Loading-Frequency Effects on Fatigue Crack Growth Behavior of a Low Carbon Steel JIS S10C in Hydrogen Gas Environment*

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Abstract
In order to clarify the loading-frequency effect on the fatigue crack growth behavior of a low carbon steel JIS S10C in a hydrogen gas environment, fully reversed bending fatigue tests were carried out. The main results are as follows. The loading-frequency effect on the FCG revealed a complex behavior; that is, not only acceleration, but also deceleration even in the same low loading-frequency range. The slight acceleration appears in the low growth rate range in which the ductile fracture mode is predominant. The deceleration appears due to the transition behavior from a quasi-cleavage fracture mode with a higher FCGR to a ductile one with a lower FCGR. This shows that lowering the load frequency does not necessarily lead to an unpredictable fatigue crack growth.

Key words: Hydrogen Embrittlement, Fatigue, Fractography, Crack Propagation, Loading-Frequency Effect, Quasi-Cleavage, Brittle Striation, Low Carbon Steel

1. Introduction

Hydrogen is expected to be one of the next generation energy sources which can solve environmental problems and the exhaustion of fossil fuels. For a fuel cell system, a variety of metallic materials such as stainless steel, aluminum alloys, alloy steel, and carbon steel are exposed to hydrogen gas through the consumption processes, such as manufacturing, transportation, and gas storage. Hydrogen has been reported to decrease the strength of metallic materials (1), (2). Some of the equipment components are cyclically loaded in hydrogen gas. Therefore, it is necessary to clarify the effect of hydrogen gas on the fatigue strength of the metals. It is important to evaluate the effect of the hydrogen gas pressure, the temperature, and loading frequency is important.

In this paper, the effects of the loading frequency on the fatigue crack growth rate (FCGR) were investigated. It has been reported that the FCGR of some metallic materials in a hydrogen gas environment is accelerated at a low loading frequency (3), (4). There are some actual components which are loaded at an extremely low loading frequency. Therefore, the fatigue test data taken at a higher loading frequency can provide an unconservative prediction for the actual equipment. However, if fatigue tests are carried out under the same condition as the actual equipment, this involves an extremely long time and high cost.
The loading-frequency effect on the FCG behavior has been previously reported. The FCGR acceleration related to the loading frequency was reported by focusing on the hydrogen gas environment (3), (4) and the hydrogen charge (5), (6). On the other hand, the FCGR has been reported to be accelerated by lowering the frequency even under the conditions of ambient air and no hydrogen charging (7). Therefore, it was assumed that the factors influencing the loading-frequency dependence in a hydrogen gas environment were the inherent strain rate dependence, intrusion/diffusion of hydrogen and the interaction of these factors. It is expected that the loading-frequency dependence is very complex. Actually, the loading-frequency dependencies are related in different ways to the materials and conditions (3)~(6). These factors have not yet been sufficiently explained.

In the case of carbon steel, it is well-known that brittle-like quasi-cleavage facets and intergranular facets appear in the fatigue fracture surface in a hydrogen gas environment (4). Such a brittle-like fracture is also observed in typical "hydrogen embrittlement" fracture. As an aspect of classical "hydrogen embrittlement", involvement of an abrupt brittle fracture or crack growth under constant load is expected in the case of fatigue crack growth in hydrogen gas. Therefore, it is considered that the loading-frequency dependence has a complex behavior. To evaluate the loading-frequency dependence of the fatigue crack growth behavior in a hydrogen gas environment, collecting the basic FCG data, clarifying the FCG mechanism and confirming the FCG evaluation method, which is based on the FCG mechanism, are considered to be necessary.

In this study, the loading-frequency effects on the FCGR of low carbon steel JIS 10C in a hydrogen gas environment was observed. In order to clarify the phenomenal loading frequency dependence and to discuss an evaluation method in the quasi-cleavage fracture region, two kinds of fatigue tests were conducted. One used a triangular wave with a lower strain rate, and the other involved duration of time at every maximum and minimum load. The fracture surfaces were observed in detail using a Scanning Electron Microscope (SEM).

2. Materials, Specimens and Experimental Procedure

The material used in this study was a low carbon steel (JIS S10C). Tables 1 and 2 show the chemical composition and mechanical properties of the material. Fig. 1 shows the specimen configuration. Specimens were machined after annealing at 1173K for one hour from a 22-mm diameter rolled cylindrical bar. The specimen was then mechanically polished with #2000 emery paper and buffed with a 0.05 \( \mu \)m alumina suspension. A small blind hole of 100\( \mu \)m diameter and 50\( \mu \)m depth was made at the center of the specimen as a crack starter. The specimen was then reannealed in a vacuum at 873K for one hour to remove the residual stress and the internal hydrogen.

