Assessment of Environmental Effect on the Closure-Free Threshold Stress Intensity Factor (SIF) Range

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1. INTRODUCTION

The applied stress intensity factor (SIF) range ΔK has been known to be a major controlling parameter in fatigue crack growth (FCG) rate *da/dN* under small scale yielding conditions [1]. Almost without exception, existing data show that the threshold SIF range ΔK_{th} tends to decrease with increasing load ratio R [2]. Schmidt and Paris rationalized this behavior solely on the basis of the crack closure concept [3]. According to their model, the ΔK_{th} obtained by the maximum SIF (K_{max})-constant test method (that ensures closure free conditions) is expected to be independent of K_{max} and to be constant. However, this does not happen for all the materials [2, 4, 5]. Though ΔK_{th} obtained in the K_{max}-constant FCG tests for many materials do not change for the tested K_{max}, some materials experience a decrease in ΔK_{th} due to an increase in the tested K_{max} as shown in Fig. 1 (Hereafter, we will call this phenomena as "the decrease in ΔK_{th} due to high K_{max}.").

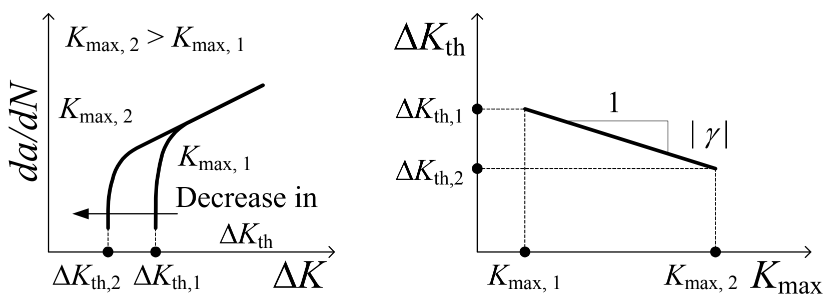


Fig. 1 Decrease in ΔK_{th} due to high K_{max} observed for K_{max} –constant tests

In our previous work, we proposed an assessment diagram to determine whether a material will experience this decrease in ΔK_{th} due to high K_{max}, and validated the diagram by showing that 0.55% carbon steel JIS S55C in air is a candidate material for the phenomena and proved the assumption by experiments [5]. We also proposed a possible mechanistic explanation of the behavior (Fig. 2). We assumed that the FCG mechanism was the same regardless of ΔK or K_{max}, considering that macroscopic crack front growth was observed as a coalescence of microscopic cracks in grains (modeled as cells in Fig. 2). Another assumption was that microscopic crack growth is selectively determined as either cyclic or static mode failure, depending on the direction of the slip plane of the grain. Then, we proceeded to propose a quantitative method to estimate the decrease rate γ in Fig. 1 [6]. To accomplish this, the conceptual FCG model that was proposed in the previous work (Fig. 2) was further developed to a concrete simulation algorithm using minimal experimental data for the purpose. The proposed method was validated by comparing predictions with experimentally determined values of γ on embrittled carbon steel.

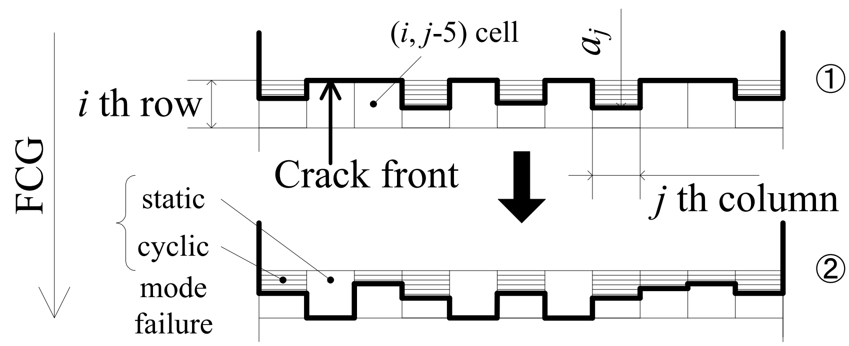


Fig. 2 The simplified microscopic crack coalescence FCG model [5]

