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A METHOD FOR ACCELERATION OF DECREASING *ΔK* FCGR TESTS

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ABSTRACT

An alternative method of accelerating decreasing *ΔK* FCGR tests has been proposed in this paper in order to address experimental difficulties that are often faced when conducting such tests using the conventional technique. The equation for the envelope that is to be followed for reducing the *ΔK* level as the crack grows has been derived from considerations of decreasing the monotonic plastic zone size at a constant rate. Through experimental assessment of the alternative method and examination of crack closure effects, it has been shown that it does not lead to the accumulation of crack growth retardation effects. The new method has been shown to be particularly suitable for high strength materials. The employment of the method for obtaining threshold regime corrosion fatigue crack growth data has been demonstrated.

KEYWORDS

Fatigue crack growth, FCGR test method, Decreasing *ΔK* test, Crack closure, HSLA steel

INTRODUCTION

Decreasing *ΔK* fatigue crack growth rate (FCGR) tests are indispensable for obtaining fatigue crack growth resistance of materials at low levels of crack driving force. Conventionally such tests are conducted by a load-shedding procedure laid down in the ASTM standard E647 [1]. In this procedure, suggested by Saxena *et al.* [2], loads are progressively reduced as the crack length a increases such that the *ΔK* envelope of the test is forced to follow the relation

$$\Delta K = \Delta K_o \, e^{C(a-a_o)} \tag{1}$$

In the above equation, ΔK_o and a_o are the stress intensity factor (SIF) range and crack length respectively with which the test is started, and C is a negative constant (standardised at -0.08 mm^{-1}). Eqn. 1 was obtained based on the requirement that the fractional change in the monotonic plastic zone size associated with the fatigue crack remains constant with increase in a so as to preclude the accumulation of overload retardation effects. Figure 1 gives a schematic of the form of the *ΔK* vs a curve described by Eqn. 1.

From the nature of the conventional *ΔK* envelope shown in Figure 1, it can be envisaged that as lower *ΔK* values are achieved, cracks have to be grown through larger and larger increments in order to produce a given reduction in *ΔK*. Due to this, and because crack growth rates decrease as the *ΔK* is lowered, longer time intervals are required to produce progressive reductions in *ΔK*. For growing down to low values of *ΔK* using the conventional technique therefore, fatigue cracks have to be grown through considerable length. In order to accommodate such cracks, specimens have to be sufficiently large. Also the number of cycles required to be imposed to grow a long crack at diminishing growth rates can often be very large, and it is often advantageous to conduct tests at high frequencies to cut down on the time requirement for tests.

To the experimentalist, using large specimens, carrying out tests through long periods, or conducting tests at high frequencies are often not viable options. This is especially true when product or component size restricts the dimensions of specimens, or when FCGR tests are to be conducted in corrosive media at low frequencies to study corrosion-fatigue behaviour. In order to cope with such experimental problems associated with conventional decreasing ΔK FCGR testing, a new relation for the decreasing ΔK envelope that considerably accelerates tests is presented in this paper. The derivation of this relation, and verification of the absence of unwanted retardation effects, notwithstanding the faster decrement rate of ΔK, is provided below. An application of the new method to obtain threshold regime corrosion fatigue crack growth data is also given.

DERIVATION OF ALTERNATE ΔK ENVELOPE

From studies on overload effects on fatigue crack growth (for example [3]) it is known that reduction of fatigue cycle amplitude can lead to retardation of crack growth rates. During decreasing ΔK FCGR testing, similar situations may arise due to the progressive reduction of load amplitudes, and cyclic loads must be reduced at a gentle rate in order to minimize retardation effects. As retardation effects are proportional to the relative decrease in the size of the monotonic plastic zone attending the crack tip, minimal retardation effects would be induced if the fractional change in the plastic zone size were very small. This requirement can be written as

$$\frac{-\Delta r}{r} = x\,, \; x \perp 1 \tag{2}$$

where r is the plastic zone size and Δr denotes the change in the plastic zone size accompanying reduction of loads, its sign indicating a decremental change. The plastic zone size can be taken as per Irwin's definition [4] as

$$r = \frac{1}{2\pi}\left(\frac{K_{\max}}{\sigma_y}\right)^2 \tag{3}$$

in which $K_{\max}$ is the maximum SIF of the fatigue cycle and σ_y is the yield stress of the material under test.