Fatigue crack growth tests were carried out under displacement-controlled fully-reversed bending. Triangular wave forms were mainly used. A duration time wave form was partly used. Fig. 2 shows the wave forms. The loading frequency in the triangular wave form tests was 6 Hz (Fig. 2 (a)) and 0.1 Hz (Fig. 2 (b)). In the duration time wave form test, a 10-second load holding at every maximum and minimum load was added to the 6 Hz triangular wave form (Fig. 2 (c)). The testing environments were 0.18 MPa and 313 K in pure hydrogen gas (99.9999 %) or nitrogen gas (99.995 %). The fatigue process was successively observed through the glass window of the chamber by an optical microscope. The loading conditions were determined by the total strain range \( \Delta \varepsilon \) measured by a strain gauge placed on the back surface of the specimen. In this study, specimens were kept in the testing environment (0.18 MPa, 313K) for one hour to insure that the hydrogen content and temperature of the specimens were uniform.
3. Results and Discussion

3.1 Fatigue crack growth behavior in hydrogen gas

In this section, the general FCG behavior in hydrogen gas is discussed. Fig. 3 shows the relationship between the FCG behavior and the crack length represented on a logarithmic scale. The FCG in hydrogen gas was higher than that in nitrogen. When \( \Delta \varepsilon_t = 0.37 \% \), the slope of the FCG is about 1 in both the hydrogen gas and nitrogen gas. This means that the FCG is proportional to the crack length \( (d/dN \propto L) \). When \( \Delta \varepsilon_t = 0.80 \% \), although the gradient in nitrogen gas is also about 1, the gradient in hydrogen gas becomes higher than 1 and the FCG is significantly accelerated in relation to the growth of the crack length.

Fig. 4 shows the typical fracture surface morphologies. Fig. 4 (a) shows that of \( \Delta \varepsilon_t = 0.37 \% \). Although the fracture surface in nitrogen mainly shows a transgranular ductile surface, the intergranular facet increases in hydrogen (the facet ratio of nitrogen and hydrogen is about 2% and about 30%, respectively). In this region, the FCG was proportional to the crack length in both the hydrogen and nitrogen gas environment in Fig. 3. This proportional relation, \( (d/dN \propto L) \), is ordinarily satisfied under the condition where a small crack under a large yielding condition grows by a normal slip-off mechanism \(^{(10)}\). Because the transgranular ductile fracture surface is dominant in nitrogen gas, it is natural that the relation is satisfied. However, in hydrogen gas, the fracture surface morphology is different from that in nitrogen; the intergranular facet increases in the fracture surface. It is considered that the intergranular fatigue crack growth mechanism in hydrogen, which satisfies the slip-based \( (d/dN \propto L) \) relation, is not considered to be the normal slip-off model; however, the mechanism is based on the slip.

Fig. 4 (b) shows that of \( \Delta \varepsilon_t = 0.80 \% \). Almost all the fracture surfaces in nitrogen show...
a transgranular ductile surface. On the other hand, the fracture surface in hydrogen mainly shows a surface showing a quasi-cleavage with brittle striations (the area ratio is more than 95% at maximum). In this region, although the proportional relation, \( \frac{d}{dN} \sim l \), is satisfied in nitrogen gas, it is not satisfied in hydrogen. FCGR is significantly accelerated with the crack length. The quasi-cleavage FCG mechanism is considered to be obviously different from the normal slip-off mechanism.

\[
\frac{dL}{dN} \propto l
\]

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**Fig. 3** Fatigue crack growth behavior in hydrogen gas environment

(a) \( \Delta \epsilon_t = 0.37 \% \)

\[
\frac{dN}{d\Delta \epsilon} = 6 \times 10^{-9} \text{ [m/cycle]}
\]

(b) \( \Delta \epsilon_t = 0.80 \% \)

\[
\frac{dN}{d\Delta \epsilon} = 9 \times 10^{-8} \text{ [m/cycle]}
\]

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**Fig. 4** Typical fracture surface morphologies. Arrow indicates direction of crack propagation

(a) \( \Delta \epsilon_t = 0.37 \% \)

\[
\frac{dN}{d\Delta \epsilon} = 6 \times 10^{-9} \text{ [m/cycle]}
\]

(b) \( \Delta \epsilon_t = 0.80 \% \)

\[
\frac{dN}{d\Delta \epsilon} = 1 \times 10^{-6} \text{ [m/cycle]}
\]
3.2 Loading frequency effect on fatigue crack growth behavior in hydrogen gas

Because the quasi-cleavage FCG mechanism is considered to be obviously different from the normal slip-off mechanism, therefore, the loading frequency dependence could show a complicated behavior. In this section, the general loading frequency effect on the FCG behavior in the hydrogen gas environment is discussed.

