Fatigue thresholds at negative stress ratios for ferritic steels and aluminium alloys in flaw evaluation procedures

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Abstract

Fatigue crack growth thresholds ΔK^{th} given in the WRC Bulletin, IIW and BS 7910 are constant values at negative stress ratios. However, the definitions of ΔK_{th} at negative stress ratios are different: K_{max} according to the WRC Bulletin and IIW, and K_{max} - K_{min} according to BS 7910, where K_{max} is the maximum and K_{min} is the minimum stress intensity factors. From fatigue crack growth tests conducted on ferritic steels and aluminium alloys in air at ambient temperatures, the thresholds expressed by K_{max} - K_{min} are variable values at negative stress ratios; that is, the threshold increases with decreasing stress ratio. The thresholds expressed by K_{max} are also variables. K_{max} decreases with decreasing stress ratio. The thresholds at negative stress ratios are not constant; they are affected by compression stress. Therefore, the thresholds given by the WRC Bulletin and IIW are slightly unconservative. The threshold given by BS 7910 is considerably conservative. A suitable definition of the threshold at negative stress ratios for application in flaw evaluation procedures is the variable threshold ΔK_{th} expressed by K_{max} - K_{min}.

Keywords:

Fatigue threshold, Stress ratio, Stress intensity factor range, Flaw evaluation, Ferritic steel, Aluminium alloy

Nomenclature

da/dN : cyclic crack growth rateK_{max} : maximum stress intensity factorK_{min} : minimum stress intensity factor$R$: stress ratio (= σ_{min} /σ_{max} =$K_{\mathrm{min}}/K_{\mathrm{max}}$)$\Delta K_{\mathrm{I}}$: stress intensity factor rangeΔK_{th} : fatigue crack growth thresholdΔK_{th0} : fatigue crack growth threshold at$R = 0.0$

σ_{max} : maximum applied stress

σ_{min} : minimum applied stress

Introduction

Fatigue of materials in the form of stress-number (S-N) curves has been investigated experimentally, and S-N curves are now common in design codes [1, 2]. It is also well known that fatigue crack growth rate$da\ /dN$ is expressed by stress intensity factor range$\Delta K\ _{\mathrm{I}}$, and the relationship between$da\ /dN$ and $\Delta K\ _{\mathrm{I}}$ is used for reference fatigue crack growth rate curves applied in flaw evaluation procedures such as fitness-for-service codes [3, 4].

Fatigue thresholds $\Delta K\ _{\mathrm{th}}$ are the stress intensity factor range $\Delta K\ _{\mathrm{I}}$ values below which fatigue crack growth rates $da\ /dN$ are negligible. The thresholds of fatigue crack growth rates are important in order to determine whether detected defects propagate or not. The fatigue crack growth thresholds are also employed in several flaw evaluation documents [5-7].

Fatigue crack growth thresholds ΔK_{th} are not easy to obtain by experiments, because it takes a long time to determine whether the crack is growing or not. Almost all thresholds for materials have been obtained under cyclic tensile-tensile loadings, which correspond to positive stress ratios. Compared with the values obtained under cyclic tensile-tensile loadings, there are not sufficient data on fatigue thresholds obtained under cyclic tension-compression loadings; that is negative stress ratios. The definition of the threshold ΔK_{th} at negative stress ratios is not clearly given in flaw evaluation documents, as far as the authors are aware.

WRC (Welding Research Council) Bulletin 194 [5], IIW (International Institute of Welding) [6] and BS 7910 [7] give fatigue thresholds as constant values at negative stress ratios. However, the definitions of the thresholds at negative stress ratios differ between the WRC Bulletin, IIW and BS 7910.

This paper focuses on the thresholds for the ferritic steels and aluminium alloys at negative stress ratios provided by the WRC Bulletin, IIW and BS 7910. Fatigue crack growth tests for ferritic steels and aluminium alloys were conducted in an air environment, and the thresholds were compared with those given by the WRC Bulletin, IIW and BS 7910. It is shown that the thresholds are affected by compression stress. A suitable definition of the threshold at negative stress ratios is proposed for application in flaw evaluation procedures.

