening ratio for \(R = 0.33\) and \(R = 0.50\) as a function of the normalized crack length \((a/W)\) is shown in Fig. 5. It can be noticed that the crack opening ratio increases initially and stabilizes at around \(a/W = 0.565\) almost regardless of the stress ratio. Such behavior (increasing and stabilizing \(U\)) is also observed by some researchers.\(^{11,29,30}\) Therefore, two regions of the crack opening ratio, i.e. \(U^S\) for stabilizing \(U\) and \(U^F\) for increasing (fluctuating) \(U\), can be defined. For both of \(R = 0.33\) and \(R = 0.50\), \(U^S\) is always less than 1, which means that the crack closure effect is not disappearing even when \(U\) reaches \(U^S\). But, as expected, \(U^F\) increases as \(\beta\) decreases, i.e. the largest \(U^S\) (> 0.9) is recorded for \(C0\) (\(\beta = 0^\circ\)). The main mechanism of the crack closure in mode I loading condition (CO) is plasticity-induced crack closure, so it can be thought that the roughness-induced crack closure can be a major factor to control the fatigue crack closure behavior under mixed-mode loading conditions. This hypothesis will be reviewed by CARP in the later section.

### 3.2 Application of the roughness-induced crack closure for the evaluation of the fatigue crack propagation behavior under mixed-mode loading conditions

As mentioned above, two regions of the crack opening ratio, \(U^F\) and \(U^S\), are observed from the relation between \(U\) and \(a/W\), and the stabilized \(U\) (\(U^S\)) is started from \(a/W = 0.565\) in our test. There are some important factors to control \(U^F\) and \(U^S\), such as the stress ratio \((R)\), the load mixity \((\beta)\) and the fatigue crack length for \(U^F\). Using multi-variable statistical modeling, the empirical equation of \(U^F\) and \(U^S\) considering factors above can be found as,

\[
U^S = 1.076 - 0.2786R - 0.1637\beta \left(\frac{a}{W} \geq 0.565\right). \tag{7}
\]

\[
U^F = 10.71 - 0.2786R - 0.1637\beta + 41.72 \left(\frac{a}{W}\right) - 36.92 \left(\frac{a}{W}\right)^2 \left(\frac{a}{W} < 0.565\right). \tag{8}
\]

For all range of \(a/W\), the overall crack opening ratio \((U^{F+S})\) can be defined using both of eqs. (7) and (8). As shown in Fig. 6, the accuracy of the empirical model of \(U^{F+S}\) is validated \((R^2 = 0.960)\) by comparing experimental results. Equations (7) and (8) is valid for \(0.33 < R < 0.50, 0 < \beta < 60^\circ\) and \(0.475 < a/W < 0.625\).

Similar to the idea of Elber,\(^3\) it is commonly accepted to use the stabilized \(U\) (\(U^S\)) for explaining the crack closure effect on the fatigue crack propagation behavior under mixed-mode loading conditions. So, two cases, i.e. \(U^S\) and
4. Evaluation of the Fatigue Crack Surface under Mixed-Mode Loading Conditions

In Fig. 9, the CARP for all stages in case of C0 and C60 is shown to investigate the effect of mixed-mode loading conditions on the characteristics of the fracture surface roughness. Characteristics of fracture surfaces are examined by the variation of CARP ($R_{CA}$). Measured $R_{CA}$ of the pre-crack of C0 for $R = 0.50$ and $R = 0.33$ is 21.4% and 14.6% respectively, but that of C60 is 0% regardless of the stress ratio. Meanwhile, the portion of $R_{CA}$ of the stage II ($R_{CA[III]}$) and $R_{CA}$ of the stage III ($R_{CA[III]}$) of C60 increases comparing with that of C0 for the pre-crack. This can be an evidence of roughness-induced crack closure which is caused by the wear of asperities due to sliding of crack surfaces under mixed-mode-loading conditions, which is also observed by Kim and Kim\(^{11}\) using scanning electron microscopic (SEM) observations. In general, the portion of $R_{CA}$ of the stage IV ($R_{CA[IV]}$) for $R = 0.33$ is smaller than that for $R = 0.50$, which means that the wear between fracture surfaces for $R = 0.33$ happens more actively. Hence, it can be explained that the crack opening ratio ($U$) for $R = 0.33$ is larger than that of $R = 0.50$. Within regions representing fatigue crack propagation, i.e. from $S_{FC-1}$ to $S_{FC-5}$, the portion of $R_{CA[IV]}$ decreases as the
fatigue crack propagates due to the faster increase of the fatigue crack driving force in mode I. Especially, the portion of $R_{\text{CA-[IV]}}$ decrease dramatically after $S_{\text{FC-A}}$ region, it can be an evidence of observing stabilizing $U$ ($U^S$) as shown in Fig. 5. So, it can be qualitatively understood the variation of $U$ by observing CARP of fracture surfaces.

5. Conclusions

In this paper, the characteristics of fatigue crack propagation under mixed-mode loading is studied using the concept of roughness-induced crack closure, and a model of the variation of the crack opening ratio is proposed based on multi-variable statistics. In addition, fracture surfaces are examined by C-scan and classified into four stages to quantify the effect of crack closure. Here are some key conclusions of this study:

(1) Though the effective stress intensity factor is introduced, the effect of stress ratio and load mixity is still observed. Two regions of the crack opening ratio, i.e. $U^S$ for stabilizing $U$ and $U^F$ for increasing (fluctuating) $U$, are observed from fatigue tests, and $U$ of lower $R$ ($R = 0.33$) is higher than that of higher $R$ ($R = 0.50$).

(2) Using multi-variable modeling considering the stress ratio ($R$), the load mixity ($\beta$) and the normalized crack length ($a/W$) for $U^F$, the empirical equation of $U^F$ and $U^S$ is proposed and validated with high accuracy. The overall crack opening ratio ($U^{F+S}$) is defined by combining $U^F$ and $U^S$, and the fatigue crack propagation behavior can be well correlated ($R^2 = 0.96$) with $\Delta K_{\text{eff,cl}}$, i.e. the effective stress intensity factor, $\Delta K_{\text{eff,cl}}$, with applying $U^{F+S}$.

(3) Characteristics of fracture surfaces are examined by the variation of CARP ($R_{\text{CA}}$) measured by C-scan. The difference of $R_{\text{CA-[IV]}}$ for $R = 0.33$ and $R = 0.50$ can explain the wear between fracture surface for $R = 0.33$ happens actively, and, the portion of $R_{\text{CA-[IV]}}$ decrease dramatically after $S_{\text{FC-A}}$ region, it is the reason of observing stabilizing $U$ ($U^S$) from fatigue tests.

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