3.2.1 Fatigue crack growth rate

Fig. 5 shows the fatigue crack growth rate at several loading frequencies. Fig. 5 (a) shows the FCGR at $\Delta\varepsilon_t = 0.50\%$. The symbol ◆ represents that for 6 Hz and ◇ represents that for 0.1 Hz. The FCGR data cross each other. In the lower FCGR region, the FCGR at 0.1 Hz is slightly higher than that at 6 Hz. In the higher FCGR region, the FCGR at 6 Hz is higher than that at 0.1 Hz. Fig. 5 (b) shows the results when $\Delta\varepsilon_t = 0.70\%$. ■ represents FCGR at 6 Hz and ○ represents that at 0.1 Hz. In this case, the FCGR at 0.1 Hz is lower than that at 6 Hz (In addition, it was confirmed that the FCGR at 0.005 Hz was also lower than that of at 6 Hz in another type test). Fig. 5 (c) shows the results when $\Delta\varepsilon_t = 0.80\%$. ● is 6 Hz and ○ is 0.1 Hz. The FCGR at 6 Hz is higher than that at 0.1 Hz, as well as in the case of $\Delta\varepsilon_t = 0.70\%$.

For this material, the FCG behavior reveals a rather complex behavior related to the loading frequency in the hydrogen gas environment. There are two cases; acceleration and deceleration, in spite of the low loading frequency (Although the differences related to the loading frequency were small and these data should have some variation, the reliability of these data were partially ensured when the below fracture surface observation result was considered).

3.2.2 Fracture surface morphologies

The above results showed that the effect of lowering the loading frequency on the FCGR undergoes only not a general acceleration behavior (3)~(7), but also a deceleration behavior. It is considered that the FCGR tendency is reflected in the fatigue fracture surface. In this section, the ‘relationship between brittle striation spacing and FCGR’ and the ‘loading frequency effect on the fracture surface morphologies’ are investigated.

Fig. 7 shows the relationship between the brittle striation spacing and the depth from the specimen surface. The observed position is just beneath the artificial hole represented in the figure. The brittle striation spacing in the randomly selected QC facet just beneath the hole was measured from the SEM image. The example of measuring the brittle striation spacing is shown in Fig. 6. The brittle striation spacing is defined by the striation spacing taken from a direction perpendicular to the striation. This direction does not perfectly
correspond to the macroscopic FCG direction. The symbols ● and ■ represent $\Delta \varepsilon_t = 0.80\%$ and $\Delta \varepsilon_t = 0.70\%$ at 6 Hz, respectively. The greater the distance from the hole becomes, the more the brittle striation spacing expands. The brittle striation spacing of $\Delta \varepsilon_t = 0.80\%$ is wider than that of $\Delta \varepsilon_t = 0.70\%$. This means that the faster the FCGR becomes, the more the brittle striation spacing expands (the farther the distance of the hole becomes and the greater applied strain becomes, the faster the FCGR becomes). The brittle striation spacing is correlated to the FCGR except for the effect of the loading frequency. The symbols ○ and □ represent $\Delta \varepsilon_t = 0.80\%$ and $\Delta \varepsilon_t = 0.70\%$ at 0.1 Hz, respectively. Similar to 6 Hz, the farther the distance from the hole becomes, the more the brittle striation spacing expands. Normally, the greater the distance from the hole becomes, the higher the FCGR becomes. On the other hand, the spacing at 0.1 Hz is much wider than that at 6 Hz (● and ○, ■ and □). However, in this case, the FCGR at 0.1 Hz is lower than that at 6 Hz. This is the opposite tendency to the above results.