2. Explanation of fatigue thresholds at negative stress ratios

2.1 Fatigue crack growth rate da/dN

It is well known that the fatigue crack growth rate da/dN is expressed by a function of the stress intensity factor range ΔK_I, and that the growth rate da/dN depends on the applied stress ratio R. The stress ratio is defined by $R = \sigma_{min}/\sigma_{max} = K_{min}/K_{max}$, where σ_{min} is the minimum cyclic applied stress and σ_{max} is the maximum cyclic applied stress. When the stress ratio R is negative, minimum stress σ_{min} is a compression stress. K_{min} and K_{max} are the minimum and maximum stress intensity factors.

In accordance with ASTM E 647 [8], the stress intensity factor range ΔK_I is expressed by

$\Delta K_I = K_{max} - K_{min}$ for 0 [?] R, and

$\Delta K_I = K_{max}$ for $R < 0$.

When the stress ratio is 0 [?] R, the fatigue crack growth rate da/dN depends on the range of the stress intensity factor $K_{max} - K_{min}$. When the stress ratio is negative ($R < 0$), the stress intensity factor range $\Delta K_I = K_{max} - 0$. Compression stress does not contribute to the crack growth rate. ASTM E 647 notes that it is conventional to use only the positive portion of the stress range to calculate the crack driving force. ASTM E 647 also notes that increases in fatigue crack growth rates can be observed as the R becomes more negative.

2.2 Fatigue thresholds

The fatigue threshold ΔK_{th} is determined by the fatigue crack growth rate da/dN versus ΔK_I, where the growth rate approaches zero. Practically, ΔK_{th} is determined as a fatigue crack growth rate of between 10^{-7} to 10^{-8} mm/cycle by tests applying a decreasing stress intensity factor.

The threshold value ΔK_{th} is also expressed by the range $K_{max} - K_{min}$ for 0 [?]R, as shown in Equation (1). When the stress ratio R is negative, the definition of ΔK_{th} is deemed to be K_{max}, in accordance with Equation (1). However, this is problematic, because the effect of cyclic compression stress on the fatigue threshold is not clear, as noted in ASTM E 647. Fatigue crack growth thresholds ΔK_{th} are currently employed in several flaw evaluation documents. These documents, containing thresholds ΔK_{th} for $R < 0$, are investigated below.

3. Application of fatigue thresholds at negative stress ratios

3.1 Fatigue thresholds given in flaw evaluation documents

WRC (Welding Research Council) Bulletin 194 gives thresholds for mild, low-alloy and austenitic steels as follows [5]:

ΔK_{th} = 6.4(1 - 0.85R) ksi[?]in. = 7.0(1 - 0.85R) MPa[?]m for 0.1< R <1.0, and

ΔK_{th} = 5.5 ksi[?]in. = 6.0 MPa[?]m for R [?] 0.1.

Figure 1 illustrates the relationship between ΔK_{th} and the stress ratio R for steels. The threshold ΔK_{th} increases with decreasing stress ratio R . When $R < 0.1$, ΔK_{th} is given by a constant value. The definition of ΔK_{th} for $R < 0$ is not clearly stated. It appears that the threshold at negative stress ratios is expressed by K_{max} only.

The International Institute of Welding (IIW) Commission gives thresholds ΔK_{th} in units of MPa[?]m for ferritic steels at elevated temperature and for aluminium alloys [6]. The ΔK_{th} for ferritic steels is given as follows:

ΔK_{th} = 2 for 0.5 [?] R ,

ΔK_{th} = 5.38 - 6.77R for 0 [?] R< 0.5, and (3)

ΔK_{th} = 5.38 for $R < 0$.

The relationship between ΔK_{th} and the stress ratio R for ferritic steels is shown in Figure 1. The threshold ΔK_{th} for ferritic steels is a constant value for $R < 0$.

The ΔK_{th} in units of MPa[?]m for aluminium alloys given by IIW is as follows:

ΔK_{th} = 0.7 for 0.5 [?] R ,

ΔK_{th} = 1.8-2.3R for 0 [?] R< 0.5, and (4)

ΔK_{th} = 1.8 for $R < 0$.