Retardation after the imposition of overloads is known to be operative through a distance that is proportional to the extent of the overload plastic zone [3,5]. Crack growth rates recover to their original levels only after the fatigue crack has been grown out through this distance. For the case of decreasing ΔK FCGR testing, a comparable situation may arise if crack growth retardation effects are brought about by reduction of cyclic amplitudes. In order to avert the accumulation of retardation effects significantly affecting crack growth rates, it is necessary that cracks be grown out through multiples of prior plastic zone dimensions before subsequent reductions of cyclic amplitudes. This condition can be stated as

$$\Delta a = y\, r, \; y \, \pi \, 1 \tag{4}$$

in which Δa is the crack growth increment between reductions of load.

Eqns. 2 and 4 can be combined for the case of continuous reduction of cyclic amplitudes to write

$$\frac{\mathrm{d}r}{\mathrm{d}a} = -\frac{x}{y} \tag{5}$$

Substitution of Eqn. 3 into Eqn. 5 gives

$$K_{\max}\frac{\mathrm{d}K_{\max}}{\mathrm{d}a} = -\frac{x}{y}\,\pi\sigma_y^{\,2} \tag{6}$$

which on integration with initial limits of a_o and K_{maxo} (the K_{max} of the fatigue cycle at start of test) produces

$$K_{max} = \sqrt{K_{maxo}^2 - Q\,(a\text{-}a_o)} \tag{7}$$

with

$$Q = 2\pi\sigma_y^{\,2}\frac{x}{y} \tag{8}$$

For the case of tests with constant load ratio R, Eqn. 7 can be re-written as

$$\Delta K = \sqrt{\Delta K_o^{\,2} - Q\,(1\text{-}R)^2\,(a\text{-}a_o)} \tag{9}$$

Eqn. 9, alongwith Eqn. 8, thus represents an alternate ΔK envelope that may be employed in conducting decreasing ΔK FCGR tests.

The conventional technique utilizes a ΔK envelope that is invariant for all types of materials and mean level of fatigue cycles. This is surprising considering that crack tip plasticity, which is thought to be responsible for retardation effects that may be induced, is majorly governed by the flow behaviour of the material and the mean load and amplitude of the fatigue cycle. In the proposed method for accelerating decreasing ΔK FCGR tests, the exact shape of the envelope is determined by the yield stress σ_y of the material under test (see Eqn. 8), and the R-ratio of the fatigue cycle (see Eqn. 9). A schematic of the ΔK envelope in Eqn. 9 is superimposed in Figure 1. It is not difficult to visualize that for appropriate choice of controlling factors, lower values of ΔK can be attained within much smaller extensions of crack length, as compared to the conventional technique. Having said that, it must be pointed out that despite the nature of the proposed envelope, it may not provide any advantage over the conventional technique in case of material with low σ_y or for tests at very high R-ratios.

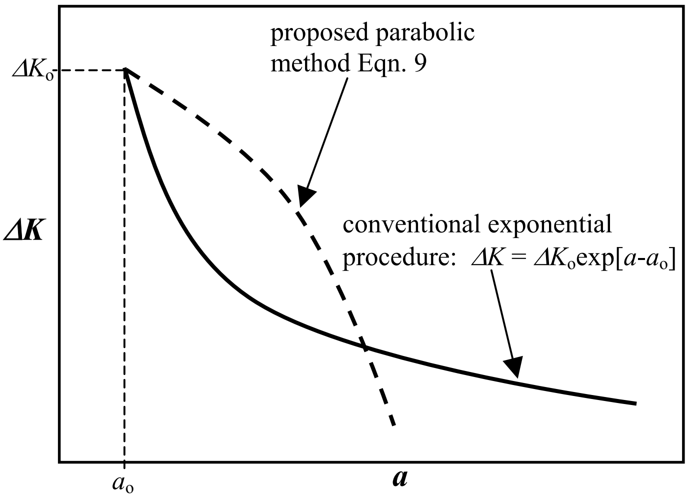

Figure 1: Schematic of reduction of ΔK with a as per conventional procedure and the proposed method

Other than the σ_y and R, x and y in Eqn. 8 will also determine the rapidity of the rate of decrease of ΔK. As an informed guess, x and y can be taken as 0.1 and 10 respectively, so that x/y is 0.01. Lumping a user preference parameter t through which the user may exercise control over the rate of ΔK decrement, Eqn. 8 can be explicitly re-written as

$$Q = 0.0628\ \sigma_y^{\,2}\ t \tag{10}$$

in which for t=1, x/y assumes a value of 0.01. In order to decide on a value of t that is optimum (i.e. one that allows the fastest rate of reduction of ΔK without inducing any retardation effects) for a given material, the effect of t must be experimentally verified. Such an exercise is detailed below for two varieties of Cu-strengthened HSLA steel that is used for naval structural applications.