It is well-known that the FCGR is reflected in the normal ductile striation spacing. Yokobori reported that the striation spacing expands related to FCGR acceleration by lowering the loading frequency in air (7). Similarly, Ebara reported that brittle striation spacing is also correlated to the FCGR (11). In this study, there are good correlations between the variations in the brittle striation spacing and variations in the FCGR upon changing the mechanical conditions, but there are no good correlations upon changing the loading frequency. For the brittle striation, the FCG mechanism is the predominant mechanism for all of the fracture surface or the change in the ratio has a constant tendency, so there could be a good correlation between the macroscopic FCGR and the local brittle striation spacing. On the other hand, in the case of the area ratio of the fracture surface with a brittle striation, there is no good correlation between the macroscopic FCGR and the local brittle striationspacing. The area ratio of the fracture surface with a brittle striation could be changed by changing the loading frequency. The change in the fracture surface morphology

![Figure 6](image)

**Fig. 6** Example of measuring the brittle striation spacing ($\Delta \varepsilon_t = 0.70\%, f = 6$ Hz, $a = 650$ µm)

![Figure 7](image)

**Fig. 7** Brittle striation spacing in hydrogen
due to the loading frequency was investigated as discussed below.

Fig. 8 shows the SEM image which represents the effect of the loading frequency on the fatigue fracture surface morphologies in hydrogen gas; (a) is at 6 Hz and (b) is at 0.1 Hz. The mechanical conditions, total strain range and crack length of each of the images in the same columns are the same. Images in the first and second columns represent the case of $\Delta \varepsilon = 0.50 \%$. The difference in the first and second columns is the depth from the specimen surface $a$; $a$ is the distance from the specimen surface and this corresponds to the crack length. The observed positions are just beneath the artificial hole. Intergranular facets with transgranular ductile fracture surfaces are seen in (a-1) and (b-1). This region corresponds to the region in which the FCGR is slightly accelerated by lowering the loading frequency as shown in Fig. 5 (a). Figs. (a-1) and (b-1) show the fracture surfaces in the high growth rate region compared to the images shown in the first column. In the case of 6 Hz, a high area ratio of brittle-like quasi-cleavage facets is seen in the transgranular ductile fracture surface. However, for 0.1 Hz, the area ratio of the quasi-cleavage facets decreased and ductile-like fracture surfaces are seen in almost all the fracture surfaces. ‘Ductile-like fracture surface’ means the fracture surface where a ductile-like striation is observed in many places. This region corresponds to the region in which the FCGR decreased due to lowering of the loading frequency as shown in Fig. 5 (c). This was the same tendency when $\Delta \varepsilon = 0.70 \%$ for $\Delta \varepsilon = 0.80 \%$. In addition, it was confirmed that the ductile fracture increases under the condition of 0.005 Hz, $\Delta \varepsilon = 0.70 \%$ (FCGR also decreases).

Fig. 9 (b) shows the relationship between the depth from the specimen surface and the quasi-cleavage fracture ratio. The measurement area of the fracture ratio is just beneath the artificial hole shown in Fig. 9 (a). To clarify the relation to FCGR, the relationship between FCGR $da/dN$ and the distance from the artificial hole is also plotted in the figure. The $da/dN$ is measured from the aspect ratio and $d/dN$. The quasi-cleavage fracture ratio increases in relation to the acceleration of FCGR; ● and ○. On the other hand, the quasi-cleavage fracture ratio decreased by lowering the loading frequency; ● and ○ or ◆ and ◇. This decreasing tendency well corresponds to the FCGR deceleration behavior at low loading frequency; see ●, ○ and ——, —— or ◆, ◇ and ——. In the high FCGR region in which quasi-cleavage facets appeared, the quasi-cleavage fracture ratio decreased and the ductile-like fracture ratio increased. The reason for the FCGR deceleration at a low loading frequency is a decrease of the quasi-cleavage fracture mode, which is a fast FCGR mode, and an increase of the ductile-like fracture mode, which is a slow FCGR mode. The reason for no correlation between the change in the brittle striation spacing and the change in the FCGR at the loading frequency is that the quasi-cleavage fracture ratio changes. Because there is a possibility that the FCGR in a brittle striation could be locally accelerated by lowering the loading frequency, these details will be discussed in a future report.