The threshold ΔK_{th} for aluminium alloys is also a constant value for $R < 0$. Figure 2 depicts the threshold for aluminium alloys. The definition of the threshold for $R < 0$ is not given in the IIW Commission document. The definition of the threshold for $R < 0$ for steels and aluminium alloys is deemed to be K_{max} only.

British Standards (BS) 7910 gives recommended fatigue crack growth thresholds for steels (excluding austenitic steels) and aluminium alloys for assessing welded joints and unwelded components [7]. For unwelded steels (excluding austenitic steels) in air and with cathodic protection in marine environments at temperatures up to 20°C, the thresholds ΔK_{th} given by BS 7910 are the same as in Equation (3).

For welded joint aluminium alloys, the threshold in air or non-aggressive environments at temperatures up to 20°C is given by BS 7910 as follows:

ΔK_{th} = 0.7 (5)

where the threshold in units of MPa[?]m for aluminium alloys is a constant value at both positive and negative stress ratios. The requirement stipulated in BS 7910 (in the chapter "Assessment for Fatigue") is to "use full stress range regardless of applied stress ratio (R)". The full stress range means σ_{max} - σ_{min}, which corresponds to K_{max} -K_{min}. The definition of the threshold for $R < 0$ is $\Delta K_{th} = K_{max} - K_{min}$. The thresholds ΔK_{th} for the steels and aluminium alloys given in BS 7910 are shown in Figures 1 and 2 as a function of the stress ratio R .

The thresholds given by the WRC Bulletin, IIW and BS 7910 are stated as constant values for $R < 0.1$ or $R < 0$, as shown in Figures 1 and 2. However, the definitions of the thresholds for $R < 0$ take two forms: $\Delta K_{th} = K_{max} - K_{min}$ or $\Delta K_{th} = K_{max}$. The expression by either $\Delta K_{th} = K_{max} - K_{min}$ or $\Delta K_{th} = K_{max}$ for R< 0 is significantly different from actual flaw evaluation analyses. Below, the stress intensity factors K_{max} and K_{min} are investigated in detail using the stress ratio $R = K_{min} / K_{max}$ and compared with the thresholds given by the WRC Bulletin, IIW and BS 7910.

3.2 Maximum stress intensity factors K_{max} at thresholds

The WRC Bulletin, IIW and BS 7910 give constant thresholds ΔK_{th} at negative stress ratio R . However, the definitions of negative stress ratio are different, as mentioned above: $\Delta K_{th} = K_{max}$ according to the WRC Bulletin and IIW, $\Delta K_{th} = K_{max} - K_{min}$ according to BS 7910. The thresholds ΔK_{th} given by the WRC Bulletin, IIW and BS 7981 are transformed to K_{max} using the stress ratio R , that is $K_{max} = \Delta K_{th} / (1 - R)$, derived from $K_{min} = RK_{max}$.

The relationship between K_{max} at the threshold and R for ferritic steels provided by the WRC Bulletin, IIW and BS 7981 is depicted in Figure 3. As shown in Equations (2) and (3), the thresholds K_{max} given in the WRC Bulletin and IIW, expressed by $\Delta K_{th} = K_{max}$ are constant at $R < 0$. However, the thresholds K_{max} given in BS 7910, expressed by Equation (3), decrease with decreasing stress ratio R .

Figure 4 also shows the relationship between K_{max} at the threshold and R for aluminium alloys provided by Equation (4) according to the IIW and Equation (5) according to BS 7910. The relationship between K_{max} and stress ratio R for aluminium alloys shows the same trend as in ferritic steels, as shown in Figure 3.

The value of K_{max} at $R < 0$ differs significantly from the values determined via either $\Delta K_{th} = K_{max}$ or $\Delta K_{th} = K_{max} - K_{min}$. Furthermore, the expression of $\Delta K_{th} = K_{max}$ = constant for $R < 0$ means that compression stress does not contribute to the value of the threshold, and $\Delta K_{th} = K_{max} - K_{min}$ = constant for $R < 0$ means that the effect of compression stress on the fatigue threshold is significantly large. It is important to define the threshold ΔK_{th} at negative stress ratios.