EXPERIMENTAL VERIFICATION OF ACCELERATED TESTING PROCEDURE

Two varieties of Cu-strengthened HSLA steels, designated here as HSLA-80 and HSLA-100, were employed for carrying out validation FCGR tests. The HSLA-80 steel had a yield strength of 650 MPa, and the HSLA-100 steel had a yield strength of 840 MPa. The steels were available in the quenched and tempered condition. Standard SENB specimens in L-T orientation, of width 20mm and thickness 10mm were used for FCGR tests that were conducted on a 100kN closed loop servo-hydraulic testing machine. The machine was equipped with a digital controller, interfaced to a computer. Tests were controlled using a software in which the desired ΔK reduction scheme could be implemented. Crack lengths were monitored by the software using the compliance technique, which was based on location independent compliance crack length relations [6]. The software performed on-line crack closure measurements following the recommendations of ASTM task group E 24.04.04 [7].

Tests were carried out in air with $R = 0.1$ and at 10 Hz frequency. For conventional decreasing ΔK tests, Eqn. 1 was used to control the ΔK envelope, using $C = -0.08\ \text{mm}^{-1}$. Tests based on the proposed method employed Eqn. 9, with Q calculated from Eqn. 10 using $t = 1$, 2 and 3, and the appropriate value of σ_y. The ΔK envelopes, normalised with respect to a ΔK_o of 25 MPa√m, arising from these values of t are shown in Figure 2 for both varieties of HSLA steels. The ΔK envelope for the conventional technique is also shown in the figure. It may be noted from Figure 2 that for HSLA-80, t=1 does not lead to any advantage in comparison to the conventional technique, as discussed earlier.

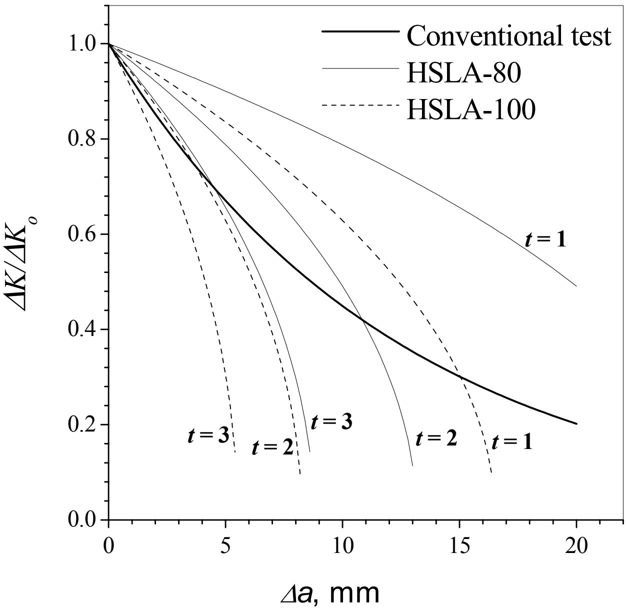

Figure 2: Normalised ΔK envelope obtained for various values of t in HSLA-80 and HSLA-100 steels

Figures 3(a) and (b) show Paris plots of the FCGR data obtained using the proposed method with $t = 1$, 2 and 3 for HSLA-80 and HSLA-100 steels respectively. The data obtained by employing the conventional technique are also included in the plots. As a first impression, it appears from the plots that the data obtained by the proposed method is compatible with the FCGR determined by the conventional technique. Data from the various tests lie within a small scatter band, which is thought to be acceptable. In order to comment conclusively on the acceptability of the data, it is necessary however to inspect the closure characteristics of the data generated. Figures 4(a) and (b) show plots of K_{cl}/K_{max} against the applied ΔK for the various tests conducted, for HSLA-80 and HSLA-100 steels respectively. K_{cl} is the crack closure SIF, corresponding to the load at 2% deviation from the open crack (i.e. linear) load-COD slope, that is determined on-line by the testing software. It can be seen from Figure 4(b) that for the HSLA-100 steel, K_{cl}/K_{max} for all tests follow the same path with reduction of ΔK. Hence for the higher strength HSLA-100 steel, variation of the rate of plastic zone size reduction, controlled by changing t, does not seem to affect crack closure behaviour. For the lower strength HSLA-80 steel, however, it is evident from Figure 4(a) that at the fastest rate of plastic zone size reduction (t=3), crack closure levels are higher, indicating that retardation effects have been manifested. It may be therefore be prudent to restrict the value of t to ≤ 2 for this steel.