In the low FCGR region in which no quasi cleavage facets appeared, the fracture surface morphology is a ductile-like fracture surface with intergranular facets. In this region, the FCGR is slightly accelerated by lowering the loading frequency. It is considered that this acceleration is an effect from lowering the loading frequency in the ductile-like FCG mode and the intergranular FCG mode. Therefore, it is considered that in the region where the FCG mode changes from a brittle-like FCG mode to a ductile-like FCG mode, the local FCGR is accelerated in the ductile-like FCG area by lowering the loading frequency.
For this material, to evaluate the loading frequency dependence in a hydrogen gas environment, it is necessary to consider the change in the ratio in the brittle-like FCG area and the ductile-like FCG area and the effect of the loading frequency on each area.

\[
\Delta \varepsilon_t = 0.50 \%, \ a = 250 \ \mu m \\
\frac{da}{dN} = 2.0 \times 10^{-8} \ [m/cycle]
\]

\[
\Delta \varepsilon_t = 0.50 \%, \ a = 250 \ \mu m \\
\frac{da}{dN} = 2.5 \times 10^{-8} \ [m/cycle]
\]

\[
\Delta \varepsilon_t = 0.50 \%, \ a = 500 \ \mu m \\
\frac{da}{dN} = 1.0 \times 10^{-7} \ [m/cycle]
\]

\[
\Delta \varepsilon_t = 0.50 \%, \ a = 500 \ \mu m \\
\frac{da}{dN} = 6.9 \times 10^{-8} \ [m/cycle]
\]

\[
\Delta \varepsilon_t = 0.80 \%, \ a = 500 \ \mu m \\
\frac{da}{dN} = 1.1 \times 10^{-6} \ [m/cycle]
\]

\[
\Delta \varepsilon_t = 0.80 \%, \ a = 500 \ \mu m \\
\frac{da}{dN} = 6.9 \times 10^{-7} \ [m/cycle]
\]

Fig. 8 Loading frequency effects on fracture surface morphologies in a hydrogen gas environment. Arrow indicates direction of crack propagation.
3.3 Duration time effects on fatigue crack growth behavior

The change in the brittle-like FCG mode to the ductile-like FCG mode, which is related to lowering the loading frequency, could be affected by the inherent strain rate dependence and hydrogen-intrusion to form a crack tip. In this section, to clarify the predominant factor in the above FCG behavior, transition and deceleration, a triangular wave with a duration time at every maximum and minimum load test as shown in Fig. 2 (c) was conducted. The strain rate in the loading and unloading process is the same as that of 6 Hz. This test is intended to provide a greater amount of hydrogen-intrusion near the crack tip region by hydrogen-diffusion during the load-holding time. Particularly, the ‘change in FCGR’ and the ‘change in fracture morphologies’ were investigated.

Fig. 10 (b) shows the FCGR. To clearly observe the FCGR transition behavior, a wave form changing fatigue test, a 6 Hz triangular wave changing to a duration time wave form, was conducted as shown in Fig. 8 (a). The wave form was a 6 Hz triangular wave until the crack length grew to 1 mm. The form was then changed into a duration time wave test. The FCGR decelerated just after changing the wave form; see ■ and ■.

Fig. 11 shows the effects of the load duration on the fracture surface morphologies. The mechanical condition of each of the images was conformed shown in Fig. 7. (a) is the 6 Hz triangular wave test, and (b) is the duration time wave test. The brittle-like quasi-cleavage fracture surface is predominant at 6 Hz. The ductile-like fracture morphology increased and the quasi-cleavage fracture morphology decreased during the duration time wave test.
Fig. 12 shows the relationship between the depth from the specimen surface and the quasi-cleavage fracture ratio as shown in Fig. 9. The FCGR $da/dN$ is also shown in the figure. The arrow indicates the depth of the wave form changing point calculated from the aspect ratio. The changing of the quasi-cleavage fracture ratio corresponds to the FCGR deceleration just after changing the wave form; see ■ and – – –.

For the duration wave test, even though the strain rate of the loading part is the same, the FCGR deceleration and transition of the brittle-like FCG mode to the ductile-like FCG mode were observed. The same tendency was observed in the fatigue test with a similar wave form which involved load-holding just after 10 % unloading from the maximum load. The effects of the strain rate during the load-holding at the maximum load were considered to be small.

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**Fig. 10**  Duration time effect on fatigue crack growth rate.

(a) 6 Hz, $a = 500 \mu m$

$da/dN = 5.1 \times 10^{-7}$ [m/cycle]

(b) 10 s hold, $a = 500 \mu m$

$da/dN = 3.0 \times 10^{-7}$ [m/cycle]

**Fig. 11**  Duration time effect on fracture surface morphology.

The arrow indicates the direction of crack propagation.
It is considered that not only the inherent strain rate dependence, but also the existing states of the hydrogen affects the transition behavior in the FCG mode. The transition behavior in the FCG mode easily occurs due to the greater hydrogen entry at the crack tip. This will be discussed in the next section.