4. Fatigue threshold tests at negative stress ratios

4.1 Experimental procedures

In order to clarify the expression of fatigue thresholds at $R = 0$ and $R < 0$, fatigue crack growth tests for ferritic steels and aluminium alloys were performed by one of the authors [9]. The test was conducted using a Vibrophore fatigue testing machine at ambient temperature. Fatigue crack growth rates da/dN and fatigue thresholds ΔK_{th} were obtained by using flat plate specimens with trough-wall center notches. Fatigue crack growth rates were obtained by decreasing the load amplitude until crack growths were not observed. The thresholds were determined after 2×10^7 cycles by a microscope at 50× magnification with a minimum scale of division of 0.02 mm.

The materials employed were ferritic steels and aluminium alloys. There were four steels: JIS (Japan Industrial Standards) SM 410 (Class 410 rolled steel for welded structures), JIS HT 800 (class 800 high tensile strength steel), A533-B low alloy steel weldments, and JIS FC 200 (gray cast iron). The mechanical properties of these steels and the geometries of the center cracked flat plate specimens are shown in Table 1. The aluminium alloys used in the tests were JIS A1100-0 (99.7% aluminium) and JIS AC4A-T6 cast aluminium. The mechanical properties and the geometries of the specimens for aluminium alloys are tabulated in Table 2.

4.2 Test results for fatigue thresholds

Fatigue crack growth rates da/dN versus stress intensity factor range ΔK_{I} for ferritic steels and aluminium alloys at $R = 0$ and $R < 0$ are shown in Figures 5 and 6. The definition of the range is $\Delta K_{I} = K_{max} - K_{min}$ for $R = 0$ and for $R < 0$. When $R = 0$, the stress intensity factor range becomes $\Delta K_{I} = K_{max}$, because $K_{min} = 0$. As can be seen in Figures 5 and 6, fatigue crack growth rates da/dN for ferritic steels and aluminium alloys decrease with decreasing stress ratio R .

Tables 3 and 4 show the thresholds ΔK_{th} for ferritic steels and aluminium alloys obtained from Figures 5 and 6. These experimental data are depicted in Figure 7. The fatigue thresholds ΔK_{th} increase with decreasing stress ratio R , as shown in Figure 7.

From the values of ΔK_{th} expressed by $K_{max} - K_{min}$, each K_{max} and K_{min} is easily obtained from the stress ratio R . For example, the threshold for A533B is ΔK_{th} = 27.5 MPa[?]m at R = -5. From the ratio

K_{min}/K_{max} = -5, the K_{max} is obtained by $\Delta K_I = 27.5 = K_{max} - K_{min} = 6\ K_{max}$. Then, the threshold expressed by K_{max} at R = -5 is K_{max} = 4.6 MPa[?]m. Tables 3 and 4 tabulate the maximum stress intensity factors K_{max} at negative stress ratios for ferritic steels and aluminium alloys respectively. The thresholds ΔK_{th} increase and the K_{max} decrease with decreasing stress ratio R. The results for K_{max} suggest that K_{max} is affected by compression stress.

5. Effect of compression stress on fatigue thresholds

From the values of R and ΔK_{th} as shown in Tables 3 and 4, the maximum stress intensity factors K_{max} are normalized by ΔK_{th0}, where ΔK_{th0} is the threshold at R = 0. Table 5 shows the ratio $K_{max}/\Delta K_{th0}$ at negative stress ratio R for ferritic steels and aluminium alloys. The ratios $K_{max}/\Delta K_{th0}$ are also shown in Figure 8 as a function of the stress ratio R . It can be seen that the ratio $K_{max}/\Delta K_{th0}$ decreases with decreasing stress ratio R . This means that the thresholds at negative stress ratios are slightly affected by compression stresses, as suggested by ASTM E 647.