Our previous works were oriented to an urgent engineering necessity; i.e., we needed to determine whether a material in “air” would experience the phenomena “the decrease in ΔK_{th} due to high K_{max}.” However, we cannot deny that air provides a somewhat aggressive environment. For example, titanium alloys are known to experience both sustained-load cracking (SLC) and the so-called “Marci effect [7, 8]” at ambient temperature in air. SLC and Marci effect is explained as a static failure contribution, observed over an “engineering time scale.” Sunder considered materials that do not show SLC nor Marci effect, and showed that static failure contribution on FCG (in his words, BMF: brittle micro fracture) can be excluded in high vacuum (< 10^{-6} torr) [9]. If the static failure in grain size order, as we insist, explains “the decrease in ΔK_{th} due to high K_{max},” we thought it important to assess the effect of environment on the phenomena, by running K_{max}-constant ΔK_{th} tests in high vacuum.

Thus, we ran K_{max}-constant ΔK_{th} tests in high vacuum for 0.55% carbon steel JIS S55C, which is known to experience the phenomena in air [5]. The experimental results showed that S55C in vacuum did not show “the decrease in ΔK_{th} due to high K_{max}”. The results support the validity of our model for the phenomena [5], that microscopic crack growth in a grain due to static mode failure accelerated the expected cyclic crack growth, while noting that high vacuum excluded the possibility of static mode failure.

2. EXPERIMENTS

2.1 Specimen Preparation

Material under consideration was 0.55% carbon steel JIS S55C, which is known to experience the “the decrease in ΔK_{th} due to high K_{max}” [5]. The chemical composition of the tested material is summarized in Table 1 (heat no. S55C-3).

The material was oil quenched after 3 hrs at 850 °C, tempered 5 hrs at 550 °C and stress relieved 8 hrs at 520 °C. The tensile test results was 0.2% proof stress σ_{YS} = 439 MPa, tensile strength σ_B = 692 MPa.

Table 1 Chemical composition of test specimens

	C	Si	Mn	P	S	Cu	Ni	Cr	Fe
Spec.	0.52 ~0.58	0.15 ~0.35	0.60 ~0.90	≤0.030	≤0.035		≤0.20		Bal.
S55C3	0.57	0.24	0.71	0.010	0.005	0.01	0.01	0.02	Bal.

The CT test specimens were prepared in accordance with ASTM-E647 [10] as shown in Fig. 3.

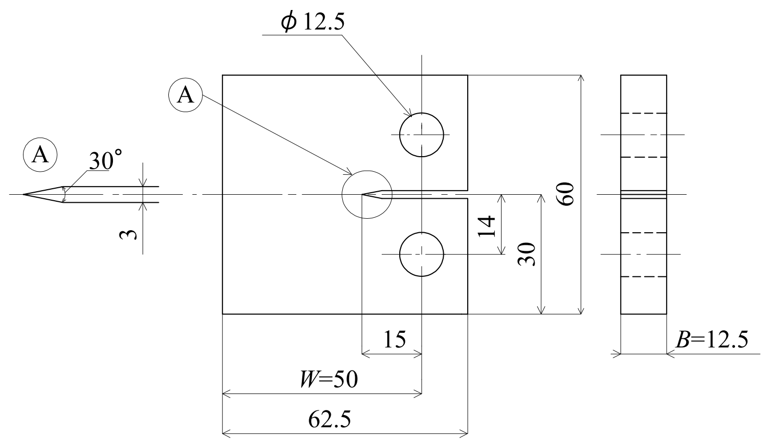


Fig. 3 Geometry of CT test specimen.

2.2 K_{max}-constant FCG tests in high vacuum

We made tests fundamentally in accordance with the ΔK-decreasing threshold test procedure specified in ASTM E647 [10] in association with a constant maximum stress intensity level K_{max} [11]. The load frequency was 30 Hz. The cyclic stress intensity range was varied according to the following equation, as specified in ASTM E647 [10].

$$\Delta K = \Delta K_0 e^{C(a-a_0)} \tag{1}$$

Here a_0 (= initial machine notch length of 15 mm+ fatigue pre-cracking of 3 mm = 18 mm) and a are initial and current values of the crack length, respectively. ΔK_0 is the initial value of ΔK set to 12 MPam$^{1/2}$ for all the materials and regardless of K_{max}. This value of ΔK_0 was chosen to make ΔK = 3 MPam$^{1/2}$ at a = 20 mm, considering the fact that the threshold ΔK of various ferritic alloys is approximately 3 MPam$^{1/2}$ in air. C is the normalized K-gradient $(d(\Delta K)/da)/\Delta K$

set to a value of $C = -0.7$ mm^{-1}, which is a deviation from the ASTM E647 specification of $C > -0.08$ mm^{-1} based on the R-constant test method. This deviation is validated in the case of the K_{max}-constant FCG test method for a value of C as small as $C = -1.2$ mm^{-1}. This is based on the work by Hertzberg et al. [12], who explained that this is true because the crack tip plastic zone size is held constant for K_{max}-constant FCG tests.