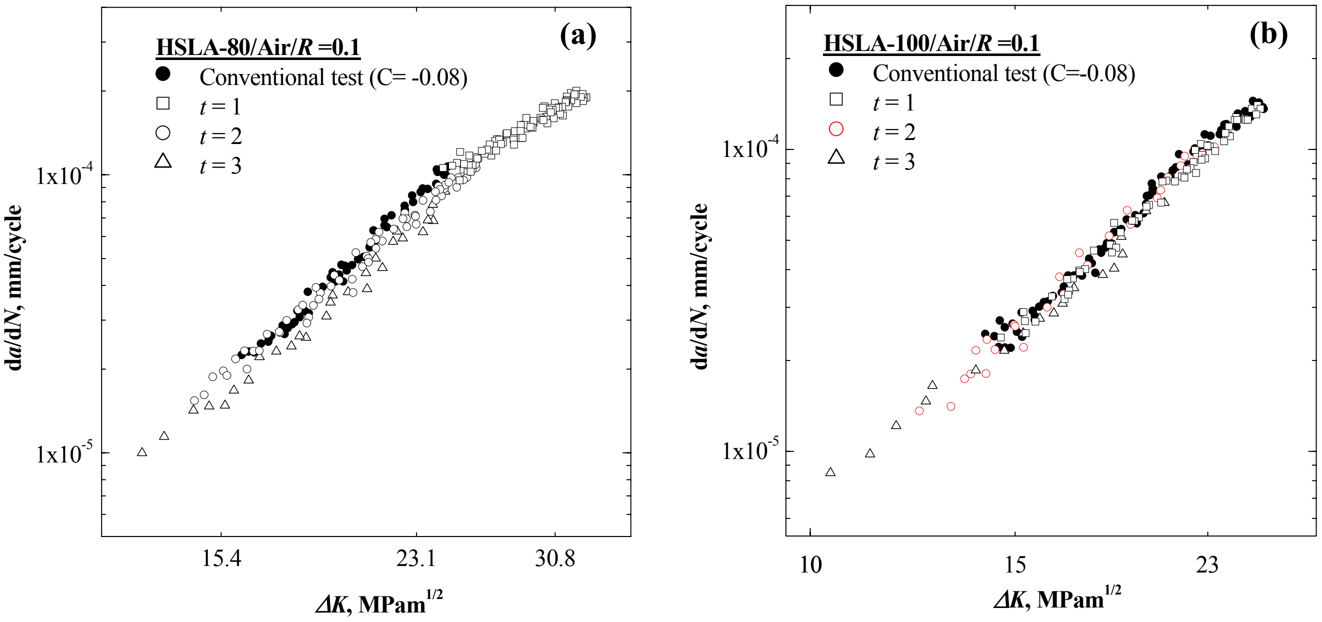

Figure 3: FCGR data of (a) HSLA-80 and (b) HSLA-100 steels obtained by using the proposed method with various values of *t*, and the conventional technique