4. Discussion

The loading frequency effects on FCGR in a hydrogen gas environment show a rather complex behavior. This depends on the transition behavior of the brittle-like FCG mode to the ductile-like FCG mode related to lowering the loading frequency.

There are some reports on the transition behavior of the brittle-like FCG mode to the ductile-like FCG mode. Neuman and Vehoff have observed the transition behavior of the brittle-like FCG mode to the ductile-like FCG mode in 3%Si-Fe\cite{12,13}. They reported that the transition behavior is related to the innate strain rate dependence of the material, and the brittle-like FCG mode easily occurs when a higher strain rate or a lower temperature condition is present. These behavior types were explained as the brittle-like FCG mode easily occurring when the plastic deformation easily occurs in relation to the innate strain rate dependence of the material. It is considered that the transition behavior mentioned in the previous section was also explained as plastic deformation at the crack tip easily occurring in relation to the innate strain rate dependence of the material.

In addition, considering the result of the duration time wave test, not only the material’s innate strain rate dependence, but also the existing states of hydrogen (especially its distribution, extent and density near a crack tip are considered to be important) affect the transition behavior of the FCG mode. It is well-known that hydrogen enhances slip\cite{14}. Therefore, it is considered that the plastic deformation at the crack tip was enhanced under the condition of a higher amount of hydrogen intrusion, and the brittle-like FCG mode easily changing to the ductile-like FCG mode. On the other hand, the brittle-like FCG mode originally occurred due to hydrogen. Such a rather complex behavior, hydrogen enhancing...
the brittle-like FCG mode and also enhancing the ductile-like FCG mode under certain conditions, has to be clarified based on the brittle-like FCG mechanism. This problem is a future issue.

The loading-frequency dependence in the ductile-like FCG mode region has been observed for A6061-T6 which has a ductile FCG mode in hydrogen gas \(15\). As a result, it was clarified that FCGR in a hydrogen gas environment is accelerated at a low loading frequency and becomes saturated below a certain frequency based on the ductile FCG mode. For the material in this study, FCGR is slightly accelerated during ductile fracture with an intergranular facet region appearing. It is considered that this FCG region shows a tendency similar to the above results; FCG is accelerated at a low loading frequency and becomes saturated below a certain frequency. (Actually, it is necessary to clarify the mechanism of the intergranular FCG and consider the loading-frequency dependence in the intergranular FCG region. However, in this case, the effect of the loading frequency on the intergranular FCG region was small because the intergranular fracture ratio was small, i.e., less than 30%).

To evaluate the loading frequency dependence of low carbon steel in a hydrogen gas environment, it is important to consider the transition of the FCG mechanism in relation to the loading frequency; the influencing factor in the FCGR might change with the FCG mechanism. Furthermore, it is necessary to divide the FCG region according to the FCG mechanism (ductile-like area and brittle-like area) and evaluate by considering the FCG mechanism of each region.

For this study, the brittle-like FCG mode is considered to change into the ductile-like FCG mode due to the effects of the strain rate and hydrogen. Furthermore, considering the tendencies of greater hydrogen intrusion enhancing the ductile-like FCG mode and the loading frequency dependence being small in the ductile FCG region, the FCG data taken at the higher frequency can be rationally used as the safety data for actual equipment in some cases.

5. Conclusions

Loading frequency effects on the fatigue crack growth behavior of a low carbon steel JIS S10C in a hydrogen gas environment were investigated in this study. The main results are as follows:

1) The loading frequency effects on the FCGR in hydrogen gas environment show a rather complex behavior. Two cases are shown; i.e., acceleration and deceleration due to the lower loading frequency.

2) The FCGR deceleration tendency depends on the loading frequency shown in 1) appeared as a result of a decrease of the quasi-cleavage fracture mode which hastens the FCGR and an increase of the ductile-like fracture mode which slows the FCGR occurring due to lowering the loading frequency. The FCGR slightly accelerated in the case of the ductile fracture predominant in the low FCGR region.

3) Based on these results, although the actual equipment was loaded under an extremely low loading frequency condition, the FCG data taken at a higher frequency can be rationally used as safety data for actual equipment in some cases.

4) To evaluate the loading frequency dependence on the FCG behavior in hydrogen gas, it is necessary to divide the FCG region according to the FCG mechanism (ductile-like area and brittle-like area) and consider the transition behavior of the brittle to ductile FCG mechanism. It is considered that the FCG mechanism is related to the loading stress, the strain rate and the existing states of hydrogen and its diffusion. These are future issues.
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