Precrack was inserted in air, and then K_{max}-constant FCG tests were run in high vacuum (< 10^{-6} torr). Two K_{max} chosen for the test were 65 and 18 MPam$^{1/2}$. Test results are summarized in Fig. 4.

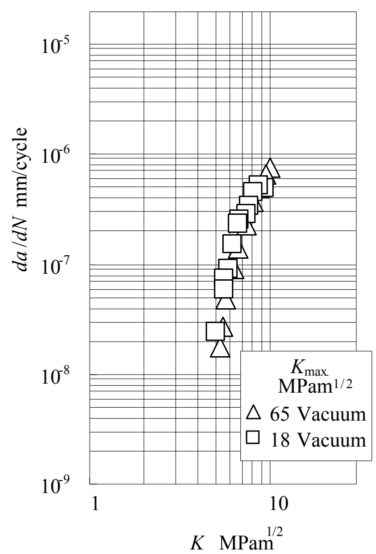


Fig. 4 K_{max}-const. test results (S55C) in high vacuum

We see from Fig. 4 that the decrease in ΔK_{th} due to high K_{max} in vacuum was negligible. From this fact, we conclude that air is a necessary environment for "the decrease in ΔK_{th} due to high K_{max}." This finding does not contradict with our qualitative model that describes the phenomena (Fig. 2, [5]), when we consider that the material embrittlement due to perhaps vapor [9] is eliminated in vacuum, so that the mesoscopic material resistance corresponding to "static failure mode" in our model is high enough to avoid the grain size level static failure at the crack front.

2.3 Fractography

Since S55C did not show "the decrease in ΔK_{th} due to high K_{max}" in vacuum, we only considered the specimen tested under K_{max} = 18 MPam$^{1/2}$, for fractograph investigation. Remember that the precrack was inserted in air. Thus, we compared fractograph of i) in air ($\Delta K \approx 12$ MPam$^{1/2}$; just before precracking ended, Fig. 5), ii) in vacuum ($\Delta K \approx 12$ MPam$^{1/2}$; just after precracking ended, Fig. 6), and iii) in vacuum ($\Delta K \approx \Delta K_{th}$, Fig. 7), by Elionix's ERA-8900FE 3D-SEM (Scanning

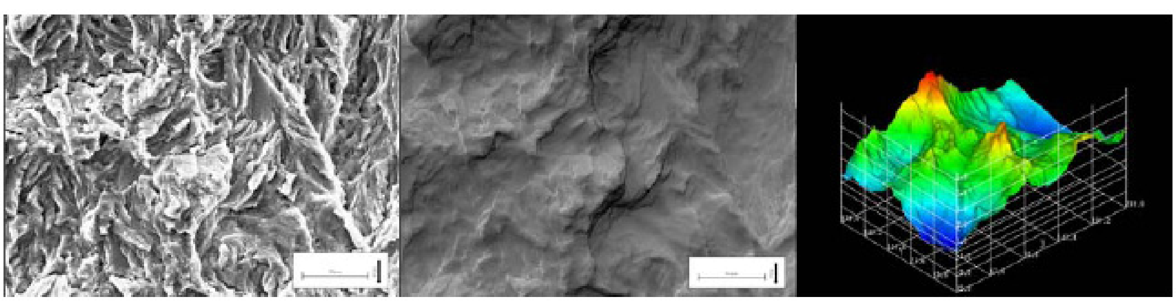
Electron Microscopy). The system has four channel secondary-electron detectors, and has a function to analyze the surface roughness. In each figure, (a) was an image obtained from the detector on the left hand, and (b) was the difference of images obtained from left and right side detectors. (c) was a bird's-eye view, drawn from the height data obtained from the system. One scale unit of (c) in the x, y and z direction is 12, 10 and 2 micron, respectively.