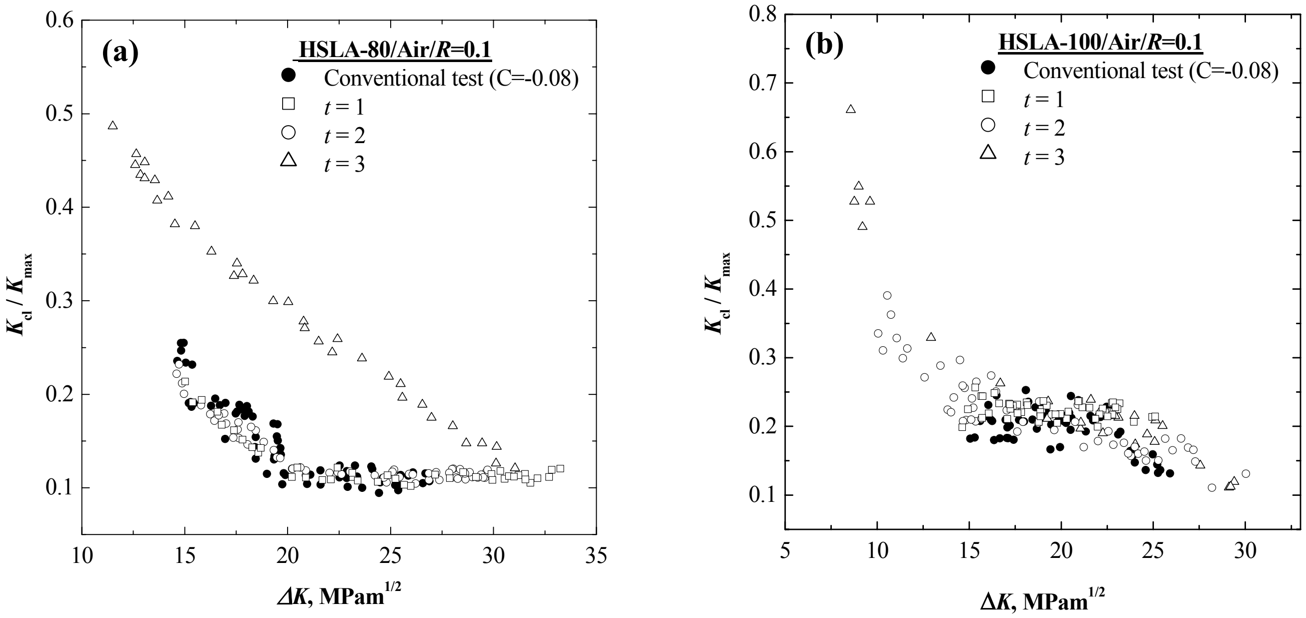

Figure 4: Crack closure behaviour in (a) HSLA-80 and (b) HSLA-100 steels during decreasing *ΔK* FCGR tests using proposed and conventional methods

From the validation studies described above it appears that the proposed scheme of *ΔK* reduction can be employed for conducting decreasing *ΔK* FCGR tests. It is also clear that the proposed method will lead to acceleration of tests only in the case of higher strength materials. An example of use of this new scheme for the generation of threshold level FCGR data is described below.

GENERATION OF THRESHOLD REGIME CORROSION FATIGUE CRACK GROWTH DATA

Corrosion fatigue crack growth rate (CFCGR) tests are typically conducted at low frequencies in aqueous environments. The time requirement for a test can often be prohibitively long if a test is stretched into the threshold regime. The proposed accelerating procedure is especially suitable for this situation.

CFCGR tests were carried out at a frequency of 1 Hz on Cu-strengthened HSLA-100 steel specimens using both the conventional technique and the proposed accelerating methodology with t = 2. The tests were conducted with the same experimental tools as described earlier. Specimens were loaded within a bath containing 3.5% NaCl solution which was part of the load train of the testing machine.

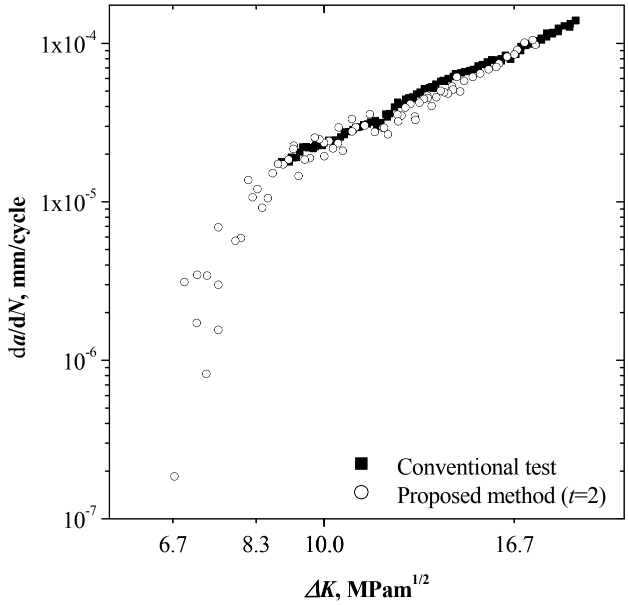

Figure 5: Corrosion fatigue crack growth behaviour of the HSLA-100 steel obtained by decreasing *ΔK* FCGR tests conducted by conventional and proposed methods

The results of the CFCGR tests are presented in Figure 5. It can be seen that for the common regime of *ΔK* in tests conducted by the conventional technique and the proposed method, the crack growth rates are comparable. Additionally it is evident that with the proposed method it is possible to achieve lower levels of *ΔK* covering a large part of the threshold regime as well for essentially the same extent of crack growth. It can be estimated that in order to grow down to *ΔK* of ~6.5 MPa√m using the conventional testing procedure at 1 Hz test frequency, the test would have to continue for ~120 hours (not considering that it may not be possible to accommodate the crack length in the specimen). In comparison, the test conducted according to the proposed method required 21 hours. It is thus demonstrated that the proposed method of decreasing *ΔK* FCGR testing provides tremendous experimental advantage.

CONCLUSIONS

An alternative method of decreasing *ΔK* FCGR testing has been proposed in this paper which substantially shortens the time required to carry out such tests by the conventional procedure. The proposed method has been implemented on two varieties of HSLA steel, and it is shown that for judicious selection of the governing parameters (i.e. *t*), the integrity of FCGR data obtained can be assured. The method is particularly suitable for use with materials of high strength and in situations where limitations of specimen size are imposed or when the time required for experimentation can be expected to be long.

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