Based on the experimental data for $K_{max}/\Delta K_{th0}$, the lower bound of $K_{max}/\Delta K_{th0}$ can be obtained semi-empirically by a function of stress ratio R , as shown in Figure 8. The relationship between $K_{max}/\Delta K_{th0}$ and R is expressed by

$K_{max}/\Delta K_{th0} = (1 - 0.7R)/(1 - R)$. (6)

When R is decreasing, compression stress gradually influences the threshold value in accordance with Equation (6). For example, the thresholds decreases to 85% due to compression stress at R = -1, and to 75% due to compression stress at R = -5.

Figure 8 also illustrates the ratio $K_{max}/\Delta K_{th0}$ as per the WRC Bulletin, IIW and BS 7910. The ratios $K_{max}/\Delta K_{th0}$ as per the WRC Bulletin and IIW are constant at 1.0, irrespective of materials, because $\Delta K_{th} = K_{max}$ = constant at all negative ratios R . The definition of the threshold in BS 7910 is expressed by $K_{max} - K_{min}$ = constant, and the K_{max} is expressed by $K_{max} = \Delta K_{th}/(1 - R)$ and ΔK_{th0} = constant. Then, the ratio $K_{max}/\Delta K_{th0}$ as per BS 7910 is easily obtained by

$K_{max}/\Delta K_{th0} = 1/(1 - R)$. (7)

The ratio $K_{max}/\Delta K_{th0}$ denoted as per BS 7910 is also irrespective of materials. The ratio $K_{max}/\Delta K_{th0}$ significantly decreases with decreasing stress ratio R .

Conclusively, based on the experimental results, thresholds at negative stress ratios are affected by compression stress. The thresholds given in the WRC Bulletin and IIW are not affected by compression stress, and the thresholds given in the WRC Bulletin and IIW are slightly unconservative. The thresholds given in BS 7910 decrease rapidly with decreasing stress ratio R , and the thresholds given in BS 7910 are significantly conservative.

Using Equation (6), the threshold for each material at negative stress ratios can be expressed as follows:

$K_{max} - K_{min} = \Delta K_{th0}\ (1 - 0.7R)$ (8)

When the threshold ΔK_{th0} is only known at R = 0, the threshold at negative stress ratios for each material can be estimated by Equation (8). For example, the threshold for SM 410 is ΔK_{th} = 8.8 MPa [?]m at R = 0, as shown in Table 3. For the threshold at $R < 0$, Equation (8) may be written as $K_{max} - K_{min} = 8.8(1 - 0.7R)$, and the threshold at R = -1 becomes $K_{max} - K_{min}$ = 14.96, which is in good agreement with 15.0 in Table 3. From the perspective of application in flaw evaluation procedures, the definition of thresholds at negative stress ratios can suitably be written using variable threshold values with $K_{max} - K_{min}$, because fatigue tests are conducted on testing machines by pre-setting the values σ_{max} and σ_{min}, so the tests proceed within this interval.

6. Summary and conclusions

Fatigue thresholds ΔK_{th} given in the WRC Bulletin, IIW and the 7910 are constant at under negative stress ratios R . However, there are two types of definitions of ΔK_{th}: K_{max} in the WRC Bulletin and IIW, and K_{max}-K_{min} in BS 7910.

From the fatigue crack growth tests conducted on ferritic steels and aluminium alloys, the thresholds expressed by K_{max} - K_{min} increase with decreasing stress ratio R , and the thresholds expressed by K_{max} decrease with decreasing stress ratio R . The thresholds ΔK_{th} are not constant at negative stress ratios; the thresholds at negative stress ratios are affected by compression stress.

It has been found that the thresholds given in the WRC Bulletin and IIW are slightly unconservative. The thresholds given in BS 7910 are strongly affected by compression stress, and the BS7910 gives considerably conservative thresholds.

Furthermore, the threshold equation at negative stress ratios for each material can be derived from the effect of compression stress, when the threshold at $R = 0$ is known. A suitable way of expressing for the threshold at negative stress ratios for application in flaw evaluation procedures is to use variable thresholds ΔK_{th} expressed by K_{max}- K_{min}.

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