Figure 5 (a)(b), which is difficult to characterize, is a typical fractograph observed regardless of K_{max} or *da/dN* (*Paris region* or ΔK_{th} *region*) in air [5]. This was not surprising considering the fact that striations are not easy to observe for carbon steels like S55C, and considering the magnification rate. Though striations were not observed in Fig. 5 (a)(b), river pattern-like marks were observed, though area ratios were small. Though not shown here, these river pattern-like marks were similar to what we observed for S55C specimens (in air) in the past [5].

On the other hand, no river-pattern like mark was found in vacuum. This was different from what was observed for S55C tested in air [5]. This result was common whether in the Paris region (Fig. 6) or in near the threshold region (Fig. 7). This result seems to be one piece of evidence that indicates static failure mode is eliminated in vacuum.

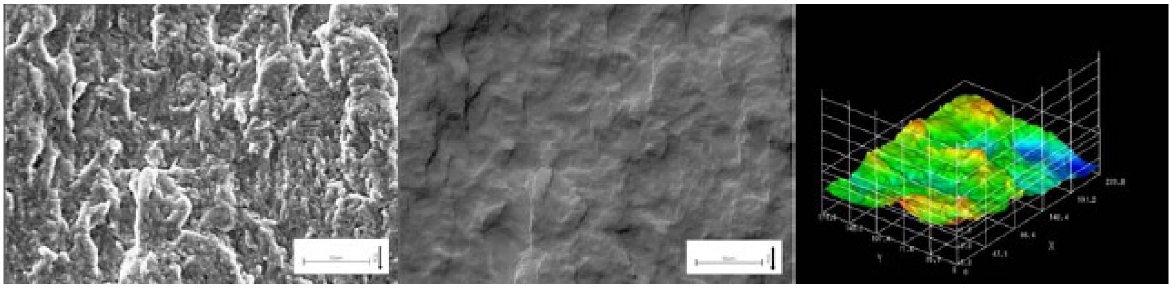
By comparing Figs. 5 and 6, whose nominal crack driving forces are close, we see that the fracture surface in air (Fig. 5 (c)) is rougher compared with that for vacuum (Fig. 6 (c)), and that the former shows more sharp edge at the tip and bottom. This observation for low carbon steel S55C was similar to the results for aluminum alloy 7075-T651 [12] and 7020 [13]. Considering that these fractographic observations were made of specimens with identical K_{max}, and if we assume that static failure mode can be eliminated in high vacuum as suggested by Sunder [9] and Pippan et al. [13], the surface roughness difference between Figs. 5 and 6 might be considered as the presence of the static facture mode. This point is still an issue for future discussion.

By comparing Figs. 6 (c) and 7 (c), both observed in vacuum, we see that the roughness does not change significantly due to the decrease in ΔK.



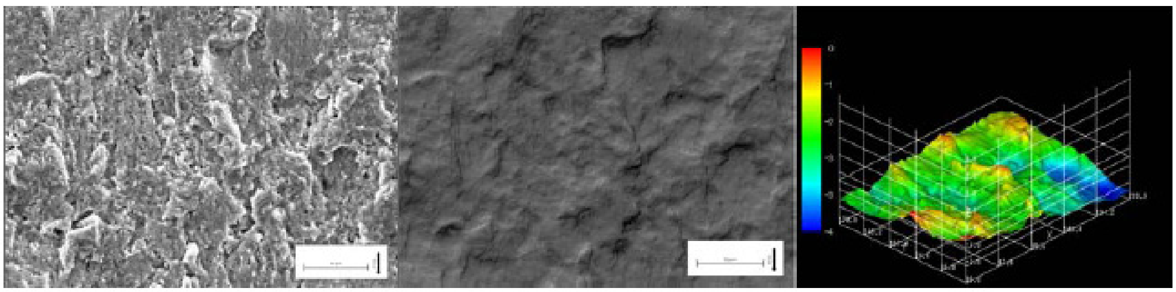
(a) (b) (c)

Fig. 5 Typical fractured surface in the Paris region (in air)
(S55C-3, K_{max} = 18 MPam$^{1/2}$, $da/dN \approx 1 \times 10^{-5}$ mm/cycle).



(a) (b) (c)

Fig. 6 Typical fractured surface in the Paris region (in vacuum)
(S55C-3, K_{max} = 18 MPam$^{1/2}$, $da/dN \approx 1 \times 10^{-5}$ mm/cycle).



(a) (b) (c)

Fig. 7 Typical fractured surface in the near threshold region (in vacuum)
(S55C-3, K_{max} = 18 MPam$^{1/2}$, $da/dN \approx 1 \times 10^{-7}$ mm/cycle).

3. DISCUSSIONS

We reported that carbon steel S55C showed "the decrease in ΔK_{th} due to high K_{max} (FIG. 1 (a))" in air, and concluded that mesoscopic static failure mode kept driving the crack front in the near threshold region [5]. The river-pattern like marks found for the material in the near-threshold region supported our assertion.

On the other hand, "the decrease in ΔK_{th} due to high K_{max}" was not observed for S55C in high vacuum. This finding can be explained on the basis that mesoscopic static failure mode is eliminated in high vacuum, as some researchers insist [9, 13].

We were focused on the topic of "the decrease in ΔK_{th} due to high K_{max}." Recently, some researchers are sharing renewed interest on the effect of mesoscopic static failure (BMF: brittle micro fracture, by some other researchers) on FCG in the Paris region [9, 13] (Fig. 8). Sunder and Pipan et al. insist that BMF is necessary for the striations to be clearly observed in the Paris region. They insist that "…Significantly, if indeed, the BMF component of crack extension accrues at the expense of the slip component, environmental fatigue crack growth cannot be interpreted as a superposition of intrinsic and environment-induced crack extension as suggested by several authors… [9]" Their idea might be interpreted that the intrinsic FCG characteristic is acceralated (Point C moves to CV in Fig. 8) by environment, or more directly by BMF. If the fact that clear striation was seen in air compared with that in vacuum (less number of striations were observed in vacuum) is to be correlated to the environmental effect on slip (or in other words, if we have to accept on the idea that one striation is formed by a single load cycle), Sunder's assertion seems to make sense.

On the other hand, there is an assertion by Vasudenvan et al. that there is a threshold ΔK for a specific FCG rate in the Paris region and that environment reduces this threshold [14]. This idea is illustrated in Fig. 8 as point C moving to CH. This idea is very similar to what we suggest for "the decrease in ΔK_{th} due to high K_{max}." If we interpret the decrease in the threshold ΔK for a specific FCG rate in the Paris region as the decrease in a mesoscopic static failure toughness due to air, then our mesoscopic model for the near threshold region (Fig. 2 [5]) might be easily extended to the Paris region. Our future plan is focused on this point: that is, to validate our mesoscopic model in the Paris region.

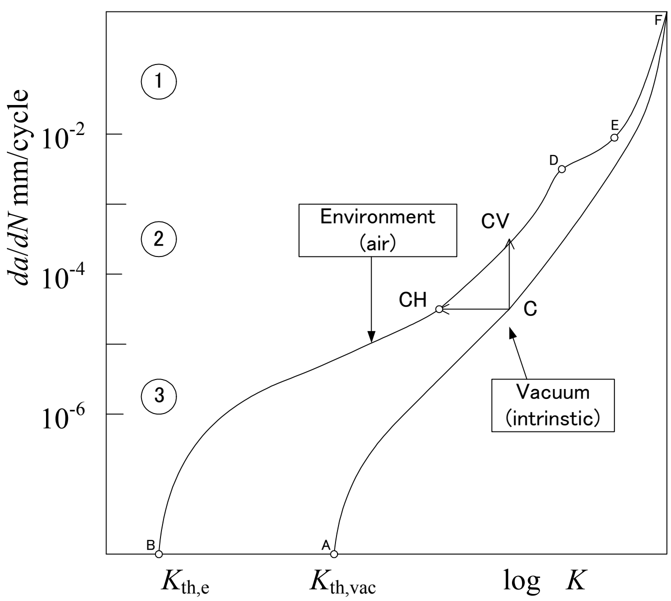


Fig. 8 Environmental effect on FCG

4. CONCLUSIONS

In this paper, we assessed the contribution of environment on "the decrease in threshold stress intensity factor (SIF) range ΔK_{th} due to high maximum SIF K_{max}," that was observed for 0.55% carbon steel S55C in air, by running K_{max}-constant fatigue crack growth (FCG) tests in high vacuum. The decrease in ΔK_{th} due to high K_{max} in vacuum was negligibly small. The results support the validity of our model for the phenomena [5], that microscopic crack growth in a grain due to static mode failure accelerated the expected cyclic crack growth, considering that high vacuum excluded the possibility of static mode failure.

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